Challenges of Integration in Semiconductor Manufacturing Firms

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Abstract— **Manufacturing efforts to reduce time to market often adopt a concurrent engineering approach that focuses on coordination and integration among engineering, production, and marketing functions. Technological complexity in the semiconductor industry requires an extension of this paradigm to include multiple engineering groups and a strong production maintenance department. Through interviews with employees drawn from engineering, production, maintenance, marketing, and other departments at three semiconductor plants, organizational problems are uncovered that inhibit successful integration within firms in this industry. Ideas for overcoming these problems are given with suggestions for future research.**

Index Terms— **Concurrent engineering, integration, semiconductor manufacturing.**

I. INTRODUCTION

CONCURRENT engineering focuses on the integration of engineering, production, and marketing functions in an effort to decrease time to market by eliminating possible manufacturability problems early in the design process [29]. Integration is defined by Lawrence and Lorsch [23, p. 4] as "the process of achieving unity of effort among the various subsystems in the accomplishment of the organization's task." It implies continual collaboration among various functions along the path from assessing market possibilities to designing a product to manufacturing the final good. Poor integration may result in any number of problems, including products that meet customers' needs but cannot be manufactured with the given equipment and processes. In such situations, products must be redesigned, perhaps several times, before a successful design is completed. The cycles of redesign that occur under poor integration delay a product's entry into the market. In industries where product life cycles are short, such delays can be especially costly. Thus, integration is a key component of the concurrent engineering paradigm.

Most work on concurrent engineering recognizes two factions of engineers in a manufacturing firm. The first faction is comprised primarily of design engineers (often called product engineers) who reside within the company's R&D unit and who are responsible for designing new products or modifying old ones. The second faction is labeled "manufacturing engineers," among whose duties it is to take a product design and determine its manufacture. A number of sources (e.g., [27], [30]) contrast these two groups in terms of salient features such as the time constraints under which they operate (long for design engineers, short for manufacturing ones) and their orientation (design engineers are creative, manufacturing engineers are pragmatic). It is widely accepted that the two groups are differentiated from one another, but that integration between them is desirable for successful product design and manufacture.

However, the use of a broad term like "manufacturing engineers" cloaks major differences and organizational boundaries that can exist within the category. Particularly in industries with highly specialized and complex manufacturing processes, many different types of engineers may work in the area of manufacturing. Semiconductor manufacturing, which serves as the setting for this study and which features tremendous complexity of product, process, and equipment [22], experiences such rapidly changing technology that processes are often immature at the point they are transferred from R&D to manufacturing [24]. Semiconductor manufacturing therefore is not a purely operational exercise; rather, engineering plays a significant role during production [24].

The engineers most directly associated with semiconductor manufacturing are divided into three major specializations: process; equipment; and product engineers. Process engineers modify and improve the technologies associated with the production process. For example, they may determine what temperature diffusion ovens should be set to permit the production of wafers for a given process (e.g., CMOS). Equipment engineers focus on how equipment should be designed and operated; for example, they may make modifications that permit automatic loading and unloading of wafers, or they may analyze why wafer scrap occurs in a certain manner on a given machine. Product engineers are concerned with a given product, which is a smaller classification than a process (e.g., many different types of products are manufactured under the CMOS process). They determine how plant equipment and processes might need to be altered to achieve the specifications of a given product. R&D engineers are also divided into two groups: device and process. Process engineers develop new processes, while device engineers develop new devices or products. The design and manufacture of a semiconductor device requires substantial coordination across the three manufacturing engineering groups, as well as between them and the groups of R&D engineers. Fig. 1 illustrates how the creation of multiple engineering groups complicates the development path for semiconductor manufacturers.

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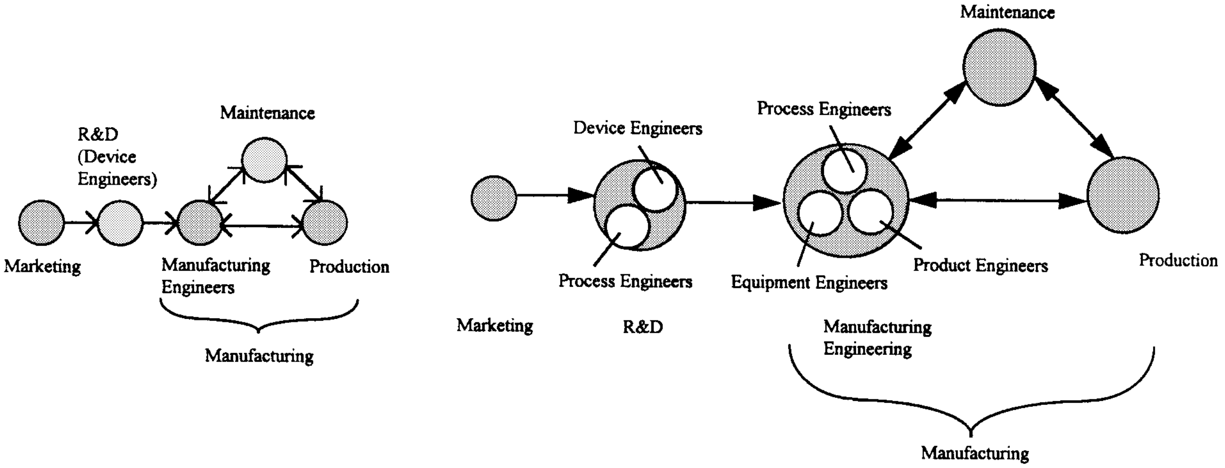

(a) (b)

Fig. 1. How multiple semiconductor engineering groups may pose new challenges to integration. (a) The traditional product development path whose integration is the objective of concurrent engineering. (b) The proliferation of engineering subgroups, in addition to strong production and maintenance departments, adds complexity to the development path for semiconductor firms.

