THE PERILS OF EXCELLENCE: BARRIERS TO EFFECTIVE PROCESS IMPROVEMENT IN PRODUCT-DRIVEN FIRMS*

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Several authors have suggested that a focus on manufacturing capability and on continued process improvement may be a powerful source of competitive advantage, yet many firms appear to have encountered great difficulties in taking advantage of this insight. This paper reports on the results of five these conducted under the auspices of the MIT Leaders for Manufacturing program at the Microwave Technology Division of the Hewlett-Packard Company. We found considerable evidence that the marginal returns to process development within the division were probably considerably higher than the division’s cost of capital, suggesting that process improvement probably was underfunded despite the fact that improving manufacturing capability had been identified as a key strategic priority.

We found no evidence that this “underfunding” reflected either a failure to recognize the problem or an overly hierarchical or rigid organization. Rather it appeared to flow from the historical strengths of the division. A devotion to leading-edge technical solutions and to immediate customer service at almost any price had created barriers to the effective funding of process improvement that were deeply rooted in the organizational structures, information systems, and formal and informal incentive structures that had evolved to support the division’s historical emphasis on excellence on product design. Our results highlight the problems that very successful product-driven companies may encounter in attempting to make continual process improvement central to their strategic mission.

(PROCESS IMPROVEMENT; ORGANIZATIONAL FAILURE)

In May of 1989, three enthusiastic students from the Massachusetts Institute of Technology (MIT) Leaders for Manufacturing (LFM) Program arrived for the start of a 6-month internship at Hewlett-Packard’s (HP’s) Microwave Technology Division (MWTDF) in Santa Rosa, California. The students had been invited to work on a series of process improvement projects identified by the plant and by Christmas had come to a number of tentative conclusions:

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BARRIERS TO EFFECTIVE PROCESS IMPROVEMENT

- Improving the plant's wafer release policy could potentially increase throughput substantially, yet the plant had no operations research or industrial engineering specialists on its staff and had never systematically reviewed its scheduling policy (Lawton 1990).

- Six process inputs accounted for 90% of the parametric electrical yield loss caused by gain slope variation (a key performance parameter) yet the division was "aware" of only four and actively pursuing only two. Preliminary estimates suggested that deeper exploration of these inputs might yield quite high returns (Moran 1990).

- Testing strategy emphasized the screening of "bad" product. Several possible additional benefits of testing, including the elimination of unnecessary processing, increased downstream capacity, and process improvement, were not considered in either the design of test structures or in the formulation of testing strategies (Vlasak 1990).

These findings and those of the students who followed them at MWTD (Becker 1991; Shapiro 1991) raised the surprising possibility that MWTD might be "leaving money on the table" in the form of unaddressed process improvement projects with the potential to yield quite considerable economic returns. Because the LFM students were presumably "marginal" resources for the plant in the sense that they were likely to be assigned projects with lower expected returns than those assigned to the full-time employees responsible for process improvement, the fact that their projects appeared to have the potential to generate considerable returns suggested either that process improvement as a whole was substantially underfunded or that organizational or informational problems within the plant made it difficult to identify some "high-return" projects. Either possibility suggested that MWTD might be failing to take advantage of some important opportunities.

These findings were all the more surprising because MWTD had both a reputation as an extremely technologically sophisticated organization and as a group with an organizational culture characterized by considerable flexibility and a high degree of personal commitment. Because several researchers have suggested that inadequate attention to process development may be an important factor in the failure of many U.S. firms to respond effectively to heightened foreign competition (Hayes, Wheelwright, and Clark 1988; Dertouzos, Lester, and Solow 1989), understanding why MWTD was apparently underfunding process development projects is thus a potential source of insight into the larger problem of why it is the case that many otherwise excellent U.S. companies have found it so difficult to take full advantage of the potential of process technology.

We found no evidence that MWTD's problems flowed from an overly hierarchical or bureaucratic organization or from arrogant management or a lack of vision. Our results suggest, instead, that the barriers to using process development as an effective competitive weapon in companies that, like MWTD, historically have been primarily "product driven" are subtle, complex, and deeply embedded in both the formal and the informal structure of the organization.

These barriers take two important forms. In the first place, a historical reliance on product development as MWTD's primary source of competitive advantage had created a deeply held common assumption that under conditions of uncertainty the returns to product innovation were considerably higher than the returns to process innovation. This assumption was deeply embedded in the ways in which resources were allocated within MWTD, so that overall funding for process development was constrained severely such that even marginal process development projects had very high returns. In the second place, the division's historical orientation to product development had led to the assumption that process development was very much a secondary function whose chief role was the support of product development. This assumption had become deeply embedded in both the organizational structures and the information systems of the division in such a way that
it was difficult to identify some potentially important classes of highly yielding process development projects.

