Interdepartmental Interdependence and Coordination: The Case of the Design / Manufacturing Interface

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The popular business press has been awash with articles and books about new forms of organization which highlight cross-functional, adaptive, learning, time-based competitive capabilities. However, academic research on understanding the various dimensions of these new forms of organization is not very far along. For industrial companies, a crucial nexus for achieving adaptivity and minimizing cycle time involves the relationship between product design and manufacturing. This paper develops a taxonomy and framework for understanding the issues involved in coordination between these departments under conditions of uncertainty and equivocality subject to time constraints on projects.

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Abstract
In contrast with the relative stability of interdepartmental coordination mechanisms in ongoing operations, coordination tasks and mechanisms typically change over the course of the product development project's life cycle. This article presents a taxonomy of these project coordination mechanisms. The taxonomy is based on an inductive analysis of development projects in nine printed circuit board operations and four aircraft hydraulic tubing operations. It distinguishes four modes of interdepartmental interaction—standards, schedules, mutual adaptation and teams (as in Thompson (1967) and Van de Ven et al. (1976))—in each of three temporal phases: pre-project, product and process design, and manufacturing. Each of the resulting twelve matrix cells represents a distinct coordination mechanism. Since the objective of coordinating design and manufacturing departments is to ensure an acceptable fit between product design and manufacturing process parameters, the most efficient interdepartmental coordination mechanism is that which is able to deal with the uncertainty of this product/process fit at least cost to the organization. Extending Perrow's (1967) analysis of the two dimensions of uncertainty to the case of product/process fit, the choice of interaction mode within each project phase is hypothesized to depend on the novelty of the product/process fit problem, and the relative importance of coordination effort across the three project phases is hypothesized to depend on the analyzability of the product/process fit problem.

(*Functional Interdependence*; *Functional Coordination*; *Product Development Projects*; *Design*; *Manufacturability*; *Uncertainty*; *Novelty*; *Analyzability*)

Introduction
As firms come under greater pressure to shorten new product time-to-market (Stalk 1988), the management of the interfunctional design/manufacturing relationship (DMR) becomes a more important competitive variable. Too often, it seems, designs are "thrown over the wall" to manufacturing, only to discover either that they are not "producible" (manufacturable) or that product design modifications would greatly facilitate manufacturing ramp-up, lower costs and improve quality (Whitney 1988, Ettlie and Stoll 1990). A growing number of companies are thus revamping their DMR in search of greater product/process fit and shorter time-to-market (Dean and Susman 1989, Ettlie and Stoll 1990). They are experimenting with design teams, design rules, transition teams, CAD/CAM integration, functional strategy mapping, job rotations and a variety of other coordination mechanisms. This article proposes a taxonomy of design/manufacturing coordination mechanisms and develops a set of hypotheses as to which mechanism is most efficient for dealing with the different types of product/process fit challenges.

These DMR innovations are of theoretical significance because they show organizations redefining the nature of the interdepartmental interdependence and redesigning the associated coordination mechanisms. At first sight, it might seem obvious that the interdependence between design and manufacturing departments must, in Thompson's (1967) terms, be of a sequential character, since it is difficult to imagine manufacturing a product that had not previously been

1047-7039/95/0602/0147/$01.25

designed. Moreover, the standard practice of most firms follows that sequential model rather closely, with the key coordination mechanism being a schedule for the hand-off of the completed product design to manufacturing. However, the innovations referred to above and discussed in greater detail in the body of this article show that organizations are reshaping this sequential interdependence and redesigning their coordination mechanisms.

The practitioner-oriented literature (for example, Dean and Susman 1989, Ettle and Stoll 1990) describes three broad classes of DMR innovations:

- Some organizations are seeking to replace the traditional sequential model of product/process interdependence with a more reciprocal model in which product and process parameters are jointly optimized. Consistent with Thompson's prediction, they use mutual adaptation as the key coordination mechanism, by conducting in-depth design reviews to assess the producibility of designs in progress or by bringing manufacturing engineers into the product design team on a full-time basis.
- Other organizations are pursuing a different strategy—in some cases, combining it with the first strategy—pushing towards a more pooled model of interdependence during the design effort. Before any given project has begun, design and manufacturing staffs define a set of producibility rules, so that when the project gets underway, product designers already know the limits within which their designs must fit, and product designs can be developed and transferred to manufacturing with minimal interdepartmental discussion.
- Yet other organizations are pursuing a third approach—once again not necessarily exclusive of either of the previous two—emphasizing the continuing reciprocal product/process interdependence after the product has been released to manufacturing. In these organizations, design/manufacturing teams remain together for several months or even years after the product has gone into manufacturing, in order to refine the product/process fit and thus further improve manufacturing quality and reduce costs.

Neither the practitioner nor the theoretical literature offers any guidance on how to choose between approaches. This article formulates several propositions that can help determine this choice.

The Theoretical Problem

Some aspects of these DMR innovations are well characterized by existing organizational theory. If changes in external competitive or technological conditions make product designs more dependent on process parameters or vice versa, then contingency models such as Thompson's (1967) or Galbraith's (1967, 1977) predict a shift toward greater reliance on design/manufacturing teams.

But other aspects of these DMR innovations are less well predicted by the established contingency models. In particular, the conceptual frameworks for classifying interdependence configurations—such as those proposed by Thompson (1967), Kiggundu (1981), McCann and Ferry (1975). Victor and Blackburn (1987a)—and coordination mechanisms—as reviewed by McCann and Galbraith (1981)—miss an important dimension, namely the temporal dimension highlighted in the second and third types of innovation mentioned above. As the phases of work unfold within a time-bound project, departments typically experience different degrees and types of interdependence, and they interact with varying intensities and via different coordination mechanisms. And as a result, in the course of a product development project, neither interdepartmental interdependencies nor coordination mechanisms are constant over time.

Organizational research has not often confronted this problem. The focus of almost all the literature to date has been on coordination in ongoing operations. Respondents are typically asked to give an overall characterization of the nature of their interdependence and of the principal coordination mechanisms (for example, Van de Ven et al. 1976). But in studying time-bound projects, such an approach will miss the temporal dimension that contributes much of the richness and complexity of the organization design problem posed in cases of product development. Since many people spend much of their time working on discrete projects, and since product development projects are critical to competitive performance, we need a theory of organization design more suited to such contexts.

The objective of this article is to develop a taxonomy of interdepartmental coordination mechanisms and to develop hypotheses as to which contingencies (normatively) require which mechanisms in coordinating functions' contributions to project work. My focus is thus triply specific. First, it is on how established design and manufacturing departments coordinate their activities, rather than on the logically prior decision of how to divide the organization into departments (c.f., for example, Galbraith (1977)). Second, my focus is on the interdependence created by project tasks, thus abstracting from interdependence due to the broader organizational context in which the departments operate. Third, after establishing a descriptive taxonomy of project coordination mechanisms, the remainder of this article will focus on the normative question of how departments should coordinate in order to manage most efficiently their interdependence, rather than on the descriptive/positive theory of how departments actually do coordinate. A descriptive/positive theory would need to highlight the influence of organizational conflict, status and politics (see, for example, Hickson et al. (1971), Pfeffer (1981), Walton and Dutton (1969), Walton et al. (1969)), whereas this article will leave such factors in the background, if only the better to highlight their impact.

