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Paul S. Adler

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SHARED LEARNING

PAUL S. ADLER
*Department of Industrial Engineering and Engineering Management,
Stanford University, Stanford, California* 94305

Total productivity learning curve results are reported for several departments of an electronic equipment manufacturer with plants in the U.S., Europe and Asia. These results were used to focus qualitative field investigations into the behavioral and cognitive determinants of considerable diversity across departments in learning curve parameters. The field investigation suggested that three forms of shared learning are critical to manufacturing productivity improvement: (1) sharing across the Development/Manufacturing interface, (2) sharing between the primary location and plants that started up later, and (3) the ongoing sharing among plants after start-up. Innovations in each of these three processes are identified and mapped onto Daft and Lengel's information uncertainty/equivocality matrix. Implications for the role of manufacturing engineering are identified.

(PRODUCTIVITY; LEARNING; MANUFACTURABILITY; UNCERTAINTY; ORGANIZATION DESIGN)

1. Introduction

This article explores the forms of learning that characterize the evolution of productivity performance at "Hi-Tech," a multi-national, multi-plant electronics firm. The focus is on the behavioral and cognitive processes that underlie the differences in learning curve parameters in the eight departments studied.

Two propositions underlie this article's methodology. First, that progress in learning curve research will be stimulated by an elucidation of the processes that give rise to both the learning curve's approximate regularity as well as to the diversity of learning parameters found in the real world. Second, at this stage of such process research, inductive field investigations combining quantitative and qualitative data can be a fruitful source of hypotheses, concepts and questions for future work.

The idea that performance improves with experience has a distinguished pedigree in psychological research at the individual level (see review by Newell and Rosenbloom 1981). The cognitive processes at work in "learning by doing" (Anzai and Simon 1979) have been progressively elucidated.

But research on the learning curve at the organizational level has remained almost exclusively focused on outcomes, rather than processes. Most of these studies have focused on better specifying the "experience" variable. Cumulative output was privileged in the original formulation by Wright (1936) and in most studies since then. Arrow (1962a) and Sheshinski (1969) examine cumulative investment as an alternative. Alchian (1959) and Hirschleifer (1962) distinguish between rate of output and scheduled volume of output. Sheshinski (1969), Rapping (1965), Stobaugh and Townsend (1975) discuss time as an alternative proxy for experience. Attention has also been paid to the functional form of the learning curve, with debate focusing on the existence of plateaus, the so-called Stanford-B effect, and the possibility of a cubic form (Carr 1946; Asher 1956; Conway and Schultz 1959; Baloff 1966a, b, 1970, 1971; Carlson 1973).

But studies of the differences in the empirical magnitudes of learning curve parameters have, with very few exceptions, contented themselves with *a posteriori* commentary. Stobaugh and Townsend (1975) comment on the fact that the cost of "standardized" petrochemical products falls much faster than that of nonstandardized ones. Hirsch (1952,

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1956) notes differences between machine and assembly operations. Asher (1956) observes differences between new aircraft and old. But the learning curve models themselves almost never incorporate any conditioning variables, one of the few exceptions being Levy's (1965) inclusion on worker training variables. The closest perhaps to a behavioral model is the search model developed by Muth (1986); but it does not address the substantive content of what is learned, only the general form of the learning process.

Another, related area of research, namely the international transfer of technology literature, might be expected to have addressed the causal factors of learning. But here too, the focus has been on more aggregate phenomena—such as whether transactions are effected in a market or an intra-firm mode (Davidson and McFetridge 1984). Very little attention has been given to the empirical exploration of the factors explaining the relative efficiency of different ways of managing intra-firm transfers.

It is not that we lack suggestions as to factors that might warrant exploration. Conway and Schultz (1956) offer an impressive list of both pre-production and during-production factors susceptible to accelerating learning. Hirschmann (1964) and Hayes and Wheelwright (1984) discuss the various managerial actions that can accelerate learning. But the empirical research has focused on better specifying the regularity of the learning curve phenomenon, not on explicating the reasons for its diversity.

Dutton and Thomas (1984) review the learning curve literature, and propose a framework for classifying the various sources of learning. Building on Levy (1965), they suggest a two-dimensional typology of learning: exogenous/endogenous and induced/autonomous. The research reported in this paper was designed to converge towards theirs, but operating inductively, on the basis of a case study in which I construct learning curves and then use them as a means of identifying issues for qualitative field exploration.

The structure of the paper is as follows. §2 presents Hi-Tech's manufacturing operations. Production of their new-generation device was divided into four departments, at least one of which was to be found in each of three plants located in the U.S., Europe and Asia. §3 defines the input measures and summarizes the different departments' input proportions. §4 defines the output measures and summarizes the output data. §5 defines a total productivity measure. §6 shows that, despite the heterogeneity of the factors influencing productivity, a classic learning curve model fits the total productivity performance record very closely. It is primarily "learning," the accumulation of knowledge in the form of manufacturing knowhow, rather than capacity utilization, that accounts for the rapid productivity growth rates experienced by Hi-Tech. Qualitative fieldwork designed to elucidate the different productivity records of the different departments identified three forms of shared learning (§7): (1) sharing across the Development/Manufacturing interface, (2) sharing between the primary location and plants that started up later, and (3) the ongoing sharing between plants after start-up. Discussions with Hi-Tech managers helped identify the factors that influenced these forms of shared learning and the various measures taken to improve them. §8 maps these improvement efforts onto a matrix developed by Daft and Lengel (1986), combining information uncertainty and equivocality; this mapping links the behavioral and cognitive processes of organizational learning. §9 identifies the implications of this analysis for the role of Manufacturing Engineers.

2. The Context

Respect for the company's anonymity demands that description of the product and process be very stylized.

Three wholly-owned facilities were involved: a prime facility in the U.S. and two secondary facilities in Western Europe and Asia.

The process involved four major departments—*A*, *B*, *C* and *D*—that form the final product in a simple flow (see Figure 1): *A* was a fabrication and assembly line; *B* was

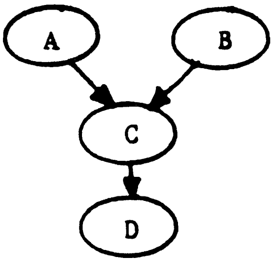

FIGURE 1. The Hi-Tech Process Flow.

primarily a highly-automated machining operation; and *C* and *D* were primarily assembly operations coupled with sophisticated testing machines.

Only some 5% of the cost of the completed machine was incurred in the *A* department and another 5% in *B*; 27% was incurred in *C* and 63% in *D* (primarily in metal casing and electronic circuits supplied by other plants). The real value of the up-stream components was, however, considerably greater, since extremely high performance standards were demanded of all components, and escaped defects at the *A* and *B* stages caused major expense when detected in the *C* or *D* departments or in the field.

The U.S. plant produced all four components, with some outside sourcing of subcomponents at the *A*, *C* and *D* stages. The European plant produced *A*s, *B*s and *C*s and had its own local suppliers of subcomponents. In the early months, it received some *A*s and *B*s from the U.S. and at the end of the study period was still importing some subcomponents. The Asian plant only assembled *C*s; it was dependent on the U.S. for *A*s and *B*s as well as for some *C* subassemblies. European and Asian *C*s were assembled into *D*s in plants left outside the scope of this study.

All three plants were simultaneously involved in the production of other devices, and the U.S. and European plants manufactured earlier generations of the same type of system.