Both problems are, in principle, "fixable." But our research also raised another disturbing possibility. It suggested that removing the barriers to effective process development may simultaneously make the process of product development less effective. If this is the case it makes the task of improving manufacturing performance considerably more complex because it suggests that the very excellence of companies like MWD may make the process of placing increased emphasis on manufacturing as a source of competitive advantage both very difficult and potentially quite risky.

The paper begins with a brief discussion of previous work in this area and then outlines the division's history, technology, and competitive environment and describes the data and methodology of the study. The paper then turns to a discussion of our results and closes with a discussion of their implications for managerial practice and for future research.

1. Background and Literature Review

The suggestion that the neoclassicist's model of "rational" resource allocation is not a good description of the actual processes of resource allocation inside firms is an old one. Simon and his collaborators first suggested that managerial decisions are better described as "satisficing" and that managers are "boundedly rational" (Simon 1947; Cyert and March 1963), and these insights have been explored further in the work of the evolutionary theorists (Nelson and Winter 1982). Bower's pioneering empirical research suggested that the set of investment projects considered by the top management of a firm was heavily dependent on the structural and situational context of the lower-level managers who generated them, and thus that there was little reason to believe that the final set of projects represented anything like a global optimum (Bower 1974). The development of a wave of intriguing models for the optimal allocation of resources to portfolios of R&D projects further highlighted the divergence between ideal and actual practice, because a series of studies found that these portfolio models, although widely disseminated, were used rarely (Clarke 1974; Fox, Baker, and Bryant 1984; Higgins and Watts 1986).

This research caught the public imagination with the publication of Made in America (Dertouzos, Lester, and Solow 1989) and a wave of other books that suggested that a lack of investment in process improvement was a fundamental contributor to the poor performance of several U.S. industries including machine tools, VCRs, DRAMs, and other commodity semiconductors (Dertouzos, Lester, and Solow 1989). The authors of Made in America, for example, suggested that although Japanese firms typically employed roughly equal numbers of process and product engineers, in the United States the ratio of product to process engineers was closer to three or four to one. Both they and the authors of Dynamic Manufacturing (Hayes, Wheelwright, and Clark 1988) suggested that this reflected a clearly suboptimal allocation of resources and attention to the problems of manufacturing and process improvement.

These ideas were accompanied by a revival of interest in manufacturing as a source of competitive advantage (Fine and Hax 1985; Noori 1990; Womack, Jones, and Roos 1990). Yet despite widespread publication of these results, the road to the elevation of manufacturing as a central player in the firm and to process development as a critical activity has been a long and rocky one. Despite the evidence of some outstanding successes and the best efforts of consultants and academics, process development remains neglected and underfunded in a wide variety of firms (Hayes and Pisano 1994).

Some researchers have explained this neglect as one more example of the inertial tendencies of large, hierarchically organized firms. Many U.S. manufacturers, this argument
runs, failed to recognize the potential of significantly increased investments in process technology because years of success had lulled them into a dangerous complacency. They had become, in effect, fat, lazy, and arrogant. These researchers thus suggested that a move to a focus on manufacturing as a source of strategic advantage required the breakdown of old hierarchical boundaries, a shift toward more "team-based" methods of working and deep strategic commitment from senior management (Hayes, Wheelwright, and Clark 1988; Pine 1993).

This hypothesis is in contrast to research in the organizational tradition, which suggests that a failure to take advantage of the potential of process improvement may reflect organizational success, rather than organizational failure. This work suggests that the evolution of industries is accompanied by the evolution of firm capabilities that are uniquely suited to the demands of that particular industry. As long as the environment remains relatively stable, or as long as technical development remains fundamentally incremental and customer requirements evolve in predictable ways, these embedded routines act as a source of strength. However, when the demands on the firm shift in dramatic and unexpected ways they become a source of weakness, crippling the firm in its attempt to respond to new competitive threats (Tushman and Anderson 1986; Hannen and Freeman 1989; Henderson and Clark 1990).

In industries in which the key source of competitive advantage is rapid product innovation, for example, this argument suggests that those firms that survive may have developed organizational structures, "routines and procedures" and "mental models" that enable them to take advantage of new technologies and of changes in customer requirements in such a way that they can introduce new products rapidly and effectively (Weick 1979; Nelson and Winter 1982). However, the same structures, routines, and models may make it very difficult for these firms to identify the potential of process improvement or to allocate resources to its exploitation.