The approach taken in this article is inductive. I studied several organizations that designed and built two different types of products: printed circuit boards (PCBs) for electronic assemblies and hydraulic tubing for aircraft. This field work led to the identification of twelve distinct mechanisms for coordinating design and manufacturing. In keeping with the canons of inductive research (Glaser and Strauss 1967), this article begins with a discussion of the methodology of the fieldwork, then presents the major findings. I first present the evidence for the existence of these twelve mechanisms and outline a taxonomy that distinguishes these mechanisms by their degree of interfunctional interaction and by their timing with respect to three phases in product development project activity. The following section uses the field work to develop hypotheses as to the features of the coordination task that should inform the selection of these mechanisms. The next section develops a cost/benefit analysis that explicates this contingency theory by graphing the relative cost of using the different coordination mechanisms to assure a given level of producibility. A Discussion section identifies some weaknesses of this study and outlines some directions for future research. An Appendix describes the context of the research in more detail for readers who may not be familiar with the tasks and technologies under discussion.

Research Methods

Sample

In order to capture a broad array of interdependence issues, I explored the DMR in two different activities: printed circuit boards (PCBs) for electronic components and hydraulic tubing for aircraft. By studying two distinct technological domains, electrical and mechanical engineering, I hoped to encompass a large variance in the nature of tasks and technologies but to maintain enough focus to allow comparisons within and across domains.

In order to capture a broad array of coordination mechanisms and to identify more accurately the underlying contingencies, I focused on cases in which a new cluster of technologies—grouped under the general heading Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM)—was encouraging firms to reconsider their DMR. As described in more detail below and in the Appendix, CAD/CAM has multifarious effects on the development process, because it changes the tasks and the technologies of design, of manufacturing, and of the communications between these departments. As a result, firms moving aggressively into CAD/CAM often find that their established approaches to design/manufacturing coordination are challenged (Adler 1989). In this context of technological change, many firms were studying their interdepartmental coordination effectiveness, and alongside the implementation of new technologies some had adopted new organizational coordination mechanisms. This created a favorable environment for my research, because the new approaches broadened the range of coordination mechanisms that I could study, and because the visibility of the coordination issues within the sample organizations had sensitized my informants to the underlying issues.

Since my aim was to identify a broad range of coordination practices—rather than to identify central tendencies—the sample was selected from firms that were actively pursuing CAD/CAM integration. A preliminary list of candidate business units was drawn up based on reputation among knowledgeable industry observers and experienced actors in the relevant industries and on accounts published in practitioner-oriented journals.

A total of 13 organizations were studied. Of the four aircraft companies, two were primarily commercial and two were military. Of eighteen PCB organizations contact, nine agreed to participate. Of the remaining nine, two refused to participate on confidentiality grounds; four were eliminated because even though they had relatively advanced CAD and CAM systems, they had no CAD/CAM integration at all; two declined because they were just bringing their first integration efforts on stream; one was too busy managing a business downsizing. The nine PCB participants ranged from very low volume, customized products to very high volume, standardized products. In some cases, boards assembled with their components represented half the manufacturing costs of the final product, and in other cases boards represented less than 5 percent of the final product's costs; in one case, included for comparison purposes, the business was devoted to PCB

Figure 1 Sample Description

Company	Product[1]	Market[2]	CAD/CAM Integration Start[3]	CAD/CAM Integration Level, 1986[4]	Number of Interviews
A	airplanes hydraulic tubing	commercial	1975	3	11
B	airplanes hydraulic tubing	commercial	1976	3	12
C	airplanes hydraulic tubing	defense	1978	3	10
D	airplanes hydraulic tubing	defense	1976	1	7
E	PCBs low complexity	engine controllers, low to very high volumes	1983, 1986	2	12
F	PCBs low complexity	avionics, very low volumes	1985, 1986	1	10
G	PCBs medium complexity	flight simulators, very low volumes	1974, 1977	2	7
H	PCBs medium complexity	computer peripherals, medium volumes	1984, 1984	2	14
I	PCBs high complexity	mainframe computers, high complexity	1977, 1978	3	11
J	PCBs low complexity	electronic instruments, very low volumes	1985, 1986	1	9
K	PCBs low to medium complexity	consumer durables, low to high volumes	1982, 1978	3	7
L	PCBs medium complexity	minicomputers, and instruments, low volumes	1982, 1983	1	6
M	PCBs low to high complexity (depending on customer)	electronics assembly, low to high volumes	NA 1978	0–2 (depending on customer)	3

Notes

[1] PCB complexity levels are: simple (1 to 2 layers), moderate (2 to 6 layers) or high complexity (over 6 layers).

[2] PCB volumes are low (less than 500 boards per year), medium (500 to 5,000), high (5,000 to 50,000) or very high (over 50,000).

[3] In airplanes, CAD/CAM integration starts when tube fabrication begins digitizing sample tubes for NC benders. In PCBs, the two integration dates refer respectively to when they began downloading drill data and when they began photoplotting artwork.

[4] The 1986 integration level is measured on a scale where 1 = downloading data from design database, 2 = extensive producibility design rules embedded in CAD software, 3 = ability to upload design revisions suggestions from manufacturing to the design database.

fabrication for other companies' designs. Given my research focus on the coordination of distinct, functionally specialized departments, I sought larger, more mature organizations for whom the differentiation of design and manufacturing functions wa a long-standing feature of the organizational structure. All the sample organizations in both activities were at least ten years old, and the smallest of them employed 240 people. Figure 1 summarizes descriptive data on the sample.

This sampling plan bore two risks: (a) firms that were active in pursuing CAD/CAM integration might be "technophiles" who focussed on technological solutions rather than organizational solutions to their coordination problems, and conversely (b), firms not pursuing CAD/CAM integration might not have needed that technology because they used more effective coordination mechanisms that would be invisible to me using this sampling plan. With respect to the first concern (a), I assumed that firms pursuing CAD/CAM would complement their technology investments with a broad range of organizational approaches to coordination, and this assumption was borne out in the subsequent research. As explained in the Appendix, CAD/CAM integration is not itself a coordination mechanism; it is merely a communication medium that can be used to facilitate coordination efforts. The second sampling bias risk (b) was minimized by my choice of activities where CAD/CAM integration was technically feasible and had proven advantages: it seemed reasonable to assume that a broader range of coordination techniques would be visible among firms who were worried enough about coordination to have begun to integrate their CAD and CAM systems. To further minimize sampling bias risks, in parallel with the analysis of the field data, I reviewed the research and practitioner literatures on interdepartmental coordination to ensure that there were no mechanisms not represented in the sample companies.