The system under study here embodied a considerable change in basic technology relative to the preceding generation. Its basic performance parameters were between 20% and 400% (depending on the parameter) above those of the preceding generation—which was merely some two years old when the new one became available. Such dramatic changes were the rule, not the exception, at Hi-Tech. Similar order-of-magnitude jumps in performance characterized the three previous generations introduced over the preceding decade.

3. Inputs: Definitions and Shares

The inputs considered in my total productivity framework include direct and indirect labor, materials, capital and inventory. It is important to include all the principal inputs, since across departments and over time the different factors accounted for very different shares.

Input quantities are defined as follows:

* Direct labor (DP): the monthly headcount of direct personnel in each department was available from Industrial Engineering records.

* Indirect labor (IP): the indirect personnel monthly headcount was not available at departmental level. A full-time equivalent headcount was therefore estimated from the Manufacturing Engineering department expenses charged to each department annually. This expense was deflated by the departmental average of manufacturing engineer's annual employment cost (salary plus benefits), and the resultant annual estimated headcount was interpolated linearly to generate a monthly series.

* Purchased materials quantity (MQ): the sum of purchased and interplant transfers (net of the Materials function's overhead burden) taken from monthly cost accounting reports gave the dollar value of the materials incorporated into the output claimed that month. A materials quantity series was derived from these data by deflation, using plant-specific company-supplied price indices.

* Capital quantity (CAP): these data were derived from Industrial Engineering reports on the potential output (in units per day, or "daily going rate") of the department's machines working three shifts per day under optimal technical conditions. The annual data were interpolated.

* Inventory quantity (INVU): this series was derived from the monthly accounting data on work-in-progress and materials inventory. To focus on efficiency rather than financial performance, it was important to deflate the value of inventory so as to correct for the rapidly falling unit costs of many of the inventoried components. This inventory was therefore valued at Cost Engineering's estimate of projected minimum cost of these components.

Of these measures, the more innovative is that of the capital input. My approach was based neither on depreciation plus returns (as advocated by Kendrick and Creamer 1965), nor on total expected returns (as advocated by Craig and Harris 1973)—although we shall shortly return to the significance of the former. Instead, the capital quantity measure has a direct engineering basis in the technical capacity of the line. It was felt that this would be a more relevant input measure for the manufacturing department manager whose performance was not measured as a profit center, let alone an investment center. We shall of course need a dollar measure to weight this capital input quantity, at which point we shall return to a measure of the cost of capital. But this weight will be a constant, and movements in the capital input series will reflect capacity changes, not financial changes. In this approach, the cost of facilities, as distinct from machinery and equipment, was reflected in the weight, not in the quantity, of the capital input.

These input quantities were weighted to form an aggregate total input measure as follows:

* Direct and Indirect labor (DP, IP): headcounts were weighted by the sum of wages and benefits to generate a total employment cost for each department and each category in each plant.

* Materials (MQ): materials needed no weighting since it was already in deflated currency units.

* Capital (CAP): the appropriate weight for the capital input is a total cost of capital. Consistent with the engineering approach to measuring capital input quantity, I used the Kendrick-Creamer approach to estimating this weight, calculating the cost of a unit of capital (capacity) by adding the return *of* capital—depreciation[1]—to the return *on* capital—its opportunity cost. For the latter, the real cost of financial capital was set at 7%, reflecting the long-run average inflation-corrected cost of a typical mix of debt and equity (Kaplan 1985). Real estate costs were ignored on the principle that manufacturing managers were not responsible for their location in high or low land-value areas.

* Inventory (INVU): this was valued at a 10% annual cost, reflecting the 7% foregone return on capital and an estimated 3% storage and handling cost. It should be noted that as managers study the lessons of Japanese Just-In-Time approaches, the true cost of this

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[1] Depreciation costs were not readily available on a department level; data was therefore culled from the minutes of the Capital Appropriations Committee. The minutes detailed the appropriations for machinery and equipment as well as facilities (structures and fittings). This data was fed into a model of the appropriation-to-installation lag developed by the Hi-Tech staff to estimate the installed asset value. Based on discussions with the staff, the average useful life of machinery and equipment and facilities was assumed to be five and ten years, respectively. Depreciation was then calculated on a linear basis.

resource could well be revised upward from 3% to reflect the cost of inventory in hiding operations problems.[2]

After adjusting these unit costs to the variable length of the accounting month, it remained to be decided whether to let these price weights evolve relative to each other or to adopt a fixed-base price scheme. Since Hi-Tech's department managers follow rather tight process "recipes" and must respect a corporate "no lay-off" policy, a fixed-weight system was adopted.

The base period was the most recent month (after checking that it was not an abnormal month). This way, build-up costs and the indivisibilities of early, small-scale operations would not cloud the results over the whole period.

Though these measures have their weaknesses, they satisfied the initial objective: to construct a theoretically consistent but managerially relevant measure of manufacturing performance.

It is important to recall that this total input measure includes purchased materials but excludes components from upstream departments. In this way we have a form of "total" productivity measure which allows measurement of the efficiency of utilization of as many resources as is compatible with the aggregation of department measures into an overall productivity measure. In particular, we are in a position to judge the efficacy of make/buy decisions.

These inputs change in relative magnitude as manufacturing ramps up. In the initial months, Indirect personnel (primarily Manufacturing Engineers and technicians) usually accounted for 80%–90% of total costs. This proportion declined steadily such that, at the end of the period, cost shares stabilized at the levels indicated in Table 1.

A comparison across components in Table 1 reveals several structural differences: *A* was somewhat more direct-labor-intensive than the other departments; *B* was relatively more capital-intensive, and *C* and *D* were relatively materials-intensive. These data reflect the technological character of the departments' production processes.

The comparison across plants is difficult because plant-specific unit costs were used. Table 1 nevertheless reflects the relative materials intensity of the overseas plants. The Asian plant was primarily an assembly operation; the European plant received some components and subcomponents from the U.S. and also subcontracted more in some departments.

TABLE 1

Approximate End-of-Period Input Shares for Each Department (%)

	A		*B*		*C*			*D*
	US	Eur	US	Eur	US	Eur	Asia	US
Direct labor	30	15	20	15	12	6	8	4
Indirect labor	20	8	30	22	14	7	5	2
Materials	30	58	10	11	62	70	75	90
Capital	16	16	35	45	7	11	9	3
Inventory	4	3	5	7	5	6	2	1
Total	100%	100%	100%	100%	100%	100%	100%	100%

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[2] I did test analyses of plant performance for sensitivity to the capital and inventory cost rates: the analysis proved very insensitive. The choice of a fixed-base pricing procedure minimized the potential impact, as did the large share of total costs accounted for by materials and indirect labor (see Table 1).

TABLE 2

Annual Output (in '000s units)

		1979	1980	1981	1982
A	US	60	572	1301	2435
	Eur	5.8	58.4	108	173
B	US	0.8	14	53	273
	Eur	0	2.6	4.1	41.0
C	US	0	0.2	1.7	17.5
	Eur	0	0	0.06	3.1
	Asia	0	0	0	0.9
D	US	0	0.04	0.4	6.5

4. Outputs: Definition and Growth

Measuring output poses its own methodological difficulties.

The quantity measure was straightforward, since monthly cost reports detailed physical quantities produced in the month.[3] In some departments, however, several distinct outputs had to be aggregated. Here, Cost Engineering's estimates of projected minimum cost were used as weights. This generated a behaviorally-motivated approach to defining an output index number, since these estimates became Hi-Tech Manufacturing's commitment to Marketing upon which pricing decisions were based.