Both hypotheses suggest that shifting organizational attention to process development may require deep-seated changes in both the formal and the informal structure of the organization; but although the first hypothesis suggests that such a shift will unilaterally benefit the organization because the primary barrier to change is an inflexible and unresponsive organizational structure, the second suggests that the such a shift may carry significant costs because the primary barrier to change is precisely the skills and knowledge developed to enable the firm to compete effectively in another dimension.

With some notable exceptions (Hayes, Wheelwright, and Clark 1988; Leonard-Barton 1988), there has been surprisingly little attention to these ideas in the context of process development. Researchers working in the field have tended to focus more on how firms may improve their allocation mechanisms, rather than on building a deeper understanding of why such a change may be so difficult (Pine 1993; Hayes and Pisano 1994). In this paper we attempt to throw light on the differences between the two hypotheses by exploring the barriers to allocating resources to process development effectively inside a particularly flexible, highly committed and fast moving organization—the MWT&D of the HP Company.

2. Data and Methodology

The Site

The MWT&D, the organization in which this research was conducted, designs and manufacturers high-frequency gallium arsenide (GaAs) integrated circuits and components. The MWT&D is a division of the HP Corporation, an extremely successful diversified manufacturer of computing and instrumentation equipment. The MWT&D's products are characterized by leading-edge performance and in many cases drive the technology of the instruments in which they are used.
For most of its history MWTD has been a captive supplier within HP and has sold only to other HP divisions. Through the late 1970s and early 1980s the division enjoyed double-digit growth as its leading position in GaAs technology enabled it to provide its sister divisions with cutting-edge products at competitive prices. The division enjoyed a reputation for technological excellence—it was proud of the fact that it employed, for example, more Ph.D.'s per head than any other division within HP—and like many other successful HP divisions, the culture at the campus-like Santa Rosa facility was characterized by hard work, mutual respect, and a distrust for rank, excess proceduralization, or hierarchy.

Traditionally, manufacturing at MWTD has been run as a "make-to-order" job shop, characterized by a relatively high-mix, low-volume production process. In 1989 the division occupied 24,500 ft$^2$ of production clean room and test and assembly areas, of which GaAs fab and test accounted for roughly 17,500 ft$^2$. The MWTD used over five distinct technologies to produce a wide variety of components including FETS, diodes, integrated circuits, modulators, filters, and resonators and production was in small batches that were carried from station to station. The primary focus of our research was the production of high-performance GaAs monolithic microwave integrated circuits (MMICs), because although these devices were a relatively small proportion of the division's sales, they were expected to generate the bulk of its future sales growth, but the status and operation of the entire plant was explored when it was appropriate.

In the late 1980s major shifts in the competitive environment placed the division under considerable stress. Declining spending by the Department of Defense, a major purchaser of state-of-the-art microwave instrumentation, coupled with increasing competition from aggressive entrants into the merchant GaAs market, conspired to force a major reevaluation of the division's strategy. By 1989, when the first Leader's students arrived at the division's Santa Rosa site, the decision had been made to attempt to increase sales significantly through a process of significantly reduced costs, increased throughput, and, for the first time, sales to external customers. Thus it was in an environment in which cost-effective manufacturing and a focus on process improvement were increasingly seen as critical resources for the division that the students began their research.

The Data

Students in the MIT LFM program are required to spend 6 months on site at one of the companies that subscribes to the LFM program. During this period they collect data that must later serve as the basis for a thesis that meets the requirements of both the Sloan School of Management and the student's home engineering department. This typically requires both significant engineering and significant managerial content.

In the case of the five theses whose results are described here, the need to do both types of work was placed at the core of the research design. The starting point for each thesis was a significant process development problem identified jointly between the student, the plant, and the faculty engineering supervisor. One student, for example, chose to focus on improving the dry etch via process used to manufacture high-frequency GaAs MMICs (Shapiro 1991). Another focused his energies on improving the scheduling of the plant (Lawton 1990). To fulfill the managerial requirement, each student then explored the following three questions as he or she conducted the technical research necessary to the solution of the engineering problem:

- How was this problem identified? Is this process typical of the ways in which process engineering problems are defined and identified?
- What does the plant believe a solution to this problem is worth? Why?
- What might a solution actually be worth?