Data Collection

The ground rules of the study were that nothing should compromise the anonymity of the participating companies. The "contact-person" was either a general manager whose responsibilities encompassed design and manufacturing or a senior manager directly involved in cross-functional CAD/CAM integration efforts. Based on preliminary contacts with this person, "discussion outlines" were sent to the business unit general manager, the CAD/CAM manager, functional managers in design and manufacturing, and at least one experienced design engineer and one experienced manufacturing engineer.

These outlines included both general questions and questions on specific product development projects. The general questions included items on the history of the business unit and its results, the time line of their experience with CAD/CAM, the evolution of the organization's skill base, changes in organizational structure, the evolution of business, functional and CAD/CAM strategies, and indices of organizational and departmental culture. The items on specific projects were designed to identify similarities and differences in the conduct of one sample of development projects conducted five years earlier and a second sample of projects conducted within the previous year. This part of the discussion focussed on the technical and business characteristics of the projects and on the specific design/manufacturing coordination mechanisms used. Each item was included in at least two interview schedules.

Semi-structured interviews of between 45 minutes and two hours in duration were conducted separately with each informant. Site visits typically consisted of two researchers (the author and one of the two research assistants working on the project) spending one and a half to two days in interviews and shop and office tours. A total of 119 managers and engineers were thus interviewed over a period from December 1985 to March 1986.

Data Analysis

Following each visit, the two researchers prepared independent assessments and detailed notes based on these interviews and on background data supplied by the companies. Following the logic of qualitative research (Miles and Huberman 1984), these notes were supplemented by an ongoing series of discussions between the principal investigator and the two research assistants around emergent theoretical constructs. These discussions sought to identify the range of factors that facilitated or impeded interdepartmental collaboration. Our initial theoretical perspective was very open-ended. The discussion outline encompassed a broad variety of organizational features that the literature suggested could influence the effectiveness of the DMR. We had hoped to do some small-sample statistical analysis to explore relationships between the rank-order of new product development effectiveness (as measured by development time, manufacturing cost and product performance) and the level of the organizational variables. To our surprise and chagrin we discovered that almost none of the sampled firms collected any data whatsoever on the product development effectiveness variables at the component level (that is, PCBs or tubes). The cost accounting system was not designed to track such variables, and the resulting databases could not be transformed to yield any useful information.

Our expectations in the area of coordination procedures were shaped by the practitioner-oriented literature which has argued that US firms have tended to rely on insufficiently interactive coordination mechanisms. We thus expected that efforts to improve coordination would lead to higher levels of teamwork. As we analyzed our field notes, however, a different pattern emerged. Our informants were often wary of what they saw as the inordinate meeting time associated with team mechanisms, and some hoped to make such face-to-face interaction unnecessary by coding into their CAD databases the required producibility knowledge. We are therefore forced to look more closely at the alternative coordination mechanisms and their respective strengths and weaknesses.

A Taxonomy of Coordination Mechanisms

The first step in our analysis is descriptive. Our framework yielded a list of 12 distinct types of design/manufacturing coordination mechanisms and a taxonomy for conceptually ordering them. Thompson's (1967) analysis is the obligatory starting point for any effort to characterize coordination mechanisms. Citing March and Simon (1958), Thompson highlighted three key generic coordination approaches: standardization or rules, plans and schedules, and mutual adjustment. Van de Ven et al. (1976) added a fourth approach, the team, which they distinguish from Thompson's mutual adjustment by the simultaneity of multilateral interactions and which typically requires physical proximity. This section presents an extension of this taxonomy of lateral coordination mechanisms in a new direction. (I leave to the next section the task of identifying the conditions under which each mechanism is optimal.)

Our fieldwork suggested that we should distinguish the coordination possibilities in each of at least three, notionally distinct, temporal phases of product development activity: (a) *pre-project coordination*, that is, coordination during the activities that precede the initiation of a given development project, (b) *design-phase coordination*, that is, during the phase required for product and process definition, and (c) *manufacturing-phase coordination*, that is, after the "release" to manufacturing operations of the product and process specifications. The key output of the pre-project phase is a set of design and manufacturing capabilities: skills, procedures, technologies, structures and so forth; the output of the design phase is a set of product and process specifications, mostly in the form of drawings; and the output of the manufacturing phase is shippable product. These phases are notional ones rather than empirically observed, since in reality they typically overlap—the development of capabilities is an ongoing process, and both product and process design often evolve after the manufacturing release—but the logical distinction between these phases will help us define the range of coordination challenges and opportunities.

(Note that this phase overlap is reduced by my definition of the design phase as including both product and process design. This definition does not imply that product and process are designed concurrently, only that the phase is considered complete when both product and process are well enough specified for a "manufacturing release." We could refine this three-phase characterization to distinguish between conceptual design and detail design, between prototype cycles, or between pilot production and mature production. In practice, coordination often takes different forms within these sub-phases. The discussion below will make such finer distinctions when they are appropriate, but for the sake of expositional simplicity I will leave the taxonomy in this three-phase form.)

In each phase we can distinguish coordination mechanisms based on the four generic coordination ap-

Figure 2 **A Typology of Design/Manufacturing Coordination Mechanisms**

	Pre-Project Phase	Product and Process Design Phase	Manufacturing Phase
Noncoordination	anarchy	over-the-wall	work-arounds
Standards	compatibility standards	design rules or tacit fit knowledge	manufacturing flexibility
Schedules and Plans	capabilities development schedules	sign-offs	exceptions resolution plans
Mutual Adjustment	coordination committees	producibility design reviews	producibility Engineering Changes
Teams	joint development	joint teams	transition teams

Figure 3 Illustrative Cases

	Pre-Project Phase	Product and Process Design Phase	Manufacturing Phase
Noncoordination	B: "Energetic anarchy" in CAD and CAM investments. L: Absence of CAD or CAM strategy.	G. J: Manufacturing mission is to "make whatever comes over the wall". Tubing (pre-CAD/CAM): Design transmits incomplete designs to mock-up	Tubing (pre-CAD/CAM): Assemblers used their knees to adjust (non-titanium) tube bends. F. G. L: Work-arounds.
Standards	I, C (earlier): CAD/CAM communication compatibility standards.	Tubing (post-CAD/CAM): Tubing bend radii and thickness design rules. PCBs except G, J: PCB line and space width design rules. E, H: Job rotations to build design engineers' knowledge of mfg. constraints.	Tubing: NC benders reduce setup time by 60-70%. PCBs: Assembly automation allows flexibility between different designs (with short set-up times).
Schedules and Plans	A: CAD/CAM task force defines detailed technology development and implementation schedule.	All PCB operations except K, M: Sign-off by mfg. department	E, H: Plan for resolving producibility "exceptions" defined at manufacturing release.
Mutual Adjustment	F, G: CAD/CAM Committee with design and mfg. representatives.	E, F, L. Producibility design reviews.	Tubing: Engineering changes required for 80%-90% of mock up tubes that did not fit first production plane the first time. PCBs: Producibility engineering changes numerous in first few months of manufacturing.
Teams	C (later): Design and manufacturing engineers brought into new IS/CAD/CAM department	E, H: Joint product/process design teams.	E, H. Transition teams.

proaches of standards, schedules and plans, mutual adaptation, and teams, and we can contrast these mechanisms with the "base case" alternative of ignoring coordination requirements altogether. The fieldwork revealed the existence of distinct, formalized coordination mechanisms in each cell of the matrix that crosses generic coordination approaches and phases of activity. The taxonomy is summarized in Figure 2; illustrative cases of each of the 15 types are summarized in Figure 3 and discussed in more detail below.