These weights differ across plants. The costs of shifting to internationally-weighted average outweighed the benefits; plant-specific minima are more directly interpretable by the plant managers.

I excluded from these cost-weights the value of materials coming into a given department from upstream in-plant departments, but included the cost of purchases from outside the plant. This way the index captured as much as possible of the efficiency of materials usage, without sacrificing the possibility of aggregating to a plant level.

The period under study is the ramp-up period. This can be seen in the data on output up to the end of 1982 presented in Table 2.

5. Total Productivity Ratio: Definition

There are several possible approaches to measuring productivity and each approach implies a certain model of production. I adopted an elementary, additive model in preference to a multiplicative model or to more complex ones. This approach follows the American Productivity Center's example and such practice-oriented researchers as Kendrick and Creamer (1965), Craig and Harris (1973), and Sumanth (1984). The additive model has the overwhelming advantage of giving a productivity measure which is intuitively understandable as the inverse of an inflation-corrected unit cost. This measure of total productivity is thus a simple ratio of total output to toal input. ("Total" is conventionally distinguished from "total factor" productivity by its inclusion of materials.)

It is calculated as follows:

$$TP_t = \frac{\sum w^{iu} \cdot Q_{it}}{\sum s^{jd} \cdot X_{jt}} \quad \text{where:}$$

subscript t = time period,
TP = total productivity,

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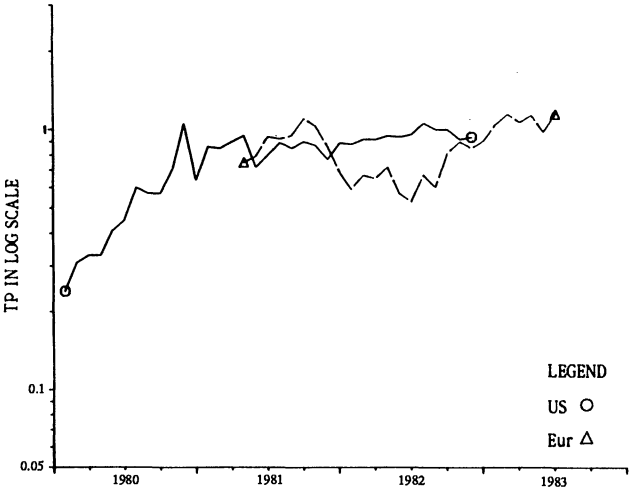
[3] Three factors brought the benefits of an inventory adjustment well below the costs: finished goods were immediately charged to the next downstream department; the cost reports only included material actually used in that month's output; and work-in-progress inventory turned out to be very small.

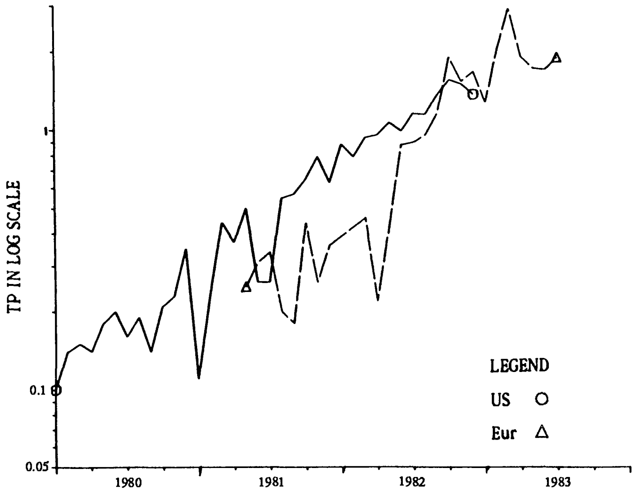
Q_i = quantity of output i,
w^{iu} = unit cost of output i at projected minimum unit cost (w^{iu} is thus a constant),
X_j = quantity of input j,
s^{jd} = unit cost of input j at base-period d (a constant),
and where the base period d is the last period under study.

6. Total Productivity Learning Curve Estimates

Graphs 1, 2, 3 and 4 present total productivity against calendar time for each department.[4]



GRAPH 1. *TP* for Department *A*. US and Europe.



GRAPH 2. *TP* for Department *B*. US and Europe.

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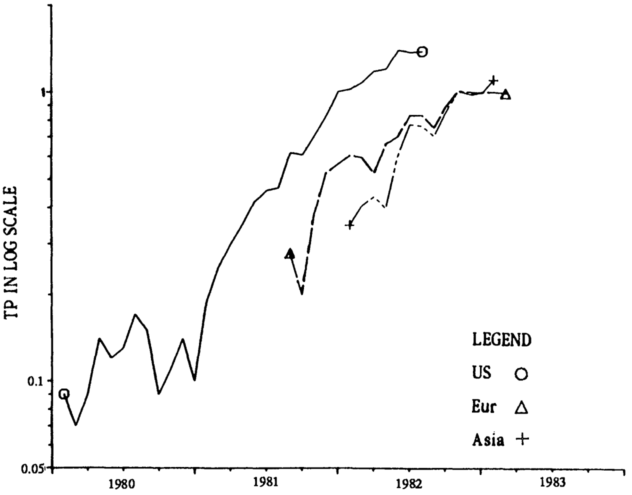
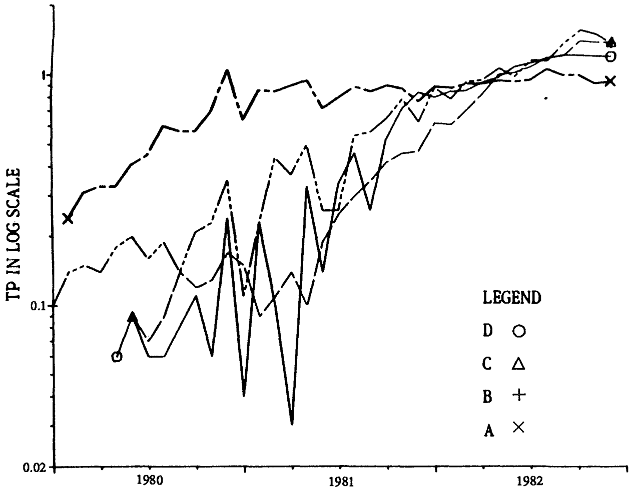
[4] It should be noted that there is no theoretical upper limit to the level of productivity, since over time technological and organizational changes shift the production function. Conversely, the projected unit costs used to weight outputs only have a minimum—rather than an asymptote—because they are current costs, rather than inflation-corrected.



GRAPH 3. *TP* for Department *C*. US, Europe, Asia.



GRAPH 4. *TP* by Department. US.

Several effects are combined in these results: direct labor learning, product and process debugging, intra- and inter-organizational adaptation, and management experience. Another paper in preparation will model the structure of these interdependent forces. Here we shall remain at a more aggregate level of analysis, characterizing overall productivity performance and identifying some of the behavioral factors and strategic choices that underlie it.

The evolution of productivity performance can be modelled with the "progress function" or "learning curve." The key independent variable of this model is "experience." Since there is some debate in the literature as to whether experience is best represented by cumulative output or time, we test both to see which fits the data better, and attempt to include them both simultaneously.