In each case, the student's research suggested that the economic impact of solving the process development problem that they had been assigned was considerably larger than the plant had initially anticipated, and that the marginal rate of return to the effort involved
was probably quite high—almost certainly higher than HP's (and hence MWTD's) marginal cost of capital. The students thus spent much of their time understanding the role of the financial systems, the organizational structure, and the culture and history of MWTD in shaping the nature of the process that allocated resources to process development. They conducted in-depth field interviews, studied secondary documents, and discussed their ideas with employees of the plant in an attempt to understand the ways in which the incentive structure, information systems, and the formal and informal organizational structure had shaped the definition of problems and their estimated returns.

This methodology has both strengths and weaknesses. On the one hand, a focus on a small number of projects and a reliance on Masters students without formal training in the tradition of managerial research naturally raises questions about the representativeness and generalizability of the results. On the other hand the detailed work required to solve the technical problems with which they were presented forced the students to develop a depth of knowledge that is usually inaccessible to a researcher. Moreover, their location on site and their day-to-day commitment to the improvement of the plant made them participant observers with extraordinary access to both the formal systems and the informal structures that shaped the organization. The students all developed a deep appreciation for the "feel" of the plant: for both its day-to-day operation and for the kinds of pressures that shaped the lives and choices of the people with whom they worked.

3. Results: Process Improvement at MWTD

High Marginal Returns to Process Development

Table 1 outlines the five critical problems chosen in consultation with the plant as the focus of the engineering theses. They ranged from an in-depth analysis of the plant's scheduling system to the detailed analysis of the sources of process variability and the optimal design of GaAs test structures. Although every problem called for substantial technical analysis and several resulted in published technical papers, each was completed within the 6 months that the students were resident at MWTD (Lawton et al. 1990; Moran et al. 1990; Moran et al. 1991).

<table>
<thead>
<tr>
<th>Student</th>
<th>Engineering Problem</th>
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<tbody>
<tr>
<td>T. Becker</td>
<td>Defining process control limits</td>
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<tr>
<td></td>
<td>How do process control limits shape ultimate product performance?</td>
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<tr>
<td></td>
<td>What are the marginal costs and benefits of changing process control limits?</td>
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<tr>
<td>J. Lawton</td>
<td>Scheduling policies</td>
</tr>
<tr>
<td></td>
<td>What is the optimal scheduling policy for the fab?</td>
</tr>
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<td></td>
<td>What kind of wafer release policy will optimize fab operation?</td>
</tr>
<tr>
<td>P. Moran</td>
<td>Defining key process parameters</td>
</tr>
<tr>
<td></td>
<td>How is gain slope (a key performance characteristic) shaped by variation in key process parameters?</td>
</tr>
<tr>
<td></td>
<td>What are the benefits of reducing variability in these parameters?</td>
</tr>
<tr>
<td>S. Shapiro</td>
<td>Improving the production process</td>
</tr>
<tr>
<td></td>
<td>Quantifying the effects of variation in process inputs in order to improve the fabrication of low inductance backside vias.</td>
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<tr>
<td>D. Vlasak</td>
<td>Design of test structures</td>
</tr>
<tr>
<td></td>
<td>What is the optimal design for on wafer test structures?</td>
</tr>
<tr>
<td></td>
<td>What is the optimal test strategy for the fab?</td>
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It is always difficult to estimate the returns to investment in process improvement, but one of the most intriguing results of the five theses was the suggestion that the returns to these presumably "marginal" projects were likely to be quite high (Table 2).

Lawton, for example, found that relatively straightforward changes in the scheduling of the plant had the potential to reduce substantially cycle time and thus to increase annual sales revenue quite significantly (Lawton 1990). Vlasak's work suggested that test structure design was failing to take into account several significant potential benefits, including the elimination of unnecessary processing and testing downstream, increased effective downstream capacity, and increased throughput of functional die and thus that increased attention to test structure design might generate quite substantial returns (Vlasak 1990). Both Moran (1990) and Shapiro (1991) suggested that the process of identifying new process development projects was systematically biased away from a focus on global, or system wide problem solving so that some important process control problems that could be solved at relatively low cost might be being left unaddressed.

Perhaps most intriguingly of all, Becker's work (1991) raised the possibility that MWT D's failure to model the economic costs and benefits of alternative screening strategies might lead it to choose process specifications that neglected important opportunities for increasing economic returns. His insight is captured in Figure 1, reproduced from Becker (1991). Becker found that MWT D was setting a key process specification in order to minimize cost, rather than to maximize profit. Because costs hardly varied over the range of the specification but profits varied dramatically, there was a significant risk that MWT D was neglecting important information in setting the specification.