The following discussion highlights the specificity of each mechanism, but it should be noted that in reality the use of the more-interactive mechanisms does not preclude simultaneous use of less-interactive mechanisms—teams, for example, also conduct reviews, establish schedules, and use standards—just as coordination in later phases does not preclude coordination in earlier phases (see Thompson (1967) on the idea that coordination mechanisms lie on a Guttman scale.)

Pre-project Coordination

Design and manufacturing can sometimes satisfy much of their overall coordination requirement prior to any specific product development project. Company H developed a useful characterization of pre-project coordination: they described it as "filling the pizza bins." The commercial pizza parlor's personnel fill a set of pizza bins so that the making of any specific pizza does not have to await the preparation of the ingredients. Similarly, the new product development project should be able to draw on a set of proven and compatible product and process technologies, rather than having to await the invention of the technologies required to realize its project objectives (see Hayes et al. 1988, Chapter 10). CAD/CAM technologies provide a nice example of such a set of pizza bins. Other key pre-project activities include formulating functional strategies for the design and manufacturing departments, cross-functional skill development, setting producibility standards, and creating approved parts databases. One key role of these pre-project activities is to capture learning from previous projects, for example, by developing better manufacturability knowledge and by refining product development procedures.

The various approaches to CAD/CAM development can be arrayed along a spectrum of increasing interactiveness. A similar range of interaction modes was identified in other pre-project activities; but since my sample had privileged CAD/CAM-intensive organizations, the CAD/CAM area provided the richest set of results and was seen by many of these companies as a particularly powerful pre-project "lever" for accelerating new product development.

Several organizations exemplified the base case of noncoordination of CAD and CAM development. Indeed, Company B had a deliberate policy of not attempting to coordinate CAD and CAM development efforts. In an approach that could be called "energetic anarchy," the company encouraged its functional departments to plunge ahead into whatever automation efforts passed a rather generous set of investment criteria and without any constraints on system compatibility. They ended up with 23 different and incompatible computer-based systems in different departments. This strategy was nevertheless considered successful, since they found that the resulting growth in automation experience and skills outweighed the inconvenience and cost of having to reprogram or replace some systems when they decided to integrate them. More often, however, the absence of strategic coordination was less well motivated than at Company B. At Company L, for example, the manufacturing manager put it simply: "We never did have and still don't have a CAD or a CAM strategy. So how could we coordinate them?" Project managers exercised considerable power in this organization, and no single project had any incentive to invest in systems that would pay off only over several projects.

Among the organizations that did attempt some coordination between CAD and CAM development, we identified several approaches. At the team end of the spectrum of pre-project coordination alternatives, Company C had brought a number of design and manufacturing engineers into a new Information Systems function to jointly develop and implement a long-range CAD/CAM strategy that would position them to compete successfully for their bid for the next major Department of Defense aircraft program. A less interactive model that still allowed for some degree of mutual adaptation was exemplified by Companies F and G, where CAD/CAM Committees were created that regularly brought together staff from the different functions to coordinate their activities.

At the other end of the spectrum of pre-project coordination mechanisms, it is possible to minimize the direct interaction of the functions in the elaboration of CAD/CAM strategies and still maintain a certain degree of consistency if the organization sets compatibility standards. Company C (prior to forming its Information Systems function) and Company I, for example, did not develop comprehensive plans for CAD or CAM systems, but instead, the design and manufacturing functions were encouraged to automate in any way that seemed appropriate with the proviso that all their systems had to be able to communicate with a central product-definition database that each of the companies had created.

Between minimal coordination by compatibility standards and coordination by teamwork or committee lay an intermediate type of CAD/CAM strategy coordination via schedules and plans. Company A exemplified this approach. With the help of CAD and CAM specialists in Design and Manufacturing, a corporate task force put together a schedule for the development and integration of CAD and CAM, but there was no formal authority over its execution and no forum for resolving the compatibility issues that subsequently emerged.

Design-phase Coordination

The fieldwork uncovered several modalities of coordination between design and manufacturing functions during the design phase. But it is important to note that the over-the-wall base case is not a caricature. Companies G and J had no mechanisms whatsoever for discussing producibility issues during the design phase; when designs were revealed to manufacturing, manufacturing had no opportunity to raise objections, and manufacturing's official mission was "to make whatever comes over the wall." Company M specialized in fabricating other companies' PCBs, and it was only recently that more than a minority of its customers had shown any willingness to collaborate in ensuring producibility. And until the recent introduction of CAD, all the aircraft tubing operations were over-the-wall cases; they threw unfinished designs into mock-up and relied on the mock-up phase to define the final specifications.

Standards can be a powerful coordination mechanism in the design phase. If, through pre-project activities and by the capture of learning from previous projects, the organization develops an explicit characterization of its manufacturing capabilities in the form of producibility design rules, these rules can be used by product engineers in the design phase to assure the producibility of their designs. In the extreme case, product/process fit can be assured without any direct interaction with manufacturing staff during the design phase. In hydraulic tubing, the introduction of CAD tools enabled designers to specify tubing paths, and the producibility of these designs was enhanced by reliance on design rules that specified allowable bend radii and wall thicknesses. In PCBs, rules specified parameters such as the width and spacing of the lines that could be reliably printed onto the PCB and the pad sizes required to effectively solder components to the board. At Company K, the proportion of board fabrication specifications that were producible the first time through increased from 40% to 95% in a two-year time span due to the development and implementation of such design rules. CAD/CAM made it much easier for design engineers to check whether their designs respected the producibility design rules, since instead of consulting a manual, they could type in a command to run an automatic design-rule check.

A second form of coordination by standards relied on design engineers' tacit knowledge of the manufacturing constraints, rather than explicit knowledge coded into rules. When design engineers accumulated experience in manufacturing or accumulated an understanding of producibility constraints through their prior project experience, they could anticipate and avoid producibility difficulties with much less direct interaction with manufacturing staff. Only two organizations (Companies E and H), however, had any formal job rotation or internship program in place to encourage the development of these skills; most manufacturing engineers interviewed were highly critical of what they saw as the lack of even an elementary understanding of the manufacturing environment among design engineers.