In claiming that productivity growth reflects learning, one is implicitly rejecting an alternative hypothesis, namely that the productivity improvement is due to greater utilization of existent capital and labor capacity. Two factors argue *a priori* against this counter-hypothesis. First, at Hi-Tech, equipment and personnel were only added incrementally (this can be seen from the input data series). Second, during the period under study, Hi-Tech faced a demand that can be considered infinite; Manufacturing's mandate was therefore to ship as much product as soon as possible to meet a rapidly growing order backlog; if capacity utilization problems did limit productivity performance, they should be considered above all the results of process and product debugging difficulties, rather than the responsibility of fluctuating market conditions. The inclusion of a capacity utilization variable will permit me to test the counter-hypothesis directly.

Several possible models of total productivity learning are:

Model 1: $\log TP = a_1 + b_1 \log CUM$

Model 2: $\log TP = a_2 + b_2 T$

Model 3: $\log TP = a_3 + b_3 \log KUT$

Model 4: $\log TP = a_4 + b_4 \log CUM + c_4 \log KUT$

Model 5: $\log TP = a_5 + b_5 T + c_5 \log KUT$

Model 6: $\log TP = a_6 + b_6 \log CUM + c_6 T + d_6 \log KUT$

where: log = natural logarithm,

TP = total productivity,

CUM = cumulative output quantity,

T = months from start-up,

KUT = capacity utilization, measured as a three-month moving average of the ratio of actual output to potential output (with potential output estimated by linearly interpolating between peaks of the logged output series).[5]

Results for the eight departments indicated that either cumulative output (Model 1) or time (Model 2) alone accounted for over two-thirds of the variance of total productivity, depending on the department (excluding the aberrant case of the European *A* department). On the other hand, utilization alone (Model 3) only accounted for an average of 14% and a maximum of 35% of the variance of productivity in the eight departments. The hypothesis that productivity growth is merely a capacity-utilization effect is thus very implausible.

On the other hand, utilization has a nonnegligible effect. Adding utilization to cumulative output (Model 4) or time (Model 5) gave rise to convincing estimations reproduced in Table 3. The inclusion of all three independent variables (Model 6) introduced an intolerable level of multi-collinearity due to the very high correlation between time and cumulative output.

Two conclusions follow. First, despite the complexity of Hi-Tech operations and despite the multiplicity of factors beyond manual learning that seem to be at work, a simple learning curve model accounts for almost all the productivity variation during the first three years of life of the new product. Even the European *A* department is accounted for in considerable measure.

Second, in most cases, cumulative output outperforms time, if only by a little, as a proxy for experience. Time, on the other hand, does outperform cumulative output in the *B* area in both the U.S. and Europe. An intuitive explanation for this difference might be based on the relative capital-intensity of the *B* area. Here, the organizational adaptation due to the changing scale of operations is perhaps less important for productivity growth than the time needed to resolve engineering problems of product and process design. It would be interesting to test this hypothesis in a broader range of industrial processes.

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[5] This definition of capacity is appropriate when demand can be considered infinite. It has the advantage of not duplicating the capital input measure, which is based on rated equipment capacity, and thus avoiding spurious correlation with the dependent variable.

TABLE 3

Testing Models 4 and 5 of the Total Productivity Learning Curve

(Standard errors in parentheses. ** signifies significant at 1% level in a 1-tail test. * signifies significant at 5% level.)

Model 4

log *TP*	=	*C*	+	log *CUM*	+	log *KUT*	R^2	*DW*	*DF*
A-US		−4.011**		0.2853**		−0.2653	0.8104	0.87	32
		(1.566)		(0.0275)		(0.3912)			
B-US		−12.72**		0.5043**		1.030**	0.9320	2.38	33
		(1.03)		(0.0257)		(0.238)			
C-US		−10.74**		0.4902**		0.5221**	0.9810	2.09	28
		(0.33)		(0.0161)		(0.0855)			
D-US		−8.631**		0.5973**		−0.3826*	0.7913	2.00	25
		(0.857)		(0.0716)		(0.2340)			
A-Eur		1.296		0.3798**		−1.360**	0.5505	0.82	24
		(0.947)		(0.0839)		(0.302)			
B-Eur		−7.520**		0.4894**		0.7825**	0.9255	1.88	19
		(0.730)		(0.0336)		(0.1694)			
C-Eur		−5.808**		0.2630**		0.6697**	0.9339	1.52	15
		(0.973)		(0.0182)		(0.2077)			
C-Asia		−6.811**		0.3899**		0.2772*	0.9511	1.86	8
		(0.640)		(0.0328)		(0.1222)			

Model 5

log *TP*	=	*C*	+	*T*	+	log *KUT*	R^2	*DW*	*DF*
A-US		−0.700		0.02911**		−0.0759	0.6348	0.50	32
		(2.422)		(0.00457)		(0.5527)			
B-US		−7.180**		0.07377**		0.9447**	0.9409	2.80	33
		(0.951)		(0.00349)		(0.2222)			
C-US		−5.972**		0.09666**		0.6878**	0.9818	2.46	28
		(0.325)		(0.00310)		(0.0813)			
D-US		−3.760**		0.1170**		0.0751**	0.7713	2.24	25
		(0.719)		(0.0147)		(0.2099)			
A-Eur		5.058**		0.02519**		−1.346**	0.4851	0.80	24
		(1.248)		(0.00575)		(0.307)			
B-Eur		−5.505**		0.09926**		0.9421**	0.9395	2.47	19
		(0.623)		(0.00610)		(0.1510)			
C-Eur		−6.127**		0.08014**		1.070**	0.8675	1.21	15
		(1.406)		(0.00822)		(0.311)			
C-Asia		−3.309**		0.1007**		0.4016*	0.9451	2.02	8
		(0.557)		(0.0090)		(0.1285)			

We can situate these results relative to the "progress ratios" observed in other industries. If the estimate of the coefficient on cumulative experience in Model 4 is b, then 2^b gives the proportionate increase in productivity for a doubling of cumulative volume, and $(2^b)^{-1}$ gives the corresponding reduction in unit costs, the traditional progress ratio. Table 4 reports these ratios. These rates are all in the lower half (faster learning) of the distribution of progress rates found in 162 cases reported in the literature (Dutton, Thomas and Butler 1984). What is more significant is the short lapse of time into which so many doublings of cumulative output are telescoped. This is one of the distinctive features of contexts in which the frequency of new product introductions is high.

TABLE 4

Progress Ratios Calculated from Model 4 (%)

	A	*B*	*C*	*D*
US	82	71	71	66
Eur	77	71	83	
Asia			76	

7. Three Forms of Shared Learning

The strength of these learning effects in a context of frequent new product introductions explains why, when competitors loomed on the horizon, manufacturing competence moved up to a higher priority in Hi-Tech's concerns. The central task of manufacturing is to climb the productivity learning curve as rapidly as possible.

The results reported in the previous section were analyzed by Hi-Tech managers. The ensuing discussions highlighted the key factors underlying differences in departmental performance and approaches to improving that performance. In this way, the preceding quantitative analysis prompted the identification of behavioral and cognitive elements of the organizational learning process. Three forms of shared learning emerged as critical levers. In the following subsections, the data is used to illustrate the operation of these levers. Future research will return to a quantitative mode to test these ideas.

7.1. *Shared Learning* #1: *The Development/Manufacturing Interface*

The impact of design engineering on the early stages of new product manufacturing was manifest in, for example, the U.S. *C* department (Graph 3). The inadequate attention paid to manufacturability was evident in the fact that when released by Development, the *C* design called for some 200 different screw types. Later design revisions confirmed that the greater part of these were unnecessary. Not surprisingly, half of the design changes in 1982 were still motivated by ease-of-manufacture or cost-reduction concerns.