Further, manufacturing engineering groups in the semiconductor industry must coordinate their work with large production operations and maintenance departments. While production is prominently considered in the concurrent engineering literature (see, for example, [8], [14], and [29]), problems along the production–manufacturing engineering interface may well be amplified for semiconductor manufacturers, if only due to the greater number of group boundaries involved. Maintenance is decidedly less considered in the concurrent engineering literature. Certainly, manufacturing sites in every industry have maintenance departments, but maintenance takes on extra importance in the semiconductor industry due to the extreme cost of equipment [24]. Many individual pieces of equipment cost in excess of $1 million, and the cost to construct a new plant may exceed $1 billion. Full utilization of well-kept equipment is therefore a primary concern.

The creation of multiple specialized manufacturing engineering groups, in conjunction with a strong maintenance department and greater engineering involvement in production, increases the complexity of the manufacturing environment for semiconductors. This paper seeks to determine whether this additional complexity spawns new obstacles to integration that are not found in simpler manufacturing environments. Its goal is to investigate factors that impede cross-functional integration and to gain insights into how to overcome them by examining product development at three semiconductor plants.

II. OBSTACLES TO INTEGRATION

Numerous obstacles prohibit the integration of various functions within a manufacturing organization. Previous research and practice have unearthed a variety of mechanisms for overcoming these obstacles (see, for example, [1], [15], [17], [18], [21], [32], and [34]). In this section, two obstacles in particular are noted, and a few mechanisms for overcoming them are discussed to provide a background for the nature of the particular questions in this study. The first obstacle is that posed by differing thought worlds; its solution often takes an administrative form. The second obstacle is slow transmission of information, whose remedy is more typically of a technical nature.

A. Differing Thought Worlds

A major obstacle to integrating diverse functions within a manufacturing firm arises from the varying educational and professional backgrounds of key players. Traditional functional boundaries may serve as clear delineators that mark differences in how people on each side of the boundary have been educated, how they tackle problems, and what they view as important. The functional boundaries thus represent interpretative barriers, or what Dougherty [12] has labeled differing “thought worlds.”

Thought worlds become strikingly—often painfully—apparent when firms employ cross-functional teams as mechanisms for facilitating integration. Such teams are common in new product development [11], [19], [31]. On a product development team, representatives from marketing, manufacturing, and R&D are united early in the design process. The expected result is a product that is designed faster (because manufacturability problems are discussed long before designs are finalized) and that is more suited to customer needs (because customer input is considered as the design progresses, not just in the initial specifications). Cross-functional team members will have differing thought worlds through which they interpret the task at hand. If the team works well as an integrating mechanism, it may improve team members’ understanding of the perspectives of colleagues in different departments. However, the differing thought worlds may cause team members to emphasize problems within their domain while deflating those in other areas [12]. As a result, individuals may come to believe that their team members do not understand them, thereby increasing perceived differences between functional areas. The net result is the hampering of internal task processes deemed crucial for team success and the failure of the team as an integrating mechanism. This potential for either success or failure has led to interest in cross-functional product development teams both in the team literature (e.g., [2], [3], and [16]; see [11] for a recent review) and in the product development literature (e.g., [13], [20], and [32]).

Because semiconductor manufacturing features a greater number of engineering subgroups than lower-technology industries, we might expect an even greater number of thought worlds in this setting. Cross-functional teams here are also apt to be larger to accommodate representation of all functions. Increased size, together with the resulting proliferation of thought worlds, might pose a considerable obstacle to team success and thereby thwart integrative efforts. To defray such potential problems, some semiconductor firms have merged key manufacturing engineering groups (e.g., process engineering with equipment engineering, equipment engineering with product engineering). In a benchmarking comparison study of 28 plants drawn from seven countries, Leachman [24] notes that the merger of engineering groups was positively associated with low defect density measures. However, further merging between manufacturing groups as a whole and R&D groups may not be as positive. Such linkages at the same 28 sites are investigated by Borrus *et al.* [9]. They note that some of the best performers maintain a clear division of labor between R&D and manufacturing engineering groups; integration is achieved by co-locating R&D and volume plants to facilitate a continuous and intense development-manufacturing interaction.

This discussion raises several questions. Does the existence of a greater number of engineering groups equate to more thought worlds? Does merging engineering subgroups diminish interpretative barriers between them? Are other integrative mechanisms beyond cross-functional teams and mergers employed to bridge the gaps among multiple engineering groups?

B. Slow Transmission of Information

Another obstacle to integration involves difficulties in passing information from one function to the next. For example, R&D engineers need to be made aware of defect problems in manufacturing when contemplating new products and processes. When integration works well, transmission of such information from one function to the other is nearly seamless. When it does not, problems ensue; for example, new products and processes may prove faulty if designed with old manufacturability information. The obstacle of information transmission across functions is often overcome with technical solutions. Integrative mechanisms include computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided process planning (CAPP) systems. More recent efforts include the development of systems featuring intelligent agents that help engineers to build shared representations of knowledge (e.g., [25]).

Integrative mechanisms for information transmission practiced by semiconductor firms include the automation of information-handling and the development of information systems that unite production planning with lot tracking and inventory policies [24]. A number of plants have implemented systems that electronically download product recipes (i.e., equipment parameters for processing that are specific to the product) upon identification of the lot through barcode scanning. Such systems integrate engineering specifications with production. Other information systems integrate production planning with manufacturing. Computerized log-in systems used on the production floor prioritize jobs at each workstation in accordance with scheduling rules and, if designed to maintain an inventory policy, may prohibit an operator from running a lot even when work-in-progress inventory (WIP) is present. Both types of systems, while reducing the possibility of costly human errors, also eliminate or reduce production operator autonomy. Perhaps in part to compensate operators for the decision-making tasks they lost to information systems, managers have increased operator involvement in analytical tasks such as problem identification and resolution via total quality management (TQM) and total preventive maintenance (TPM) programs.