A somewhat more interactive form of design-phase coordination was the sign-off procedure through which manufacturing signals that it accepts responsibility for making a product to the design specifications. This procedure gives manufacturing the right to veto the specifications as infeasible or to refuse to accept responsibility because some of the required documentation is lacking; but it does not create a forum in which product/process fit issues can be negotiated in any detail. All the PCB organizations except Companies K and M had a sign-off procedure, and Company J relied on it extensively. Company F had only instituted such a procedure in 1983, since previously the design engineering function did its own (very cursory) producibility check. At Company G, there was a sign-off procedure, but manufacturing almost never had the power to effectively veto any package that design wanted to push through.

An even more interactive but less common coordination procedure was the producibility design review. While design reviews were a common procedure for ensuring the coordination of different subunits within the product design department, manufacturing engineering was often not invited. So several organizations had formalized producibility design reviews, reviews conducted with the aim of ensuring that producibility considerations were being respected. Companies such as PCB operations E, F and L that relied on design reviews found that they needed to have several such reviews rather than incorporating the review into the sign-off procedure. The drawback to an end-of-design-cycle review is simply that by the end of the design cycle, considerable effort has been expended to optimize the design from a performance point of view. Even abstracting from the natural tendency of designers to develop a loyalty to their design, producibility improvement suggestions were strongly resisted at this late stage, since revisions to one element of the design typically entailed many time-consuming revisions to other parts of the already accomplished design work. Some other organizations (all the aircraft companies and PCB operations G and L) had producibility engineers who reviewed designs at certain checkpoints in the design cycle; but most of these organizations reported finding that because the producibility engineers reported to (product-) design management, they lost the acuity of their manufacturing point of view.

Companies E and H were the only ones experimenting with a product/process team approach. They had until recently relied on sign-offs and reviews, but found that the competitive pressures on cost and the time lost due to post-release producibility-motivated design changes forced them to reconfigure their procedures. These companies therefore brought manufacturing engineers into the design process earlier, both to begin developing process designs as early as possible and to offer product designers informal advice on how to enhance the producibility of their emerging designs. The dividing line between reviews and teams is blurred, since these reviews also provide a forum for discussing product/process fit optimization. But formal in-progress reviews were often resented because they required design engineers to take valuable time out of design activities in order to prepare for review meetings. Even teams, however, consume a lot of meeting time, and Company E had developed an explicit policy of using this mechanism only for projects that required significant innovation in product or process (see discussion in the following section on "Underlying Interdependencies").

Manufacturing-phase Coordination

Product designs are often changed after the product specifications are sent to manufacturing. In the sample firms, the base case of no coordination during the manufacturing phase often took the form of "work-arounds." In aircraft tubing, these work-arounds occurred when, for example, assembly personnel bent the tubes over their knees to adjust the radii set by the tube fabrication department. With the transition from aluminum to titanium tubing—which is much less pliable—such tweaking became physically impossible. In the PCB case, several informants in manufacturing at Companies F, G and L mentioned the persistence of product design modifications made by manufacturing and not reported to customers or to designers, but absolutely necessary (according to these manufacturing engineers) to ship reliable product. There were, of course, several alternatives to work-arounds; as in the other phases, there was a spectrum of coordination mechanisms ranging from those based more on standards to those requiring more direct collaboration.

At the standards end of the spectrum, most of the PCB and tubing organizations had made considerable investments in manufacturing flexibility. In the pre-CAD/CAM days, the only way to achieve high levels of flexibility in manufacturing was to avoid the use of specialized equipment and to rely on general-purpose equipment, and thereby to incur higher average operating costs (Hayes and Wheelwright 1984). Flexibility could only be had in the form of "slack" (Galbraith 1977). But CAD/CAM and other engineering innovations have mitigated this trade-off. Newer CAM systems for PCB component insertion often had storage capacities for a larger number of different types of components and their computer controls enabled them to alternate between different board designs at minimal costs. In hydraulic tubing, the flexibility of NC benders reduced set-up times by 60% to 70% (according to Company B). New CAD systems drastically reduced the drafting time associated with incremental design changes, since these could be made as modifications to an existing data file.

A more schedule-based form of manufacturing-phase coordination was visible in Companies E and H. Here the producibility issues that had not been resolved at the point of manufacturing release were carefully defined and listed as "exceptions," and a schedule and plan for their resolution was established. Some of the other organizations occasionally used this mechanism too, but in a more ad hoc manner, to signal items of major concern: very few organizations apart from E and H had committed enough resources to producibility assurance to be able to establish such a detailed exceptions list prior to manufacturing release.

Engineering changes (ECs) represent a common form of mutual adaptation in the manufacturing phase: in a frequently encountered scenario, design "throws the drawings over the wall" to manufacturing, and in the subsequent months manufacturing sends back a list of changes required to ensure producibility. (ECs are also the way the organization coordinates the implementation of minor changes required by customers or proposed by marketing.) Manufacturing engineers in most of the PCB companies complained about the frequency with which designs needed producibility modifications after their formal release to manufacturing. And in tubing operations before the introduction of CAD/CAM, first-time-fit ratios (the proportion of tubes requiring no adjustment going from the last prototype to the first regular production aircraft) averaged between 10% and 20%, necessitating a huge flow of ECs. Not only did CAD/CAM help many of the sampled organizations avoid many of the errors that occasioned ECs, it was also helping them to manage the EC cycle more efficiently by ensuring faster processing of design changes.

Under pressure to ensure a higher quality product/process fit, two of the sample PCB organizations (Companies E and H) had established "transition teams" for some of their projects. In this approach, some design engineers moved with the design into manufacturing on temporary assignment, so as to make themselves available on a full-time basis for whatever design revisions were required. This innovation helps deal with a common problem: design personnel move on to the next product design project after the last one is released to manufacturing, and they are typically reluctant to give ECs for the previous project as high a priority as their new product development activities. This rotation was also seen as a way of developing design engineers' understanding of manufacturing.

The Underlying Interdependencies

The second step in our analysis takes us from the descriptive taxonomy outlined in the previous section to normative theory. This section presents hypotheses concerning the nature of the contingencies that, in the normative contingency approach taken in this article, should inform the choice of coordination mechanisms. The field data are used to motivate these hypotheses, but I leave for subsequent research the task of testing them. I will continue to bracket the various cognitive, political or cultural factors that may impede the organization's recognition or implementation of this "optimal" design.

The task to be accomplished by design/manufacturing project coordination mechanisms is that of ensuring the fit between product and process parameters. Depending on the degree of uncertainty of this fit, different coordination mechanisms are needed (March and Simon 1958, Thompson 1967, Galbraith 1977). Following a long line of organization theory (starting with Perrow (1967), Daft and Macintosh (1981), Withey et al. (1983), Fry and Slocum (1984), Victor and Blackburn (1987b)), I propose to conceptualize product/process fit uncertainty in two dimensions; our fieldwork suggested that the two key dimensions are the degree of fit novelty and the degree of fit analyzability.