But the cure was almost as painful as the disease. These design revisions, and others like them, constituted a major disruption of manufacturing when, as in the case of Hi-Tech's new product, they emerged at the rate of nearly one per day even in the third year after start-up.

A simple image of the losses created by inadequate sharing of experience between Design and Manufacturing is given in Figure 2, which presents the U.S.-*C* case. The European *B* department suffered from similar problems.

Other factors may have contributed to the loss symbolized by the shaded area of Figure 2, but our discussions with Hi-Tech staff pointed to difficulties at the Development/Manufacturing interface as the key problem. Moreover, the unanimous opinion seemed well-founded that the shaded area represented an avoidable deficit rather than the precondition for an exceptionally rapid subsequent growth.

The cost of this deficiency of shared learning was not primarily in the excessive cost of the first few units, but more importantly in the delay in filling orders. The productivity stammerings of the first year translated into delays in the take-off of the cumulative output curve. At a stage of industry development where customers were becoming increasingly impatient with such delays and had a growing number of alternative sources, such timing deficiencies could be critical.

In response to the problems encountered in this program and the competitive urgency of overcoming them, Hi-Tech developed a policy of *earlier manufacturing involvement*

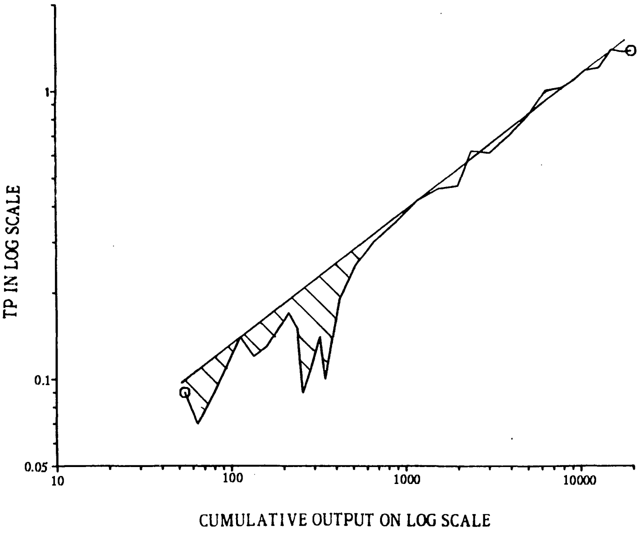

FIGURE 2. Shared Learning #1: The Development/Manufacturing Interface.

in design. A large contingent of manufacturing engineers (40% of *A* department, 59% of *B*'s, etc.) was moved into Development to guarantee that manufacturability concerns were reflected in the design of the next generation product.

In this way, management hoped to break down the "wall" between the two functions and to transform their adversarial relationship. The old relationship, where Manufacturing was only called in at the design review stage, was perceived as having the advantage of offering a clear demarcation of responsibilities. But when departments whose cooperation is critical adopt such a defensive vision of their relationship, it is hardly surprising that the result be a conflict between technological sophistication and producibility.

The culture of the American engineer is still such that in this conflict producibility is the consistent loser (Adler 1989). The development engineers saw themselves as closer to "science," less burdened by "firefighting," and therefore more prestigious than the manufacturing engineers. And indeed their perception was shared by the manufacturing engineers themselves, as well as by a senior management team often drawn from a development engineering background.

The shift of the manufacturing engineers into Development was part of a broader effort to change the status of Manufacturing. Other initiatives included: (a) a plan for the manufacturing engineers now in Development to rotate back through Manufacturing when the product they work on in Development is released; (b) enforcing a stricter discipline on the number and accuracy of engineering changes released to manufacturing; (c) developing a closer relationship with a smaller number of vendors whose processes and quality levels could be certified by Hi-Tech engineers; and (d) involving the Materials function in discussions of new product design so as to minimize the number of new part numbers.

7.2. *Shared Learning #2: Start-up Transfer*

Plants that started later seem to start at higher productivity levels. This is probably not an accidental regularity nor a statistical artifact. The U.S. debug experience was traditionally shared with other plants by the intermediary of tooling blueprints and process specifications. Secondary plants, however, retained a considerable degree of autonomy, reflecting the autonomy of the plant managers who are held responsible for their costs.

One can estimate the magnitude of this sharing at start-up as in Figure 3. The constant term in the learning curve model gives an estimate of the intercept of the productivity learning curve and the *y* axis; it therefore provides an estimate of the "job one" (or "day one") productivity at the secondary facility (designated *a* in Figure 3). One can then calculate the amount of experience (log of cumulative output) of the U.S. facility that, at some earlier point in time, gave the U.S. this level of productivity (this amount is designated *m* in Figure 3). The "sharing ratio" can then be computed simply as the ratio of this estimated U.S. experience (*m*) to the actual experience (*n*) that the U.S. facility had accumulated at the secondary facility's day one (Jucker 1977).

When the sharing efficiency is estimated in this way, as the ratio of estimated (*m*) to actual (*n*) prime facility experience at secondary facility's start-up, we find that the European *C* department shared 68% of the U.S.-*C* department's experience, Asia's *C* department shared 51% of the U.S.-*C* experience, and Europe's *B* department shared 68% of the U.S.-*B* experience. The accuracy of these figures is limited by the fact that we have used plant-specific weights on inputs and outputs; as a consequence, while productivity growth rates are reliable, comparison of productivity levels is subject to further analysis. There is, furthermore, a risk of oversimplification in interpreting these data as reflecting only interplant transfer of competence. The European facility in particular was already engaged in the production of preceding generations of machines. As has been pointed out, however, the product and process characteristics of the new generation were very different from those of the preceding one. Calling this ratio a "sharing ratio" is thus reasonable in light of the dependence of secondary facilities on the U.S. experience.

One difficulty in interpreting this sharing ratio is obvious upon examination of the *B* case. European performance accelerated sharply after start-up difficulties that were due to U.S. tardiness in transmitting process specifications and to some serious design flaws. Therefore, my estimate of the intercept based on the estimated average performance improvement rate measured over the entire period is considerably lower than that which is given directly in the data. Using the estimated intercept, the sharing ratio is 68%, while using the actual intercept, the ratio is 150%.[6] In other words, the job one performance

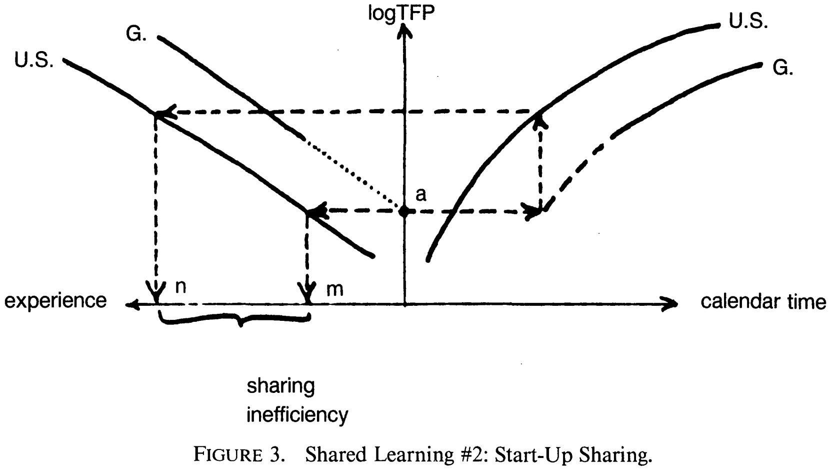

FIGURE 3. Shared Learning #2: Start-Up Sharing.