The types of questions that arise here are focused on the interaction of new technical systems with existing social ones. For example, do new information systems create “turf wars” across engineering boundaries as one group gains access to information previously “owned” by another? Do the systems change status and power relationships, and do they alter the nature of job roles? In short, are the integrative gains achieved through information transfer in any way diminished by the losses that might emerge if the social order of work is disrupted?

III. RESEARCH QUESTION

This study is exploratory in nature. Its intent is to investigate how the added complexity of the product development path in semiconductor manufacturing may impede integration. It expands previous work by recognizing the diversity among manufacturing engineers in this industry. It asks two basic questions. Will we find obstacles that inhibit integration along the boundaries that separate the various factions of manufacturing engineers, as well as across the boundaries that separate these groups from R&D, production, and maintenance? If we do find such obstacles, will existing integration mechanisms, or variations thereof, be sufficient to overcome them?

IV. METHODOLOGY

A. Sample

Three semiconductor fabrication plants were selected so as to represent a range of semiconductor processes and environments. The plants included a gallium arsenide (GaAs) plant, a silicon R&D plant, and a silicon volume production plant, each from a different firm. The parent companies of the plants were each involved in producing a range of semiconductor products; for example, the parent company of the GaAs plant also owned several silicon plants. Gallium arsenide and silicon refer to the substrates, or wafer material, on which chips are built. Gallium arsenide is considered preferable for a small number of applications, such as certain wireless communications devices; silicon is more universally employed. The silicon volume production plant manufactured large quantities of established products, as well as smaller quantities of new, recently developed products. The silicon R&D plant, like most such plants, had limited production facilities on-site to support its work; volume production was conducted at sister plants (similar to the volume plant in this study) upon final development of a product. The GaAs plant was a "volume" producer in that it did not hand off its developed products to any other plant for their production. However, because the volume of gallium arsenide products was small, in many senses it operated much like an R&D facility. In part to assess whether integration issues within the semiconductor industry are generalizable to other high-technology manufacturing enterprises, a product development facility from an unrelated hard drive manufacturer was added to the study. This facility was responsible for developing new hard drive products; in doing so, it worked closely with its offshore manufacturing site. Four establishments thus constitute the sample.

B. Data Collection and Analysis

Data was collected via on-site semistructured interviews designed to identify key issues of integration. An interview protocol (see Appendix) was developed through which a number of work processes and tasks could be investigated, including transferring processes from R&D plants to manufacturing plants, bringing new equipment on-line and participating on cross-functional teams. Interview questions were related to constructs, such as conflict, cooperation, group interaction, and rewards, that were expected to help depict integration within each firm. For example, by examining the causes of intergroup conflict, one might uncover integration barriers and perhaps gain insights for overcoming them. Similarly, discussions of what meetings an engineer attends and who else is present might lead to an exploration of what functions should be represented at each meeting, why some functions fail to participate, etc. Such information reveals more clearly the state of integration within the firm. Questions were directed at both administrative and technical aspects of integration; thus, for example, goals and rewards as well as information systems were covered. Interviews ended with an open question asking if there were other issues or topics not inquired about, so that interviewees might share unprobed experiences.

Fifty-one individuals were interviewed; roughly half were engineers or engineering managers from R&D and manufacturing groups (having job titles such as process, product, equipment, device, manufacturing, new process introduction, and integration engineer), one-third were production operations staff (managers, supervisors, and operators), and the remainder were distributed across maintenance (managers and technicians), assembly, test, marketing, and human resource functions. Interviews typically lasted half an hour.

Notes from the individual interviews were organized by site. Key points and statements were extracted from the interviews and organized into summaries by functional area and site. These summaries were then content analyzed for similarities and differences across sites and across functional areas. Clear themes were recorded and double-checked against the full interview notes to ensure consistency. All data analysis was conducted by the author, who compared notes across interviewers (an additional interviewer was present at two of the four sites) to ensure accuracy. In cases where a discrepancy in the notes occurred, hosts at the sites were contacted for clarification. The full notes were then checked against the summaries to guard against the possibility of overlooking or misrepresenting important information.

V. RESULTS

Four general themes emerged from the interviews, representing problems which together and individually prevent the integration of manufacturing engineering groups, as well as the integration of manufacturing engineering with other functions, particularly R&D. The themes cover boundary management, status, teams, and communication.

A. Boundary Management

At the boundaries of different functions (e.g., between different engineering groups), there is a blurring of both responsibility and accountability that impedes the work of individuals on both sides. Accountability was differentiated from responsibility by the interviewees in the following sense: one can be responsible for the performance of a task without being held directly accountable for it by an external other. Thus, accountability is responsibility coupled with the oversight of a stakeholder.

Problems in accountability are exemplified by a case from the silicon R&D plant. The process engineers in this plant contend that they are accountable to the device engineers, who hold them to tight deadlines. Device engineers are designers; they create designs for chips based upon specifications that are provided by marketers or, in the case of internal demand, by other engineers. If device engineers are working on the design of a chip that is to have a certain functionality, they depend upon the process engineer to guarantee that this functionality can be achieved with a given manufacturing process. The process engineers in turn depend upon the production operators and their supervisors to aid them in running the tests and experiments that may be necessary to answer the device engineers' questions. However, the process engineers cannot hold the operators and supervisors accountable because organizational boundaries separate engineering from production. Because the production personnel report to a different set of managers than the process and device engineers do, they feel a lesser obligation to meet the demands placed on them by the process engineers.