A greater degree of fit novelty creates uncertainty by making the choice of product design parameters more sensitive to the choice of process parameters or vice versa. The fit novelty of a project can be defined as the number of exceptions with respect to the organization's experience of product/process fit problems. Fit novelty, my field data suggest, is increased by the newness of product and process technology. Moreover, if the perceived business significance of the project is greater, the fit requirements will be more demanding, thus increasing the degree of perceived fit novelty.

Speaking normatively then, greater fit novelty calls for more intensive use of the available product/process fit information, and thus should lead the organization to intensify the information transfer between design and manufacturing departments. Thus the first hypothesis:

H1. *The higher the degree of novelty, the closer to the team end of the spectrum the coordination mechanisms should be.*

The fieldwork provides some motivation for this novelty/interaction hypothesis. Take first the design phase. At one end of the spectrum, new designs sometimes represented very minor modifications of products with which manufacturing had extensive experience. While this was rarely the case in pre-CAD hydraulic tubing, PCBs were sometimes generated as extensions to an existing product family, and in these cases, once manufacturing had learned how to handle the first version, the subsequent versions required little interaction beyond that required to ensure the appropriate modifications to the documentation. The more typical case, however, was where the product or process parameters had been changed significantly relative to previous projects, and where as a result the manufacturability of the new design was not fully assured without some more extensive design-phase coordination effort. The greater the degree of product/process fit newness—the larger the number of exceptions with respect to the established product/process fit experience base—the greater the degree of interaction required.

This logic was most visible at Company E, which had developed an explicit set of criteria for deciding how much design-phase interaction a given project would need. They distinguished four levels of interaction: (1) over-the-wall, then rely on the manufacturing prototypes to resolve residual fit issues; (2) a meeting with manufacturing staff early in the design phase to set some general parameters, then rely on the sign-off to ensure that they had been respected; (3) designate liaison people to conduct occasional in-progress design reviews; and (4) implement a full product/process design team. The choice of interaction level was based on a number of factors, most prominently whether the product and process technologies were: (1) proven carryovers from earlier projects, (2) minor refinements, (3) major changes, or (4) unproven new approaches. Company H, the only other company to employ the team approach, had a similar, albeit implicit, decision rule: it was "obvious," to quote the decision manager, that one doesn't need the team mechanism if the producibility issues had all been resolved in a previous, very similar project.

In the aircraft industry, there had been much less experience with the more interactive forms of design/manufacturing coordination during the design phase.

But one of our informants at Company B retraced the history of his company's coordination mechanisms over the preceding four decades, and noted that the only times the team concept had been attempted were when they were going to use a new material such as titanium or plastic, and design engineers needed manufacturing's direct input in order to assure aircraft performance characteristics.

Turning to the degree of interaction during the manufacturing phase, we can easily see that the extent of direct interaction between design and manufacturing, as opposed to exclusive reliance on the available manufacturing flexibility, depends on the novelty of the specific set of product/process fit issues created by the specific project and not resolved in prior phases. If the product/process fit issues had all been experienced in previous projects or resolved prior to manufacturing release, the flexibility of the existing manufacturing procedures was able to cope with the new product release and there was no need to redefine the product or process specifications as a result of manufacturing experience. If, however, the product/process fit issues embodied numerous exceptions with respect to prior experience, resolving them all in the design phase became too time-consuming, and so the product was released to manufacturing with a list of "DFM exceptions" and a schedule for resolving them. If the exceptions were more numerous, the manufacturing function would subsequently propose fit-enhancing changes in the form of ECs. If these ECs were too numerous, or if their formulation required extensive reexamination of the product/process fit, then the presence in manufacturing of some design engineers in a transition team would be indicated. Such was the experience of Companies E and H.

Evidence for the novelty/interaction hypothesis in the pre-project phase was found in the evolution of Company I's CAD/CAM strategy. As long as they were making incremental innovations in the design and manufacturing technology of their PCBs, sufficient coordination could be assured by the rule that all CAD and CAM systems had to be able to communicate with the product definition database. But as they moved out of the traditional "through-hole" technology and into "surface-mount" technology, the design parameters and the manufacturing process were both changed substantially. As a result, they found they needed a core CAD/CAM group that could manage all the emerging issues in a timely manner.

The second dimension of fit uncertainty is analyzability. Fit analyzability can be defined (following Perrow (1967)) as the difficulty of the search for an acceptable solution to the given fit problem. Fit issues can be more or less numerous—which defines the degree of novelty—but whether they are few or many in number, they can be easy or difficulty to resolve, and this defines their analyzability. Analyzability, my fieldwork suggested, will be particularly low when a new product requires a new manufacturing process, when the design tools do not allow a representation of the entire product, and when these tools do not allow simulation of product performance.

A lower degree of analyzability creates uncertainty by impeding the resolution of product/process fit issues at the current phase of the development process. Lower analyzability therefore calls for the creation of new product/process fit information, in particular by passing from the very abstract characterization of likely products and processes that guides the pre-project capabilities development activity, to the less abstract characterization that emerges from the design phase in the form of drawings and specifications, to the very concrete characterization of product and process that is created with the manufacturing output. Thus the second hypothesis:

H2. *The lower the analyzability of the product/process fit problem, the greater should be the share of later phases in the overall coordination effort.*

It was primarily the analyzability problem that limited the effectiveness of pre-project mechanisms. To use the case of Company I's CAD/CAM strategy once again: even with a joint design and manufacturing engineering team, the challenge of surface-mount was such that they needed a pilot facility to accumulate prototype experience on actual development projects in order to determine the new product/process tradeoffs.

The fieldwork also uncovered cases where even a fully joint team in the product/process design phase could not resolve all the fit problems without going to the manufacturing phase. At Company H, our review of several project histories yielded the following list of factors that increased the magnitude of the post-manufacturing-release producibility effort: engineers' lack of DFM training and know-how, the number of radically new product or process features, schedule pressure for early shipments, and competitive cost pressures. (The discussion also revealed the role of factors that go beyond this article's normative premise: post-release efforts were greater when organizational politics and culture or individual personality clashes impeded up-front interfunctional collaboration.)

In order to explore further this second hypothesis, two follow-up case studies were conducted in two contexts in which the analyzability of the typical fit problems was particularly contrasted: integrated-circuits and internal-combustion engines. Company N designed and manufactured application-specific integrated circuits (ASICs). Solving product/process fit problems is a high priority in IC design because of 90% of the development effort must be scrapped if any changes are made to the product design after release to manufacturing. Even small changes have repercussions throughout the layout and routing scheme, and a whole new mask set must be produced. Company O designed and manufactured engines for farm equipment, and their projects have many ECs in an effort to continually improve cost and quality.

At Company N, chip development teams did not include manufacturing engineers. All the relevant manufacturability knowledge had been coded into their CAD database. In the ASIC case, all this knowledge could be coded because it extended not much further than a characterization of the line and space widths that could be reliably assured. There was intensive design/manufacturing collaboration in the pre-project phase to develop these design rules; but during the project itself, as long as design engineers respected those process capability limits, there was neither need nor time for interaction with manufacturing: the analyzability of the fit problem in IC design was almost total, and so, under pressure to shorten time-to-market, all the coordination effort was pushed into the pre-project phase.