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[6] In order to see whether this result was due to the plant specific weighting system, the productivity data using U.S. factor price weights and U.S. output values on the European quantity data was recalculated. The actual intercept's sharing ratio falls only modestly from 150% to 138%.

of the European plant was in reality better than the then current U.S. performance level. Indeed, plant personnel in the European *B* department felt themselves to be particularly competent relative to their U.S. counterparts. Their sentiment was not entirely without justification, since in the preceding period the Europeans had demonstrated considerable autonomy and creativity in developing a new machining process for the *B* department. The contrast between the sharing efficiencies calculated with estimated and actual intercepts indicates that, like any tool, the sharing efficiency ratio can be misapplied.

The *A* case is important in this regard for two reasons. First, it shows that there are instances where the ratio is simply inappropriate. Here the yield crisis that blocked progress in Europe generates an absurdly high estimated intercept (see Graph 1). Second, the *A* department yield crisis has direct bearing on the problem of shared learning. It was explained by management as the result of insufficient engineering commitment to the objective of worldwide "commonality" (identicalness) of production lines. Commonality was seen as necessary for two reasons. First, process commonality guaranteed identical products worldwide—which is a particularly important objective when the short product life-cycles make the management of product phase-out strategically delicate. Second, commonality is valuable when the technological sophistication of the process, its "reach" into poorly mastered process techniques, is such that any substantial divergence of process designs risks multiplying operational problems beyond manageable levels. Consider for a moment the real technological uncertainty of some of Hi-Tech's processes: one part of the problem that plagued European *A* department operations turned out to be the result of an almost undetectably small difference in chemical composition between the cleaning solution supplied in Europe and in the U.S. The same company supplied the solution in both locations and was quite unaware of any chemical difference at all. The sensitivity of Hi-Tech's process was such that new measurement techniques were needed to control the solution's quality.

As reflected, with its limitations, by the sharing ratio, the management of this transfer of expertise was felt by the participants to have been very poor. In the *C* department for example, documentation for Europe's tooling did not arrive in time from the U.S., and a last-minute crash program involving numerous trans-Atlantic shuttles was required. The lower efficiency of the Asian transfer points principally to the relative weakness of the Asian plant's engineering staff. Dedicated primarily to the assembly of purchased components, the Asian plant had not yet developed a broad manufacturing engineering base.

The response of Hi-Tech to these experiences was to centralize the authority for worldwide production of various products in U.S.-based *product managers*. A new level of management, one level above the regional department manager, was created to ensure that process technologies were better specified when the product specifications were transmitted to the secondary facilities. This new degree of centralization was complemented by procedures that ensured that secondary facilities sent a more important engineering group to the U.S. during the final design stages and start-up period. They could then return to their facilities with a greater depth of understanding of the new technologies.

These latter procedures for personnel transfer are particularly important. A great deal of leverage can be generated by more exhaustive documentation; but for every extra degree of explicit knowledge, there is new tacit knowledge to be established: uncodified and as-yet-uncodifiable know-how, understanding why other options have not been adopted, etc. Other industries, for example, petrochemicals, where manufacturing technique has traditionally been competitively more critical than in electronic equipment, have developed a broad repertoire of managerial approaches for assuring the cooperative learning necessary for effective technology transfer. Industries like electronic equipment are now following suit.

7.3. *Shared Learning #3: Ongoing Cooperation*

Both graphs and learning curve estimations show that different plants often maintained stable but different productivity growth paths. The U.S. *C* department, for example, had a consistently higher growth rate than its European and Asian counterparts. Such persistent divergence in productivity growth is disturbing when, as in the case of *C* (and perhaps of *B* in the future), it was not a matter of the later starter catching up. An overall corporate optimum calls for the ongoing sharing of experience such that slower plants benefit from others' experience.

In the *C* case, discussion with plant management highlighted the advantage of the U.S. plant due to the presence of the development laboratory on the same site. Although officially a part of a separate organization, development engineers were always within reach to help debug problems that emerge in production.

In the *B* department on the other hand, the particularly rapid post-start-up productivity growth of the Europeans seems to have been due to a more technically proficient workforce, both engineers and directs. The U.S. plant did not seem to be benefitting from this expertise. The consensus opinion was that this was due to a "not-invented-here" syndrome on the part of the U.S. department.

Figure 4 presents the *C* case. The angle β (beta) is the difference in the rates of productivity growth. If the fit of the learning curve is good, then this can easily be calculated from the estimated coefficients.

These disparities pose a complex engineering management issue: how can Hi-Tech simultaneously sustain greater centralized control over new product introduction by the prime facility and yet maintain a level of competence at the secondary facilities sufficient to assure both start-up and ongoing learning? Conscious of the temptation to underestimate this level of competence, Hi-Tech management instituted a policy of official recognition by the product managers of distinct *centers of competence* for specific subprocess improvement projects in secondary facilities. In this way they hoped to give some expression to secondary facilities' engineering creativity.

8. Mapping the Development of Interdepartmental Relations

We can use a framework developed by Daft and Lengel (1988) to map the behavioral and cognitive transformations of interdepartmental relations identified in the previous

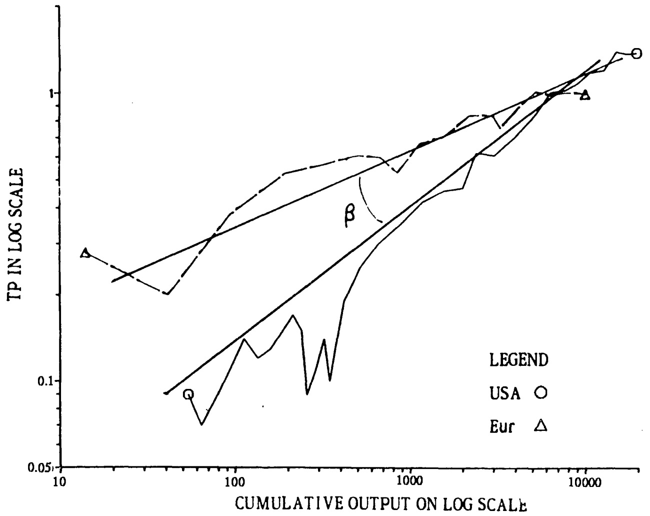
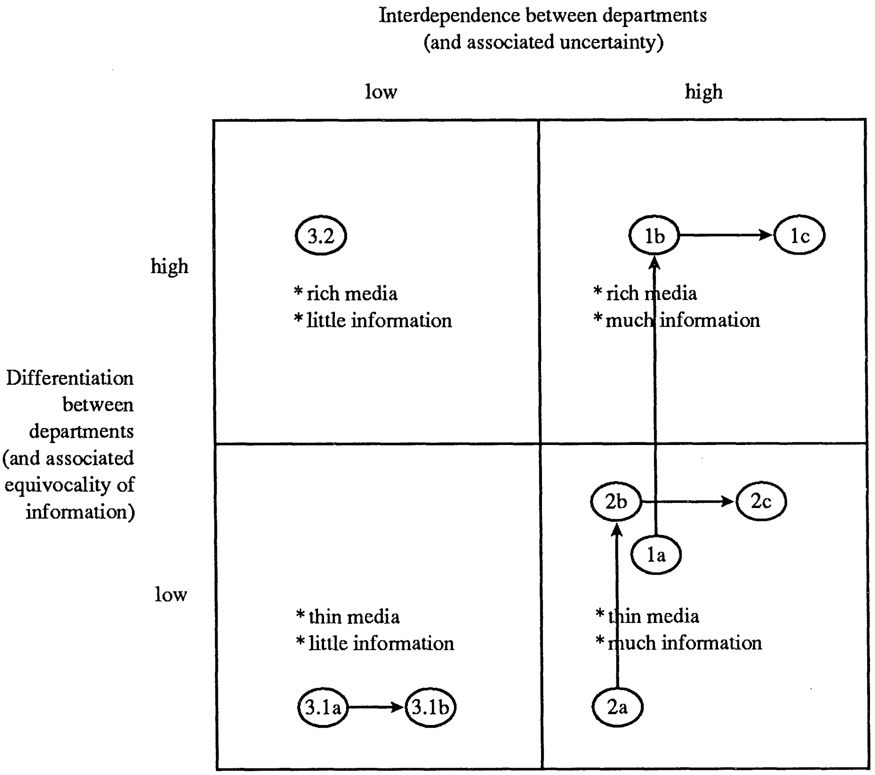