The silicon volume plant has been experimenting for several years with organization restructurings intended to increase cross-functional accountability. Under the current structure, employees are organized by process type into units called "areas." Within a given area, engineers, production staff, and maintenance crew all report to the same manager, termed an area owner, who is typically a senior engineer. If anyone within the area has a problem, he approaches the area owner, who directs all resources. This single point of contact for engineering, operations, and maintenance issues is thought to engender a more customer-responsive system. The new organizational structure replaced one in which all senior engineering, operations, and maintenance personnel reported directly to the plant manager. In other words, there were no divisions based on process type. Under the old system, everyone had greater amounts of information because, in the absence of department or process boundaries, problems in one area became a subject of concern for all. The staff was fully integrated into a unified whole, with members collectively responsible for plant performance. Under the new system, information is more concentrated; however, accountability is higher. Before, since responsibility was collective, no one championed problems. It was too easy to assume that someone else was taking care of whatever problem might have arisen. As one maintenance technician commented, “There would be a pool of bodies at a problem but no real ownership.” The new area owners may not see the entire plant picture, but they are accountable for their piece of it.

Like accountability, responsibility is also blurred across organizational boundaries. A universal problem in this realm emerged in defining responsibilities between production operators and engineers. In the eyes of production staff, operator skills have increased over the past several years as a result of training received in continuous improvement and quality programs. The rise in skills often has been accompanied with an increase in operator responsibility and autonomy, and that is where the conflict with engineers begins. Operators and supervisors in the sample noted that most manufacturing process engineers fail to recognize and utilize operator skills. Subsequently, operators feel left out of the loop. One operator complained:

> We get no feedback from the second shift engineer. He doesn’t tell us when he releases held lots. His notes are too vague to identify what he did so that we can learn and next time do it ourselves.

Engineers, for their part, argue that operator skills are too narrow for them to find root causes of problems or to understand complex situations. For this reason, many engineers at the silicon volume plant make most decisions themselves rather than granting authority to operators. It would seem that, over time, a certain level of trust might develop between engineers and operators that would encourage the engineer to relinquish duties as he observed an operator’s capabilities grow. But this event doesn’t happen at the silicon volume plant, in part due to rotation of engineers among process areas (one operator remarked, “We change engineers like we change our shirt.”).

Responsibility struggles also can be found in regard to equipment ownership. A case in point arose at the silicon R&D plant, where process engineers are formally delegated equipment ownership. One engineer, acting within the bounds of his authority, negotiated an external service contract with the equipment supplier. In doing so, he neglected to consult the maintenance manager, whom he knew opposed an external contract because he believed the plant could save money by servicing the machine internally. The external contract provides the plant with expertise beyond what can be achieved through training its maintenance technicians. However, now some of the technicians refuse to work on the equipment altogether. The engineer blames the organizational separation that places maintenance in its own department with its own manager for the creation of an environment in which such behavior is tolerated. Although formal ownership had been established in this case, the informal lines of responsibility were blurry enough to cause resentment and frustration on both sides of the boundary.

Responsibility problems occur within the engineering ranks, too. At the GaAs plant, engineers are separated into two groups: integration and process. The “integration engineer” position was created as a step toward bridging the gap between device engineers and manufacturing engineers. (In Fig. 1, an integration engineer can be conceptualized as someone residing on the arrow that connects R&D to manufacturing engineering.) Most of the new integration engineers were formerly R&D engineers. As such, they completed every engineering task associated with small volume production (e.g., process development and device physics). Under the new arrangement, both integration and process engineers have sustaining and development duties, but process engineers have much more of the former and integration engineers much more of the latter. Thus, process engineers are more tightly linked to production, while integration engineers share a large interface with R&D. Although the separation occurred over five years ago, tensions over job roles and duties still exist. Conflict arises largely because process engineers perceive that integration engineers are trying to do their job. Notably, this perception does not extend to new integration hires who, because they do not share the same organizational history as the longer-tenured integration engineers, do not try to take on tasks outside their job description.

The issues of boundary management reveal two paradoxical situations: on the one hand, two different groups may vie for responsibility over a set of tasks, while on the other hand, no single group may be held accountable for various decisions or tasks. Although the formal boundaries separating groups are well-delineated via separate titles and management, the informal ones that govern interactions across groups are still hazy. In other words, titles and group associations are made clear, but job roles are not. Furthermore, few administrative structures exist that would promote coordination and cooperation across group boundaries.

B. Status Distinctions

Another major obstacle to integration is caused by existing status distinctions in the plants. These status distinctions are drawn on the basis of job title and function. Status distinctions have ramifications not only for how individuals perceive themselves and their group, but also for how they behave toward employees with different status. For example, status distinctions are part of what allowed the device engineering group to put pressure on the process engineering group at the GaAs plant as described in the previous section, and for the process group to feel resentment.

In the status hierarchy of the engineering groups in this sample, the highest status is accorded to engineers working on new products or process technologies, which is considered exciting, cutting-edge, and challenging work for an engineer. Lower status is accorded to engineers who handle the day-to-day manufacturing problems that surface during production. This problem is particularly evident at the silicon volume plant, where an R&D group works on-site, but in a separate building. There, many volume plant manufacturing engineers would like to join the R&D group because they consider the work more prestigious. Even within the R&D group, the device engineers are a bit aloof to the process engineers, who work more closely with the volume plant. In fact, process engineers in the R&D group complained that in order to receive help from device engineers on their projects, they frequently had to take their requests to the vice-president of engineering.

Quite naturally, engineers with high status enjoy it, and might be reluctant to give up the associations that grant it to them. However, the increasing emphasis on designing products for manufacturability may be helping to transform the status hierarchy within engineering and thus aid integrative efforts, as suggested by an engineer at the silicon volume plant:

> Manufacturing engineers like to come to [the new product development group] for the technical status. But as manufacturing science gains credibility, the status is changing. The perception still remains, but to transfer a product now you must do more in terms of manufacturability. You must demonstrate Cpk, yield, and throughput data from the fab [plant]. Manufacturing is much more sophisticated now.