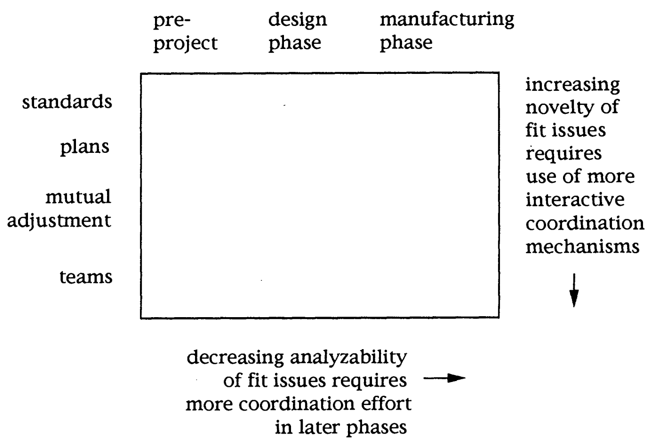
Engine manufacturing represented the other extreme. At Company O, the nature of the mechanical engineering and metal forming tasks seemed to make exclusive reliance on design rules impossible. Despite their best efforts to characterize their manufacturing capabilities, numerous, albeit often minor, product design changes were made after release to manufacturing. Given their high volumes, intense cost competition, and severe quality requirements, engine designs were being continually refined for several years into mature manufacturing. In order to ensure the aggressive pursuit of these changes and the timely processing of the resulting ECs, Company O had assigned the design engineers to remain responsbile for their product for its entire life, effectively acting not just as a transition team—as in Companies E and H—but as a "life-cycle" team.

While we are accustomed to thinking of VLSI chips as very complex products, the producibility problems posed by at least some types of such products (such as cell-based ASIC designs) are much simpler than those posed by engines. At a very modest loss of silicon real estate, the Mead-Conway (1980) methodology of VLSI design condenses the producibility design rules down to a handful of simple mathematical relationships. By contrast, the producibility constraints in internal combustion engine design have yet to be successfully codified. Given the extensive engineering efforts that have been deployed over the decades in the study of engine manufacturing, it seems plausible that the greater difficulty of the engine producibility problem stems from the greater "dimensionality" of the underlying technical challenge and the associated analytic intractability, which in turn stems at least in part from the much greater number of distinct manufacturing processes in engine manufacturing: VLSI fabrication involves many steps, but these are multiple passes through a small number of processes (coating, exposing, etching, etc.)

The design of coordination mechanisms is thus hypothesized to have two dimensions. First, the choice in the interaction dimension—between standards, plans, mutual adaptation and teams—is a function of the degree of novelty of the product/process fit problem. Second, the choice in the temporal dimension—between pre-project, product and process design, and manufacturing phases—is a function of the analyzability of that fit problem (see Figure 4).

It is important to recall that any given development effort will involve more than one product/process fit problem and that these different problems will typically evidence different degrees of novelty and analyzability. So the optimal coordination approach for the project will involve a portfolio of mechanisms, the mix being determined by the relative importance of the different types of fit problems.

Figure 4 Interdependencies and Coordination Mechanisms



The assumption guiding this contingency-theoretic analysis is that organizations (a) can recognize the nature of the interdepartmental interdependence they face and (b) can implement the appropriate coordination mechanisms. As the above discussion suggests however, even among firms facing objectively similar types and degrees of fit uncertainty, there was a considerable range of variation in their coordination approaches. The two assumptions of contingency theory help frame the issues for a descriptive/positive account of the role of cognitive, political and cultural factors shaping actual coordination practices (see Adler 1992b).

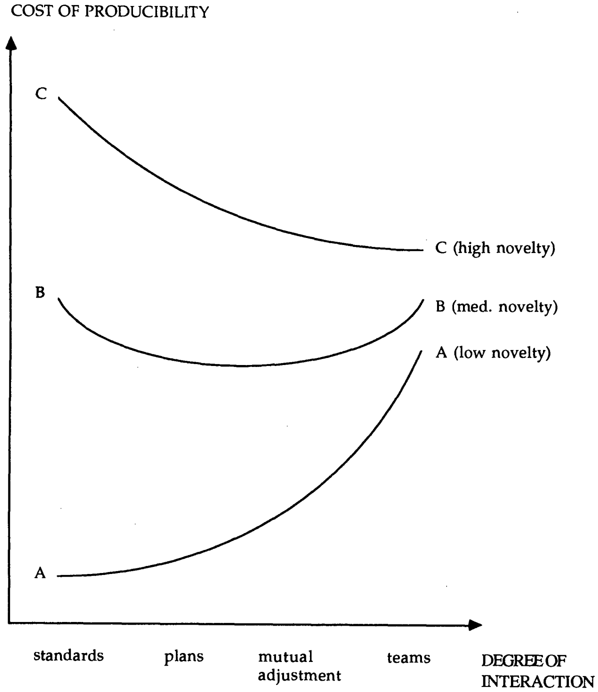
A Cost/Benefit Framework

The previous section presented hypotheses concerning the choice of an optimal approach to assuring producibility. This section seeks to make more explicit the cost/benefit tradeoffs that underlie these hypotheses. The key variable in this analysis is the "cost of producibility" (COP), which can be defined as Crosby (1979) defines the cost of quality: the total costs of preventing, assessing and correcting producibility problems. In the case of producibility, the key costs are (a) organizational costs in the time required to coordinate between the functions, (b) costs in redesigning the product or process, and cancelling or reordering components and equipment, and (c) opportunity costs in the income foregone by being later to market if producibility assurance should delay shipments (see Krubasik 1988).

The assumption underlying the proposed cost/benefit analysis is that in both the interaction and the temporal dimensions, the economically rational organization should choose the coordination mechanism that minimizes the cost of producibility while assuring an acceptable level of producibility. In the following analysis, the competitive benefits of a given level of producibility will initially be held constant, and with this assumption the cost/benefit optimization problem reduces to a cost-minimization problem.

Taking the interaction dimension first, the curve AA in Figure 5 shows the case of a relatively low level of product/process novelty and the COP of the different mechanisms in this case. Following Thompson (1967, p. 56), I hypothesize that if the fit novelty of the project is low, the COP will be at its minimum when the organization relies on standards, and COP will be successively greater if the organization uses plans, mutual adjustment, or teams. (Although the four modes are normally conceptualized as categorical, the earlier discussion showed several intermediate cases, and so I have taken the liberty of drawing continuous lines to simplify the graphics.) The economically rational organization will choose the least costly coordination mechanism that can assure acceptable fit. In the case of a project with low fit novelty (AA), this optimal coordination mechanism is standards, and use of more elaborate mechanisms would be wasteful "over-coordination."