FIGURE 4. Shared Learning #3: Ongoing Cooperation.

section. Daft and Lengel develop a map of the cognitive dimensions of organizational learning. They distinguish two dimensions of interdepartmental relations: degree of differentiation (as analyzed by Lawrence and Lorsch 1967 for example) and strength of interdependence (as per Thompson 1967 for example). Differentiation, they argue, creates a corresponding degree of equivocality of information, and therefore, the need for richer information media linking the departments. They use a scale of media richness that increases from rules to formal information systems, special reports, planning, direct contact, integrator roles and group meetings. Interdepartmental interdependence, they argue, increases uncertainty, and (*ceteris paribus*) uncertainty can be resolved by more information transfer within a medium of given richness.

We can use this characterization of the cognitive challenges of shared learning to trace the behavioral innovations introduced at Hi-Tech: see Figure 5.

(1) The Development/Manufacturing interface was doubly transformed. The first



1 = Development/Manufacturing relations
    (1a to 1b) = transfer some developers into Mfg with design
    (1b to 1c) = create Production Engineering within Development
2 = Start-up relations between Manufacturing sites
    (2a to 2b) = create international Manufacturing start-up team
    (2b to 2c) = create international Product managers
3.1 = Ongoing relations between Manufacturing sites
    (3.1a to 3.1b) = create Centers of competence
3.2 = Ongoing Development/Manufacturing relations
    (leave unchanged the pattern of informal relations between Development and Manufacturing after start-up)

FIGURE 5. Changes in Interdepartmental Communication (adapted from Daft and Lengel 1986).

part of this arrow represents the fact that, while the differentiation between Development and Manufacturing was always seen as high, management had not designed their interdepartmental relations to adequately reflect the associated equivocality of information. The idea of having part of the Development team move with the design into Manufacturing added richness to the medium, substituting a team or task force for the "over the wall" information transfer method. The second part of this arrow expresses the idea that the increased competitive importance of rapid new introduction forced management to recognize a greater degree of interdepartmental independence, thus to acknowledge a greater degree of effective information uncertainty, and thus to increase the amount of information transferred between functions. By shifting part of Manufacturing Engineering into Development as Production Engineering, management accelerated the information transfer between product and process design, allowing more interations in both, and thus allowing greater product/process optimization (Clark and Fujimoto 1987).

(2) The start-up transfer between primary and secondary manufacturing sites was similarly doubly transformed. First, the differentiation of plant processes was more accurately assessed. Acknowledging that commonality was difficult to achieve and could not be simply dictated, management created an international start-up team that added richness to the media for inter-plant communication. Second, competitive pressures made rapid international ramp-up and commonality more critical. International product managers allowed the firm to deal with a greater degree of interdependence by increasing the amount of information being communicated between sites.

(3) The third form of learning—ongoing cooperation—occasioned relatively less organizational innovation. Relations between sites (3.1) were transformed by the introduction of centers of competence: this acknowledgement of the interdependence between sites should increase the amount of information transferred between them. But no plans were made to increase the richness of the communication media through which process innovations in one site could be shared with other sites; occasional face-to-face meetings rather than simple reports would probably be needed. The informal relations between Development and Manufacturing (3.2) were not changed, although one might anticipate some future evolution as a result of the creation of Production Engineering group.

This discussion serves not only to link the cognitive and behavioral dimensions of organizational learning, but also to clarify the differences between organizational and individual learning. Two distinctively organizational elements are clear:

* First, it was primarily organizational culture and the associated status hierarchy—rather than any individual cognitive limitations—that impeded earlier recognition by Hi-Tech of the "true" character of the two key interfaces.

* Second, the key factor forcing the organization to refine its assessment of the appropriate degree of differentiation and interdependence was strategy—the effort to find a better fit with a changing environment.

9. Conclusion: The Role of Manufacturing Engineering

One opportunity for further developing behavioral and cognitive theories of learning would be to examine the role of manufacturing engineers. Bridging the gap between Development and Operations, responsible for start-up capability at secondary facilities, and assuring ongoing technical cooperation between plants, Manufacturing Engineering accounts for a good proportion of the costs and explains much of the productivity improvement in both a statistical and a managerial sense. As we have seen, the importance of Manufacturing Engineering to Hi-Tech's performance led Hi-Tech to broaden its definition of the knowledge-base and of the behavioral roles required of manufacturing engineers:

* On the cognitive dimension, manufacturing engineers were challenged to broaden their knowledge-base. Production engineers rotating back into Manufacturing Engineering would bring back with them a better understanding of the rationale of the product design, and they would thus be better equipped to assess problems and improvement proposals for both product and process. Similarly, the international start-up team would enrich the secondary facilities' manufacturing engineer's grasp of the more tacit, uncodified elements of the process technology.

* On the behavioral dimension, these two organizational innovations demanded of manufacturing engineers that they play a broader role, more responsible for the manufacturing ramp-up, and process design commonality.

The previous section identified culture and strategy as two key factors contributing to the distinctively organizational character of these learning processes. The same two factors appear to be at work in the case of Manufacturing Engineering, but closer examination reveals that it is precisely these factors that risk undermining the viability of the effort to broaden Manufacturing Engineering.

First, Manufacturing Engineering's broadening was jeopardized by the relatively low status of Manufacturing Engineering. When a group of manufacturing engineers was moved into Development to form the Production Engineering group, those who remained in Manufacturing found that their "fire-fighting" role was even further accentuated to the detriment of more creative, proactive functions. Nothing was done to improve their difficult relations with materials purchasing or operations. Morale "crashed." Three years later, the idea that the new Production Engineering staff should rotate back through Manufacturing Engineering when the product they work on in Development moves into Manufacturing had yet to be acted on.

Such a culture loses the opportunity to capitalize on the richness of manufacturing engineering problems as a source of process improvement ideas. These incremental, post-start-up improvements are often a major source of productivity growth. If Hollander's data (1965) are at all representative, they may be the principal source of long-term productivity improvements. Both autonomous process change initiatives by the manufacturing engineers and a good backflow of information from them to the development engineers are essential to this ongoing incremental productivity enhancement. Combining the "big leap" capability of rapid introduction of radically new products and processes with the "small step" capability of incremental enhancement seems a major challenge to Hi-Tech as to other firms.