An interesting complication of the status issue was observed at the GaAs plant. The role of the semiconductor product line—the GaAs plant's divisional partner—is to produce products at the circuit level. The role of the GaAs plant is to produce wafers, each of which might contain any number of circuits. The status problem unfolded in the following manner: the manager of the product line group was instructed to run his operation like a small company in order to survive drastic cuts in sales. The manager encouraged his group to be "market-focused" and a "world-class manufacturer"; these words were echoed in interviews by his engineers. To this end, the group went through considerable training in customer needs. In fact, the entire marketing subgroup is composed of engineers trained in marketing. The product line group now considers itself a plantless manufacturer; it views the GaAs plant as its supplier, on nearly equal par with other suppliers outside the firm with which it could contract.

The manager of the product line group noted that, during the transition process, his engineers experienced difficulty in "dropping their tests and data and making products without pedigree." No doubt, they had trouble adjusting to their new marketing and manufacturing tasks. Conceivably, part of the difficulty might also have arisen from their own changing view of themselves in the division's status hierarchy. Certainly, an undercurrent of resentment was detected that emanated from the product line group toward the GaAs plant, which had not been forced to transition along the same lines. It was claimed that the GaAs plant was only beginning to realize that the product line was its customer, and that the GaAs plant was more interested in being an R&D group than in being a "real GaAs plant." In this scenario, we see the unusual possibility (in a semiconductor firm) for marketing and operations functions to take on higher status than R&D groups, but only because those positions are filled by engineers who were associated with a former high-status circuit design engineering group.

The interview data suggests that differences in status and power foster psychosocial responses (such as resentment) that impede integration by aiding in the development of an "us-versus-them" mentality. Such responses, when coupled with unaligned goals, are certain to thwart coordination efforts.

C. Problems with Teams at and Across All Levels

Teams are as omnipresent in high-technology manufacturing firms as they are in most other U.S. industries, and teamwork was a word heard often in the interviews. As is common elsewhere, the ideology of teams has infiltrated the culture of the organizations in this sample. The silicon R&D plant had just begun a program of cross-functional teams for product development. The GaAs plant, which employs project teams across functions, recently added a section on teamwork in the performance evaluations of its engineers. The silicon volume plant had just restructured into four area-based teams as described above after a period of experimenting with one large team across all plant areas. Engineers at the hard drive manufacturer were on so many different cross-functional development teams that they complained their entire day was spent in team meetings. The atmosphere around the conference areas at that site gave credence to their claims, as a crowd of people was milling about, and each meeting room was reserved for every hour of the day.

For some engineers, the team experience has been quite satisfactory. Device engineers at the silicon R&D plant would like to work more on cross-functional teams with process engineers, product managers, and sensor engineers. They want to involve process engineers more in development work because they believe this group needs to know that what they do (as process engineers) contributes to a final product. For other engineers, particularly those who are accustomed to independent work, the change to teamwork has not been entirely welcome. A dissatisfied engineer at the silicon R&D plant related her experiences:

> Everyone [at this site] goes through a continuous improvement training course for four days. There is so much emphasis on teams that it is leading to some burn-out. We need more emphasis on [engineering] work groups rather than on problem-solving teams.

Part of the problem with teamwork stems from the way the team concept is implemented at the sites. At the silicon R&D plant, engineers reported that they are expected to lead one to two problem-solving groups simultaneously. Management's emphasis is placed on team leadership; mere membership on a team is not enough. Similar sentiments were expressed at the GaAs fab. As a result, engineers at both sites commented that they tended to put most of their effort into teams that they led, and contributed much less to those on which they were only members, as they knew they would get far less recognition for the success of the latter.

The silicon volume plant has had its own share of problems with a team program implemented for production operators. This plant has been a leader in the industry in the establishment of self-directed production work teams, with a program history extending back to the early 1980's. However, the program evolved over the years and the organization restructured several times, so that the teams now find themselves with less autonomy than they once held. The loss is partly through management design and partly through unplanned system dynamics. Management made a deliberate decision to remove maintenance technicians from the operator teams, largely because of the tremendous resentment the technicians had shown in being united with the production operators, who they considered as having far lower skills, training, and status. By doing so, management removed the team members with the highest technical degrees and with the most detailed knowledge of equipment. The drop in team skill was accompanied by a loss of team autonomy. In addition, the introduction of new processes greatly increased the complexity and diversity of products within the plant. This change severely limited the autonomy of the operator teams, whose base of knowledge is no longer broad enough to cover the enlarged spectrum. According to the operators, the entire situation is made worse by the hiring of new engineers, who are insecure in their positions due to the operators' greater experience, and who "run ragged doing it all themselves." An engineer compared his experiences at the plant with a lower-technology materials plant he worked at previously, noting that "in plants where there are fewer technical problems, you can concentrate more on [team] cultural issues." The volume plant, overwhelmed with technical problems, could not afford this luxury.

Teams can be a great mechanism for integration within a firm, but they falter if not organized within a supporting framework of goals, incentives and rewards. Misaligned goals and incentives and disparate reward systems discourage cooperation and coordination across functions. For example, at the silicon volume plant, the boundary between engineering and maintenance is made more difficult to bridge because the incentives for the two groups are often at odds with one another, as pointed out by an engineer, "Their goal is just to get the machines to run, not to make good product. There are problems getting them to buy into the organization." The boundary between engineering and production at this plant is likewise plagued with goal alignment mishaps. There, status differences hamper efforts to convince manufacturing process engineers to work on manufacturing problems, rather than on projects more tightly associated with R&D.

Notable advances in addressing the misalignment of goals and rewards across groups are being made. For example, a process engineer at the GaAs plant observed the rising importance of manufacturing in his firm, noting that of the four projects on which he was currently working, the two in manufacturing had the highest priority. However, fire-fighting activities still are not rewarded. Recognition for teamwork is slowly rising, but not by enough to affect the current ranking system (in which every engineer is ranked and placed in bands of performance). Engineers claim that the ranking system at times motivates individual engineers to act in ways that might benefit them personally while forsaking team objectives. An integration engineer at that plant further noted that rewards are not as public for mature technology projects. Engineers on new products (i.e., product engineers) get more attention, as that work seems more exciting. Likewise, engineers performing manufacturing breakthroughs at the silicon volume plant believed they were not rewarded highly enough when compared to engineers working on new designs or processes.