These results must be interpreted with caution, because they reflect forecasts of potential benefits rather than a retrospective analysis, but given their magnitude they nevertheless raise a number of puzzling questions. We found no evidence that they reflected organizational failure of the conventional variety—that they were the result of an overly rigid

<table>
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<th>Student</th>
<th>Managerial Issues</th>
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| T. Becker | Defining process control limits  
Defining screening criteria without careful modeling of economic returns may lead to the adoption of process control limits that are significantly suboptimal. |
| J. Lawton | Scheduling policies  
Improved wafer release could substantially reduce cycle time, possibly resulting in as much as a $110 to $210m increase in annual sales revenues, yet MWT D employed no industrial engineering specialists and had never undertaken a significant review of its wafer release policies. |
| P. Moran  | Defining key process parameters  
Six process inputs account for 90% of parametric electrical yield loss due to gain slope variation, yet MWT D was "aware" of only four and actively pursuing only two. Preliminary estimates suggest that the return to incremental work in the area could be quite high. |
| S. Shapiro | Improving the production process  
Inadequate characterization of the back side via process during process development made it quite difficult to address subsequent manufacturing and reliability issues. |
| D. Vlasak | Design of test structures  
Test structures designed to improve circuit design, not to lay the foundations for improved manufacturing capability. Test strategy emphasizes screening of out of specification wafers, rather than improvement of the process. Several possible additional benefits of testing, including the elimination of unnecessary processing and testing downstream, increased effective downstream capacity and increased throughput of functional die, are not considered in the design of test structures. |
or bureaucratic organization or that they reflected turf wars, arrogance, or an inability to understand the changing competitive dynamics of the market. Instead they seemed to have two explanations. The first is that a shortage of resources was forcing MWTD to leave a number of promising projects unaddressed. This idea is captured graphically in Figure 2. Even if all the available process improvement projects had been identified accurately, if the total resources available to fund process improvement were limited, marginal projects potentially would have had very high returns. The second possible explanation is that MWTD was misestimating the returns to process improvement projects, so that the organization was, in some senses, undertaking the “wrong” set of projects (Figure 3).

Unfortunately, without access to data about every available process improvement project—both those that were undertaken and those that were not—it is impossible to distinguish between these two explanations with any degree of precision. In general we came to believe that both captured some portion of the truth. Since 1989 MWTD has tripled the output of the plant, suggesting that the rate of return to the projects that were being chosen by the process engineering department was quite high and lending support to the hypothesis that the marginal projects identified for the students to pursue were likely to generate quite high returns because the resources available to fund process development were in themselves so limited that only very high return projects could be funded. However, we also identified a number of factors that led us to believe that in at least some cases the dynamics more typical of the hypothesis outlined in Figure 3 were in operation: that some high-return projects were being left unfunded because the process engineers were not identifying adequately all their potential benefits.

Both explanations warrant attention, because both imply that the process of process development at MWTD could have been improved. By understanding the barriers to effective process development in an organization like MWTD we can begin to understand the subtlety and pervasiveness of the problems that face a company that has historically
focused its efforts on the development of new products as it moves to make manufacturing a primary source of competitive advantage. In the next section we expand on these ideas by using examples from the theses to illustrate the ways in which the assumptions and patterns of behavior, which were developed during MWTD's historical focus on excellence in product development, combined to make a switch to a focus on product development particularly difficult.
Limited Resources Available for Process Development

All five theses suggested that many important process improvement opportunities were left unaddressed because of an acute shortage of process development resources. Vlasak's remark summarizes the flavor of this result:

While the potential benefits of improved testing seem to be generally recognized within the Device Engineering Group, none of the engineers have had sufficient time to scope the problem and attack it. (Vlasak 1990, p. 16)

Lawton's finding that the division had never hired an individual with a specialist industrial engineering or operations research background, Shapiro's finding that new devices were sometimes transferred to manufacturing before the process that produced them had been characterized adequately, and Vlasak's suggestion that test structures were, in general, designed as aids to the development of new devices, rather than as aids to the improvement of the manufacturing process, all reflect this dynamic.

The vast majority of available process engineering resources were spent in "fire fighting" or in reacting to immediate problems in the plant's operation. Nearly every manager in the process development group felt that they had very few resources to devote to the kinds of systematic, longer-term process improvement efforts exemplified by the LFM theses, although they were all sure that such projects were well worth pursuing. Although engineers found it relatively straightforward to obtain approval for major capital purchases, hiring additional people was extraordinarily difficult. At the time of the thesis work HP had a hiring freeze in place, but even within MWT it was difficult to reassign people across functional or task boundaries. Major pieces of capital equipment might sometimes sit for days or even months until someone found the time to bring them online (Moran 1990).