This cultural challenge to broaden Manufacturing Engineering was intertwined with a strategic challenge. The strategic challenge lay in how to reconcile Hi-Tech's business strategy of becoming a high-volume, low-cost producer and its technology strategy of constantly pushing to the frontiers of product and process technology:

* The business strategy dictated that Hi-Tech routinize as much and as early as possible—no Engineering Changes after Manufacturing release should be needed, let alone revisions to changes already introduced. Thus the exhortation: "Design it right the first time."

* The technological reach of Hi-Tech's products and processes, however, made this ambition unrealizable. Moreover, the danger was real that such an understanding of the means of attaining manufacturing efficiency would inhibit the product and process innovation essential to long-term competitiveness. There was simply too much manufacturing productivity improvement coming from incremental post-start-up adjustments.

As technological change accelerates, this strategic tension intensifies for a growing segment of industry. Along with it, the conflicting pressures on manufacturing engineering will also intensify. If manufacturing engineering is indeed a key element in the learning curve process, future research could profitably be focused on how this occupational group can respond to these pressures.[7]

[7] This research was conducted while the author was a Post-doctoral research fellow at the Harvard Business School. Professors Robert H. Hayes and Kim B. Clark were responsible for its overall direction as one of three parallel studies on plant performance pursued by Professor Russell Radford, Professor Bruce Chew and the author (see Hayes and Clark 1985). Research assistance was provided by David Castenholz and Chris Needham. Funding was provided by the Harvard Business School Division of Research. This version has benefitted from the comments of Steven Wheelwright and several anonymous referees.

References

Adler, Paul S., "A Plant Productivity Measure for 'Hi-Tech' Manufacturing," *Interfaces*, 17, 6 (November-December 1987), 75–85.

———, "When Knowledge Is the Critical Resource," *IEEE Trans. Engineering Management*, 36, 2 (May 1989), 87–94.

Alchian, A., "Costs and Output," in M. Abramowitz (Ed.), *The Allocation of Economic Resources: Essays in Honor of B. F. Haley*, Stanford University Press, Stanford, CA, 1959.

Anzoni, Y. and H. A. Simon, "The Theory of Learning by Doing," *Psychological Rev.*, 86 (1979), 124–140.

Arrow, Kenneth, "The Economic Implications of Learning by Doing," *Rev. Economic Studies*, 29 (April 1962a), 166–170.

———, "Economic Welfare and the Allocation of Resources for Invention," in N.B.E.R. (Eds.), *The Direction and Rate of Inventive Activity*, Princeton University Press, Princeton, NJ, 1962b.

Asher, H., *Cost-quantity Relationships in the Airframe Industry*, Rand Corp. R-291, Santa Monica, CA, 1956.

Baloff, Nicholas, "Start-Ups in Machine-Intensive Production Systems," *J. Industrial Engineering*, 17 (January 1966a), 25–32.

———, "Learning Curves—Some Controversial Issues," *J. Industrial Economics*, 14 (July 1966b), 272–282.

———, "Start-Up Management," *IEEE Trans. Engineering Management*, EM-17 (November 1970), 132–141.

———, "Extensions of the Learning Curve—Some Empirical Results," *Oper. Res. Quart.*, 22 (December 1971), 329–340.

Bohn, Roger, "Incorporating Learning into Managing and Modeling Production," Harvard Business School, September 1984.

Carlson, J. G., "Cubic Learning Curves: Precision Tool for Labor Estimating," *Manufacturing Engineering and Management*, 71, 5 (1973), 22–25.

Carr, G. W., "Peacetime Cost Estimating New Learning Curves," *Aviation*, (April 1946), 76–77.

Clark, K. B. and T. Fujimoto, "Overlapping Problem-Solving in Product Development," Harvard Business School Working Paper 87-048, 1987.

Conway, R. and A. Schultz, "The Manufacturing Progress Function," *J. Industrial Engineering*, 10, 1 (1959), 39–53.

Craig, Charles E. and R. Clark Harris, "Total Productivity Measurement at the Firm Level," *Sloan Management Rev.*, (Spring 1973), 13–29.

Daft, R. L. and R. H. Lengel, "Organizational Information Requirements, Media Richness and Structural Design," *Management Sci.*, 32, 5 (May 1986), 554–571.

Davidson, W. H. and Donald G. McFetridge, "International Technology Transactions and the Theory of the Firm," *J. Industrial Economics*, 32 (March 1984), 253–264.

Dutton, John M. and Annie Thomas, "Progress Functions and Production Dynamics," New York University Business School Working Paper 82-29, May 1982.

———, "Treating Progress Functions as a Managerial Opportunity," *Acad. Management Rev.*, 9, 2 (1984), 235–247.

———, ——— and John E. Butler, "The History of Progress Functions as a Managerial Technology," *Business History Rev.*, 58, 2 (1984).

Eccles, Robert, "Control with Fairness in Transfer Pricing," *Harvard Business Rev.*, (November–December 1983).

Hayes, Robert B. and Kim B. Clark, "Exploring the Sources of Productivity Differences at the Factory Level," in Kim B. Clark, Robert R. Hayes and Christopher Lorenz, *The Uneasy Alliance: Managing the Productivity-Technology Dilemma*, Harvard Business School Press, Boston, 1985.

——— and Steven C. Wheelwright, *Regaining our Competitive Edge: Competing through Manufacturing*, Wiley, New York, 1984.

HIRSCH, W. Z., "Manufacturing Progress Functions," *Rev. Economics and Statist.*, 34 (May 1952), 143–155.

———, "Firm Progress Ratios," *Econometrica*, 24 (April 1956), 136–144.

HIRSCHLEIFER, J., "The Firm's Cost Function—A Successful Reconstruction," *J. Business*, 35 (July 1962), 235–255.

HOLLANDER, S., *The Sources of Increased Efficiency: A Study of Dupont's Rayon Plants*, MIT Press, Cambridge, MA, 1965.

KENDRICK, JOHN W. AND DANIEL CREAMER, *Measuring Company Productivity*, National Industrial Conference Board Inc., 1961.

LEVY, F. K., "Adaptation in the Production Process," *Management Sci.*, 11 (April 1965), B136–B154.

MUTH, JOHN F., "Search Theory and the Manufacturing Progress Function," *Management Sci.*, 32, 8 (August 1986), 948–962.

NEWELL, A. AND P. S. ROSENBLOOM, "Mechanisms of Skill Acquisition and the Law of Practice," in J. B. Anderson (Ed.), *Cognitive Skills and Their Acquisition*, Lawrence Erlbaum Assoc., Hillsdale, NJ, 1981.

OUCHI, WILLIAM G., "Markets, Bureaucracies and Clans," *Admin. Sci. Quart.*, (March 1980).

RAPPING, L., "Learning and the World War II Production Functions," *Rev. Economics and Statist.*, 48 (February 1965), 98–112.

SHESHINSKI, E., "Tests of the Learning by Doing Hypothesis," *Rev. Economics and Statist.*, 49 (November 1967), 568–578.

STOBAUGH, ROBERT B. AND PHILLIP L. TOWNSEND, "Price Forecasting and Strategic Planning: The Case of Petrochemicals," *J. Marketing Res.*, 12 (February 1975), 19–29.

SUMANTH, DAVID J., *Productivity Engineering and Management*, McGraw-Hill, New York, 1984.

WRIGHT, T. P., "Factors Affecting the Cost of Airplanes," *J. Aeronautical Sci.*, 3 (February 1936), 122–128.