Very clearly, reward and recognition systems (sometimes reflecting status differences, other times magnifying team problems) had set up incentives that stifled integrative efforts by making it seemingly less worthwhile for individuals to perform crossover tasks or to aid employees in other functions.

D. Communication Problems

Almost all of the problems discussed so far are administrative in nature. Technical obstacles to integration did arise in relation to communication and information systems. Problems were noted in terms of the content, delivery, and amount of information transmitted across functions. Although a few interviewees were well satisfied with the information they received in the course of carrying out their duties, a more common sentiment was that too much information was transmitted and received. A typical remark came from an engineer at the silicon R&D plant:

> We never have time to think anymore. We do everything on the fly. There is an information overload—you can spend all day reading mail. No time to plan, to think, to read, to learn.

In addition to the problem of the amount of information being sent was the problem of the delivery system itself. At the silicon R&D plant, the introduction of a new information system for the tracking of lots through the plant restricted production supervisors' data access and control. The supervisor who noticed the problem alerted his superior, but no one was quite sure who had set the system's security restrictions, and so no changes were underway to revert the new system to the authority structure of the old one. Diversity in the product mix at the plant also causes conflict in the use of the new system. Codenames for various products are very similar. Thus, an operator who fails to pay strict attention may enter the wrong recipe name into a machine; the resulting error can be extremely costly. Such errors feed into the conflict between operators and manufacturing engineers. For their part, the operators complained about both the amount (five to ten forms a day, each up to five pages long) and the format (written as opposed to verbal) in which information was relayed to them from process engineers.

These comments confirm that not all problems in integration are administrative in nature. They also illustrate that while information systems are often lauded as solutions to integration problems, they can become problems in themselves if they fail to match the established work organization.

VI. DISCUSSION

A. What Is Unique About Integration Among Semiconductor Manufacturers?

The interview data in this study suggests that many of the problems besetting cross-functional integration in semiconductor manufacturing are administrative in nature. In this sense, the problems of integration for these manufacturers do not differ in substance from those in less technology-intensive manufacturing environments, but they do differ in scale. Whereas in a simpler environment, integration problems may dissuade coordination among marketing, production, and engineering factions, in the semiconductor environment, further divisions within the manufacturing engineering group and the R&D group prevent coherence and cooperation even within these factions. For semiconductor manufacturers, it appears that the integration problem is ultimately made more complicated by the greater number of group bound aries.

One of the clear findings of this study is the existence of status distinctions among engineers. Previous work has noted status distinctions between R&D and manufacturing engineers (e.g. [8], [27], and [30]). Wheelwright and Clark [32] observed that in a semiconductor firm they studied, manufacturing engineers were rated two to three job grades lower than design engineers with equivalent job responsibility and impact on competitive position. Nor are such status differences unique to this industry. Pelled and Adler [26] report that in three high-technology firms (a computer company, a defense contractor, and an electrical systems component manufacturer) where they examined cross-functional product development teams, engineers associated with manufacturing had lower status than those in design did. In fact, at one firm, manufacturing engineers were viewed as the engineers that had been rejected by the design group. Armstrong [6, p. 99], retired Vice President for Science and Technology of IBM, recently spoke of how such status perceptions are born:

> [There is] an insidious intellectual pecking order that most of us pick up from the air and water in graduate school. I refer here to the view that “research is better than development,” “science is better than engineering,” “physics is better than chemistry,” and so on down the line. In those days, manufacturing was so far beyond the experience of top-flight science and engineering schools, it was not even at the bottom of the pecking order. This pervasive but foolish set of intellectual prejudices is one of the most dysfunctional parts of the university culture.

Thus, that status distinctions exist among engineers is well documented. What is new in the current findings is that these status distinctions exist even within the manufacturing engineering group, and that they appear to impede the integration efforts of concurrent engineering practices. In other words, where many of us would see engineers of a single stripe (“manufacturing”), the engineers within this domain are keen to note distinctions. Furthermore, these distinctions carry with them differences in status. As a result, they blur issues of accountability, contribute to a lessening of incentives for cooperation, and foster a determination to work on projects deemed more prestigious.

We see the net effect, for example, in the coordination difficulties between integration and process engineers at the GaAs plant. Both groups are considered manufacturing engineers, and both share development and sustaining duties. However, the integration engineers have greater ties to device engineering (R&D), while the process engineers have greater ties to production. The integration engineers are meant to serve as a buffer between the process engineers and the product engineers; they form an integration subsystem in the terms of Lawrence and Lorsch [23]. Yet, in their relations with the process engineers, they themselves are not immune from status distinctions that hamper integration, the very end they are to achieve. This finding implies that any solution that seeks to address status distinctions within a semiconductor firm must not only resolve differences among marketing, production, and engineering, many of which may arise from diverse educational backgrounds, but also among manufacturing engineers, whose educational backgrounds are more similar, but whose roles within the firm and whose areas of expertise are quite different.

Analogous arguments can be made for integration problems that the interview data unveiled in the area of boundary management, teams, and communication; namely, while the nature of the problems are very similar to those in lower technology manufacturing environments, the scale is larger among semiconductors. Also, as expected, conflicts between the manufacturing engineering groups and their production-site counterparts in maintenance and production severely limit integration efforts.

An additional note can be made in regard to boundary-management problems. The interview data suggest that integration among manufacturing engineering groups is hindered when accountability and responsibility are not clearly established among engineering factions. This idea is perhaps best illustrated again by the GaAs plant. There, process engineers complain that integration engineers have yet—after five years—grown accustomed to their new roles, and as a result still attempt to assume many of their old duties, which are now under the jurisdiction of the process engineers. Such a situation suggests that the two groups lack sufficient differentiation. Lawrence and Lorsch [23] showed in their sample of chemical processors that the highest performing firms were those with highly differentiated, yet highly integrated, functions. They went on to note that groups with low differentiation competed for tasks, and that this competition thwarted integration. It is this latter scenario that one sees among the GaAs plant manufacturing groups.