This allocation of resources between product and process development reflected deeply held beliefs and patterns of behavior developed during the years that MWT's competitive performance had been defined by its ability to meet leading-edge product specifications. Taken together, these beliefs and patterns of behavior embodied the assumption that the marginal returns to investment in product development were significantly higher than the marginal returns to investment in process development. Process development was funded to the level necessary to introduce the product and maintain the process, but beyond this level the division had no mechanisms in place to allocate greater resources to process development.

At the divisional level, for example, process development was managed by simply setting a ceiling on the number of process engineers employed at MWT. No one in senior management had responsibility for comparing the marginal returns to product and process and thus there were no mechanisms in place for expediting the degree to which any particular level of investment in process improvement was the "right" level. In the absence of any formal mechanism the level of the process development budget was inevitably a reflection of historically derived assumptions as to how much process development was the "right" amount. Thus one interpretation of our results is that while shifts in the competitive environment were such that by 1989 the marginal returns to process improvement were quite high, these shifts were effectively invisible to senior management. Suggestions similar to that advanced by Lawton, for example, that quite small changes in scheduling practices might save the division many millions of dollars and thus that adding full-time expertise in scheduling techniques might be a highly profitable investment, were apparently never made because there was no mechanism through which they could have been raised easily. The focus of the division had always been on producing a leading-edge product. As long as the products continued to be leading edge and there was comparatively little pressure to reduce costs all the incentives at the senior level were to invest in new product development.
vestments in new kinds of process development (such as scheduling expertise) were not made simply because they were not considered.

The same process of deeply held, almost invisible assumptions constraining the allocation of resources between product and process development was also visible at the local level. For example, for many years the "heroes" of the division had been those that could push the boundaries of solid state physics to design a single device that far outshone its rivals. Improving the manufacturing process was seen as a less important goal. Thus the device development process put much more emphasis on rapidly meeting customer needs than on the development of a robust manufacturing process, and process engineers tended to measure their own success by their ability to produce leading-edge devices, rather than by their ability to produce them reliably or in quantity. Thus devices were sometimes transferred to manufacturing before the process that produced them had been characterized adequately, and test structures were oriented almost entirely toward the needs of the device engineers. The allocation of resources was embedded in deeply held cultural assumptions that could be expressed in rules of thumb such as "transferring something quickly into manufacturing is more important than fully characterizing the process" (Shapiro 1991) or "test devices are useful in so far as they tell us about device performance" (Vlasak 1990) that acted to constrain the resources allocated to process development even as MWTD's competitive environment shifted such that some relatively high-return projects were left unaddressed.

**Difficulties in Project Identification**

Overall constraints on the resources available for process development probably explain why some of the projects identified by the plant as potentially high-return activities remained unfunded until the student's presence made it possible to pursue them. However, our results also suggested that effective process development was constrained by the fact that process development engineers were probably underestimating the potential returns to certain kinds of process development projects. We identified two key barriers to accurate quantification of the returns to process development: *inadequate information* and a *fragmented or local focus*.

MWTD engineers seeking to improve the production process were forced to grapple with problems handicapped by *inadequate information* on two fronts: the technical and the economic. On the one hand the dynamics that we described above meant that comparatively few resources had been allocated to the problem of process characterization, so that many process engineers had only a limited understanding of the relationship between some key process parameters and some key product specifications. (The engineering research of Becker, Moran, and Shapiro all focused around the development of richer models of the production process.) Without adequate models many process engineers were essentially "flying blind" in their attempt to improve the process.

On the other hand, MWTD had little information as to the economic benefits of many potential process improvement projects. From its inception in the 1970s to 1988 MWTD had been managed as a captive supplier and had been treated entirely as a cost center within HP. Any difference between transfer price and actual costs was charged back to the customer divisions as "residual." Thus while MWTD could readily identify the benefits of cost reduction, any increases in revenues or margins at the customer division that resulted from improved delivery dates or better performance were captured entirely by the customer divisions and were formally invisible to MWTD.