A final point that arises from this study concerns the generalizability of the current findings to high-technology manufacturers beyond the semiconductor industry. The integration barriers mentioned by engineers at the hard drive manufacturer were almost entirely directed at the engineering/marketing interface. For this reason, they were not detailed in the results section, as this interface is covered well in other sources (e.g.,

[14], [23], [27], [33]). But it is worthwhile to consider briefly why so little attention was paid to intergroup tensions within the engineering faction there. Perhaps the most plausible reason has to do with how cross-functional development teams at the hard drive manufacturer were organized. There, unlike at any of the semiconductor firms, such teams were universally led by marketing representatives, not engineers, and in that firm, marketing enjoyed higher status than engineering. This single fact so dominated the thoughts of engineers in the interviews that it diminished the salience of finer distinctions within the engineering group itself. Thus, while it is clear that the semiconductor plants differed from the hard drive manufacturer in terms of where pressing integration problems lie, it is conceivable that their situations would be more similar in the absence of these organizational structure and status differences.

B. Implications for Managers

This research suggests several recommendations for semiconductor managers who wish to improve integration. To the extent that other high-technology firms also have multiple engineering groups, the recommendations may be equally applicable to them. The suggestions are focused on the engineering subgroups within the firm. Other sources (e.g., [14], [25]) contain recommendations for integrating engineering as a whole with marketing and production functions.

1) Managers Should Strive to Lessen Status Distinctions Among Manufacturing Engineers: From this study, it seems that quite a number of the status distinctions observed within the engineering ranks derive from group associations to the traditional rivals of design and production, in that groups with greater association to design have higher status than those associated with production. The trading of engineers between R&D and production plants has been identified as a best practice among semiconductor firms [24]. An extension of this practice may prove beneficial within manufacturing engineering itself. In other words, engineers should be traded among the process, product, and equipment groups at the production site.

However, the manner in which the practice is implemented is critical if status parity is to be gained, as illustrated by the following example. In a case study comparing U.S./Japanese development procedures at two firms, Brown [10] notes that the U.S. firm transfers fully developed technologies from the R&D plant to the volume plant, then restricts modifications to the process made at the volume plant in an effort to prevent declines in product yield. The restrictions are at times difficult to enforce because the volume plant's process engineers prefer solving new process problems (which may not be part of their job assignment) to writing up documentation for process changes (which is). The Japanese firm does not ramp up production at the R&D plant but instead completes the technology at the volume plant. Thus, the Japanese firm relies on the type of manufacturing engineer innovation that the U.S. firm explicitly prohibits. By stifling the process engineers' creativity in this manner, the U.S. firm may eventually find it difficult to hire talented manufacturing engineers [5]. At the Japanese firm this possibility is more remote, as all engineers follow a career path that includes repeating stints in both R&D and volume plants. So, even though both firms practice a best-practice policy of trading engineers between the R&D and volume plants during the handoff period, status differences are reinforced at one firm while mitigated at the other, thereby making integration more difficult at the first firm than at the second.

Another way to break down status distinctions is to publicly reward accomplishments in areas that are viewed as less prestigious. Thus, manufacturing-oriented achievements should be acknowledged with rewards of the same caliber as design-oriented ones. In performance evaluations, credit should be given for successful integrative efforts, such as when design engineers agree to tackle a manufacturing-oriented problem with process engineers. To provide incentives for such behavior, evaluations from individuals external to the department might be solicited when conducting an engineer's overall performance evaluation.

2) Managers Should Consider Decreasing the Number of Manufacturing Engineering Groups: One suggestion for improving integration is to simply remove the very organizational artifact that makes coordination more difficult for semiconductor manufacturers: the existence of multiple manufacturing engineering groups. Appleyard and Edulbehram [4] suggest that only two categories are required: sustaining and project. Sustaining engineers would have primary responsibility for fire-fighting duties on the production floor, with little involvement in research or special projects. These latter engineering tasks would be performed by the project engineers, who in turn would be disassociated from everyday production concerns. One very foreseeable problem with a sustaining/project dichotomy is that it reinforces status distinctions. Further, Saeed *et al.* [28] hypothesize that if product engineers acquire specialized knowledge of production procedures relevant to their area of developmental expertise, then fewer engineering changes due to manufacturability problems would result. A natural extension of this thought suggests that strictly project engineers would fail to gain focused manufacturing knowledge, and engineering changes would continue. Nonetheless, some reduction in the number of manufacturing engineering groups would certainly reduce coordination complexities, and thus it merits consideration, especially in light of the findings by Leachman [24] regarding the quantitative performance benefits associated with merging engineering groups. Merging of engineering groups might also help prevent the formation of differing "thought worlds" of the type described by Dougherty [12].

3) Managers Should Reward Manufacturing Engineers for the Accomplishments of the Teams in Which They Participate, Not Just the Ones They Lead; Leaders Should Be Chosen with Care: Reward and incentive systems that fail to recognize the value of team member contributions hamper integration efforts by not providing motivation for coordination. To facilitate integration, managers should see that their manufacturing engineers are properly rewarded for their teamwork. Informally, member-based team recognition can be achieved by consistently referring to the team by a name given to it or chosen by it, rather than referring to it in terms of the leader's name. In departmental meetings, members should be publicly praised for the accomplishments of the teams in which they participate. More formally, evaluation systems must be designed to recognize and reward team participation and successes. For example, evaluations from team members outside the department can be incorporated into an individual's overall performance evaluation.

The situation at the hard drive manufacturer, where team leadership was always held by marketers, thus causing resentment among engineers, further suggests that managers should be aware of how team leader selection can reinforce status barriers. Wheelwright and Clark [32] point to the problems that arise when the team leader is a "lightweight" in terms of organizational power and status. Yet, if status within the firm is based upon function, then choosing "heavyweight" leaders will only serve to perpetuate status distinctions. It appears that the problem of team leadership is tightly interwoven with issues of status distinctions; a manager must carefully consider both when establishing cross-functional teams.

4) Managers Should Assess Which Process and Equipment Engineering Tasks Can Be Assumed by Production and Maintenance Personnel (i.e., Operators and Technicians) Then Make Clear the Lines of Accountability and Responsibility So that Manufacturing Engineers Feel Comfortable in Relinquishing These Tasks: When operators and technicians are trained to usurp simpler manufacturing engineering tasks, engineers are free to work on more challenging work that is distanced from fire-fighting duties. The result is a win–win situation. Operators and technicians enjoy job enrichment that increases their technical skills and adds variety to their daily tasks [7], and engineers are able to distance themselves from many of the chores that ultimately reduce their status in the eyes of product engineers. If the lines of accountability and responsibility are made clear (e.g., everyone knows who can make what decisions regarding equipment use, job priority, etc.), and the information systems support those lines, then integration between manufacturing engineering, production, and maintenance is greatly aided. Cross-functional meetings can serve as a forum in which engineers, operators, and technicians, for example, can reach consensus over task assignment and job roles, thereby assuring that everyone is familiar with their responsibilities, and that they agree to the roles that they are to fulfill.

C. Areas for Future Research

The results of this study suggest two major avenues for future research. First, it would seem worthwhile to document manufacturing engineering organizational structures and the various types of administrative and technical mechanisms employed to facilitate integration among groups from a large sample of semiconductor firms. A comparison of structures and mechanisms to performance would provide valuable insights. Second, extension of the larger sample to include a wide range of high-technology manufacturers would help to answer the question of generalizability of the integration problems among semiconductor manufacturers unearthed in this study.

VII. CONCLUSION

The concurrent engineering paradigm seeks to integrate downstream manufacturing activities with upstream ones in order to reduce time to market. Often, a concurrent engineering effort focuses on the merging of marketing, R&D, and production functions via cross-functional new product development teams. In this paper, it was argued that the integration of functions within semiconductor manufacturing extends the concurrent engineering paradigm. The presence of a variety of manufacturing engineering groups at the production site, in addition to a strong and essential maintenance department, complicates the problem of integration across functions in this industry. Results of the study suggest that many of the integration problems faced by semiconductor firms are administrative in nature. These problems must be addressed with a variety of organizational changes aimed at the proper management of status, boundaries, teams, goals, rewards, and information systems.

APPENDIX
INTERVIEW PROTOCOL

COMMUNICATION (CM)

CM1. Consider a typical day. Walk us through it and tell us whom you communicate with. What people are you in contact with the most as you perform your job?
CM2. What do you talk about or what is the content of the messages you exchange?
CM3. Does the current information system facilitate or impede your work? What systems do you share across groups?
CM4. Are the communication modes sufficient for you to perform your job effectively? Is there anything you would change or add?
CM5. What types of meetings do you attend? Who else attends? How frequently do you attend? Why did you first start attending (e.g., job title requires it)? What do you gain from them? What is their purpose?

CONFLICT (CF)

CF1. When you agree/disagree with people you work with, what do you usually agree/disagree about? With whom do you usually agree/disagree? (OK to answer by job title, need not reveal a name.)
CF2. What causes conflict? How have you resolved these conflicts?
CF3. What can be done to prevent these problems from occurring in the first place?
CF4. Which groups or individuals do you work exceptionally well/poorly with? Why?
CF5. Perhaps you could tell us the greatest challenge or obstacle you face? How do you address this challenge?

GOALS, REWARDS, and INCENTIVES (GR)

GR1. What are the measures on which your performance is based (e.g., quantity, quality, timeliness)?
GR2. Do goals exist? Who sets them?
GR3. Are you rewarded for your performance? If so, how (e.g., money, praise)?

GR4. Does the reward system seem fair and logical? Does it cause conflicts for you in your job?
GR5. For what sorts of behavior do you recall your organization rewarding/punishing people?

RELATIONSHIPS (RE)

RE1. Who are your direct customers/suppliers? Who are your (other) stakeholders?
RE2. How frequently are you in contact with these people?
RE3. If a problem arises in your relationship with them, how is it resolved? Who do you turn to for help?
RE4. How accountable are you to your customers? How accountable are your suppliers to you?
RE5. How important is your reputation to getting your job done?
RE6. To whom would you complain about your suppliers? To whom would your customers complain?

ADDITIONAL QUESTIONS

For Supervisors And Managers (SM)

SM1 With whom (and to what extent) do the people you supervise interact directly (outside the group)?
SM2 How do you manage this interaction (e.g. reports, informal conversations, participate in negotiations)?
SM3 What groups would you say your people interact with the most in performing their job?
SM4 Do problems emerge in the interaction of the two groups? If so, how are they handled?
SM5 Would you characterize that interaction as one with peers, or do status differences exist?
SM6 What benefits/disadvantages do you see in the current organizational structure?
SM7 What are your work group/unit's long term and short term goals and mission?

For Engineering & Production (EP)

EP1. How much contact do you have with production/(other) engineering?
EP2. How would you describe your relationship with them?
EP3. What are the types of issues you discuss with them? What tasks do you coordinate with them?
EP4. What types of things lead to conflict or problems between your groups and theirs?
EP5. What do you think can be done to reduce the number of problems that arise?
EP6. Do you think you understand the production/(other) engineering group well? Do you know what their goals and incentives are? Do these present any conflict with your own?
EP7. What has been done to facilitate your interaction with these groups? What else would you do, if anything?

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