This method of accounting for MWTD's contribution had its roots squarely in the history of the division and again reflects the deeply held assumption that as long as MWTD met its technical goals and delivered truly outstanding products, attention to factors such as cost, yield, and throughput were of secondary importance. MWTD was originally the "tech center," or the research and development function for the microwave instrument divisions
from which it was spun out. As such it was charged simply with developing the best possible devices. Because volumes were low and customers were relatively insensitive to price, communication between MWTD and the instrument builders downstream could be restricted rationally almost entirely to a discussion of technical specifications. The employees of MWTD were secure in the knowledge that they were "doing their job" as long as they could deliver the best devices in the world, and thus treating the division as a cost center imposed no significant penalty.

However, once MWTD attempted to reorientate itself to a more cost-oriented strategy the legacy of this approach severely constrained the information available to MWTD engineers. As they came to try to estimate the economics return from, for example, increasing yield or improving time to market, they were forced to rely on inadequate information as to the ultimate economic impact of their decisions.

Vlasak, for example, found that the cost accounting system in use in the division substantially overstated the benefits of screening "bad" wafers from the process while giving few insights into the benefits of improved yield, more rapid time to market, or improvements in capacity availability. Becker found that screening criteria were set with little reference to their impact on the marginal profitability of the instrument division. All five theses suggested that in choosing process development projects MWTD engineers had almost no information about the economic benefits of increased capacity, of improved process control, or of reductions in cycle time and improved time to market.

Our results also suggested that in some cases the returns to process improvement projects were underidentified as a result of a fragmented or local focus in the process of problem solving. For example, Moran found that within MWTD the responsibility for maintaining, improving, and adding the processes involved in fabricating finished wafers fell to the process engineering group, which reported directly to the manufacturing engineering manager (Figure 4).

The engineers in the group each had responsibility for one set of associated process technologies, whereas the device engineering group had the responsibility for the fabrication of completed devices and was organized by device type. Thus for any given problem in the plant there was likely to be an interested device engineer who's device was not yielding well and an interested process engineer who's process might have been causing the yield loss (Figure 5).

Responsibility for the generation and approval of process improvement projects rested with the process engineering supervisor, who was constrained to allocating manpower from his or her current staffing level. Each supervisor's top priority was fire fighting on the production line or immediate support for the current process. After this obligation was met, the supervisor allocated time between process improvement and new process introduction as he or she saw fit.

This structure made it difficult to allocate resources to projects for whose evaluation a more global view of the production system was required. Major efforts whose benefits might cut across operating boundaries—improving plant scheduling, for example, or rethinking testing strategy—were beyond the scope of the first-level managers who were in control of what process development resources were available. For example, Lawton found that while individual engineers were vividly aware of the unsatisfactory nature of the current scheduling system, no single individual felt that they were in a position to be able to contribute to its improvement. Vlasak found that many test structures were left unused and that there was little discussion of the trade-offs implicit in the current test strategy and speculated that this might partially reflect the local focus of the first-level engineering supervisors responsible for much of the resource allocation.

This focus on local optimization also is consistent with the division's history of excellence in product development. If manufacturing is viewed primarily as a service function whose role is to be immediately reactive to product development, process development
and support are managed optimally when it allows individual device engineers to work closely with particular processes. Moreover, the delegation of responsibility to first-line supervisors who are identified closely with particular groups of processes allows process engineers to feel that they are, in some sense, "really" product engineers—heroes whose mastery of complex technologies allows the division to make technological history. The management of the manufacturing system as a coherent whole requires a significantly different outlook and a correspondingly different set of values and skills.

4. Discussion and Conclusions

Our results are consistent with the belief that an increased focus on process improvement may be a critical source of competitive advantage. The preliminary analyses conducted by the LFM students suggested that process improvement projects such as gaining better control over the process, changing the scheduling of the plant, improving test strategies, and redesigning the relationship between product and process design all had the potential to improve MWTD’s competitive position substantially and that the return to these kinds of marginal projects was quite high—almost certainly considerably higher than HP’s marginal cost of capital—suggesting that MWTD may have been “leaving money on the table” in its allocation of process development resources. However, MWTD’s experience highlights the fact that taking advantage of these opportunities may be particularly difficult for organizations that have competed historically through excellence in product design.

MWTD’s approach to process improvement appears to have reflected two important dynamics: first, the (largely tacit) belief that products were the source of (nearly all) economic returns and, second, a degree of difficulty in identifying high-return process improvement projects that stemmed from a lack of good quality economic information.
about the benefits of improved process control and the *local or fragmented focus* apparent in much of MWTD's process improvement work. The belief that product improvement was inherently more profitable than process improvement was deeply embedded in the structure, information and incentive systems of the firm, and shaped both the locus of organizational attention as it was expressed in the resource allocation system and the information filters that individuals used to allocate their time and guide their problem solving, so that when "push came to shove," improved product performance was considered consistently to be more valuable than reduced manufacturing costs or a more robust process and the resources available for process development were constrained severely. This problem was compounded by the fact that limited information and the local focus of process development problem solving meant that the returns to some classes of potentially high-return process improvement projects were probably consistently underestimated. Table 3 summarizes these factors as they were highlighted within each thesis.

Taken together these factors provide an immediate explanation for MWTD's difficulties in allocating appropriate resources to process development. Faced with very limited resources, inadequate information about the economic benefits of process improvement, and with only a limited understanding of the relationship between process improvement and product specifications, the first-line managers charged with process improvement did their best to devote resources to promising projects but some promising opportunities were inevitably left unaddressed.

Notice that our analysis suggests that this result is as much a reflection of MWTD's historical strength as it is any of any "strategic" or "organizational" failure. The MWTD did not constrain the resources available for process development or fail to identify all the returns available from particularly promising projects because its managers were uninformed or because MWTD's organizational structure was overly rigid or hierarchical. On the contrary, MWTD displayed a quite exceptional degree of organizational openness and commitment. The MWTD's experience highlights the fact that these kinds of difficulties are better understood as necessary consequences of the division's historical success.
TABLE 3

Explaining the Managerial Issues Raised by the LFM Theses at MWTD

<table>
<thead>
<tr>
<th>Student</th>
<th>Possible Explanations</th>
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| T. Becker   | Defining process control limits  
Relationship between process and product parameters not fully understood. MWTD managed as cost center: overriding focus on cost minimization rather than on the revenue or profit maximization: marginal benefits of improving the process not quantified correctly. |
| J. Lawton   | Scheduling policies  
Problem solving process biased against "global solutions."  
IT systems fail to highlight the benefits of improved scheduling.  
Industrial engineering, operations research holds very low status within the organization. |
| P. Moran    | Defining key process parameters  
Chronic shortage of resources: process engineering understaffed?  
Key trade-offs made by first-line supervisor with limited knowledge of system dynamics.  
Projects chosen with limited information and without reference to the possible benefits of increased manufacturing predictability, faster learning or faster time to market. |
| S. Shapiro  | Improving the production process  
"Techno macho" ethos of the division leads to a focus on device performance, not process control or cost reduction. Handoff from development to manufacturing dominated by need to be first to market, enormous pressure from customer divisions: emphasis on process capability rather than on process robustness. |
| D. Vlasak   | Design of test structures  
Design of test structures dominated by device engineers, not manufacturing personnel.  
Benefits of screening overstated, benefits of using test structures to improve process unquantified. |

The MWTD's excellence in product design was supported by much more than excellent technology and an outstandingly fluid and committed organization; it also was supported by a network of formal and informal mechanisms that implicitly reflected the belief that product design was the primary source of value for the organization. Moving the organization toward a more balanced focus on product and process as important thus required much more than the simple strategic recognition that such a move was appropriate. It also required substantial changes in both the formal and the informal resource allocations mechanisms at the division coupled with quite dramatic changes in the information systems and, potentially, in the organizational structure of the plant. Research done over the course of a number of other LFM theses, conducted at a wide variety of sites, is consistent with this conclusion (Dombrowski 1992; Leonard 1991; Morgan 1991; Shipp 1991).

Because such changes are not without risk this research thus raises another difficult and perhaps more fundamental question. The MWTD's excellence in product design was supported by a wide-ranging array of formal and informal mechanisms that together embodied the idea that product design and introduction was the primary source of economic value. To the degree that a focus on manufacturing excellence requires changes in these mechanisms, there may be a real danger that in moving the organization toward a focus on measures such as process improvement, cycle time, and process capability and in changing the information systems and reward structures that supported the "old regime," the firm will loose some of the capabilities that have made it a technological leader. Supporters of a renewed focus on manufacturing suggest, probably correctly, that improved manufacturing capability also may improve the quality and timeliness of product design. But MWTD's experience raises the question as to whether this is necessarily so and suggests that in moving to become more process focused, product-driven companies run some risk of losing the central capability that has sustained them. This issue is an active focus of our ongoing research.
Epilogue

The research described here took place over 5 years ago. Since that time much has changed at MWTD. Throughput has risen threefold, and the division has made enormous progress in responding effectively to the competitive challenges with which it is faced. Nevertheless, we believe that a deeper understanding of the difficulties that MWTD experienced in making this transition may prove valuable to other product-focused companies who may today face similar challenges.1

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