Figure 5 Selecting the Optimum Degree of Interaction



Explicating this argument for each phase in turn:

• In the pre-project phase: at relatively low levels of projected fit novelty, it is relatively easy to ensure consistency of CAD and CAM development efforts through the simple rule dictating compatibility with the product definition database, and coordinating CAD and CAM development via such a rule requires little expenditure of organizational effort. But coordination costs increase as the approach changes to development schedules, standing Committees, and the establishment of new Systems departments.

• In the design phase: if the fit novelty is low, the coordination effort required to achieve acceptable fit is low for design rules and increases as one passes to sign-offs to reviews to teams.

• And in the manufacturing phase: if the fit novelty is low, it is not difficult to ensure the level of manufacturing flexibility required to ensure fit, and coordination costs increase as one progresses towards the more interactive mechanisms.

In Figure 5, I hypothesize that this relationship is curvilinear because it seems intuitive that producibility assurance efforts will experience "declining returns," that is, the incremental reduction in the risk of misfit will progressively decline as one passes from less interactive to more interactive coordination mechanisms (for a given level of coordination effort). This proposition remains to be tested, of course, but it is consistent with Thompsons' (1967) characterization of the different interaction mechanisms as lying along a Guttman scale, so that organizations that employ team approaches do not deprive themselves of the benefits of standards, planning and mutual adjustment mechanisms. The AA curve thus shows the standards mechanism as the most cost-effective coordination mechanism for projects with low levels of fit novelty.

If we turn now to projects where the novelty of the product/process fit problem is greater, several changes are noteworthy. The corresponding COP curve will be higher because all the coordination modes are strained by the effort to deal with this increased novelty. But the strain is plausibly greatest on the less interactive modes, since it becomes very difficult to establish a sufficiently comprehensive set of pre-project, design-phase, or manufacturing-phase standards in the presence of higher amounts of novelty.

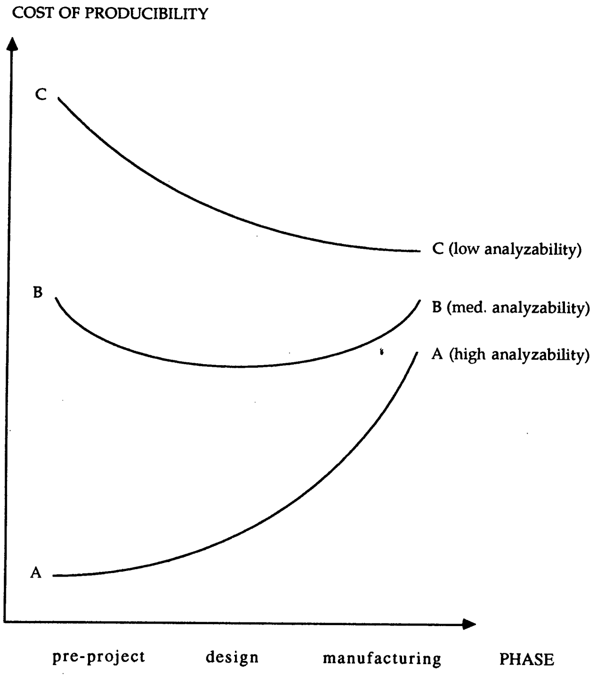
For projects with a moderate degree of fit novelty, it is thus more costly to coordinate using either standards or teams than by the planning or (nonteam) mutual adaptation mechanisms that lie in the mid-range of the interaction spectrum. Instead of AA, we would expect to find BB. At even higher levels of novelty, however, standards may simply be impossible to formulate, and plans and mutual adaptation may be less cost-effective than team mechanisms: design reviews, for example, can become more time-consuming than joint teams, and ECs can become more burdensome than a transition team. So at high enough levels of fit novelty, the COP curve looks more like CC.

The hypothesized curvilinearity of the COP curve can now be seen to be a necessary condition of validity for the present theory: without this curvilinearity, the choice of coordination mechanisms for projects with an intermediate level of fit novelty would be indeterminate and it would be impossible to explain why plans and mutual adjustment mechanisms should ever be used.

We can use this representation to analyze the impact of different market demands on the choice of interaction mechanisms. As increase in the market's quality and cost demands—due to changing customer preferences or to intensified competition—will increase the benefits of producibility. This increase is formally equivalent to an increase in the degree of "effective novelty" faced by the project, and thus will translate upward and rotate clockwise the COP curve, shifting the optimal coordination mode further towards the more interactive end. This can be seen clearly in the comparison of Company E and Company J. Both produced relatively low-complexity PCBs, and new products typically represented similarly large changes in product and process parameters. But Company E produced in much higher volumes and operated in a more cost-competitive industry. As a result, they needed to be much more attentive to the fine-grained detail of product/process fit. In other words, they confronted a higher level of effective novelty. Company E therefore attacked cost reduction opportunities, including those associated with product/process fit refinement, much more aggressively than Company J. As the model predicts, Company E made much more extensive use of the more interactive, team mechanisms than Company J.

We can also use this representation to analyze the impact of new technologies such as CAD/CAM on the choice of interaction mechanisms. (I return to CAD/CAM's impact on the temporal dimension below.) CAD/CAM reduces the effective novelty of the fit issues confronted by the project in several ways. First, CAD/CAM allows cost-efficient storage and retrieval of product designs and process-control programs, and new designs and programs can thus be created by modifying old ones rather than starting from scratch. And second, CAD/CAM reduces the costs associated with the use of standards mechanisms: as mentioned earlier, computerized design rule checkers made these standards much easier to use than manual documentation designed to accomplish the same ends, and CAM technologies reduced the cost of manufacturing flexibility. These effects would tend to translate downward the COP curve and rotate it counterclockwise, making the less interactive mechanisms relatively more attractive for a given project. But CAD/CAM is often accompanied by the introduction of other information technologies that facilitate communication. As Allen and Hauptman (1987) have argued, technologies for project management and configuration control might be expected to reinforce reliance on less interactive mechanisms such as standards and schedules, while technologies for knowledge transfer such as bulletin boards could encourage reliance on more interactive, team mechanisms. Which CAD/CAM effects will

Figure 6 Selecting the Optimum Phase of Coordination



dominate would seem therefore to be an empirical issue rather than a matter for theoretical prediction. Indeed, this indeterminacy may help explain the confusion among the managers interviewed as to whether over the longer term these new technologies will encourage greater reliance on cross-functional teamwork or greater self-reliance of design engineers armed with producibility-checker software.

Turning now to the temporal dimension, the same general logic can be applied (see Figure 6). Whereas the COP of the various interaction mechanisms are measured primarily in meeting time, the COP associated with relying on different phases are measured primarily in the costs of redesign, the costs of reordering equipment and components, and time-to-market opportunity costs.

Curve AA in Figure 6 shows the COP associated with the different phases in the case of a project with a very high level of product/process fit analyzability. When the fit issues are very easy to analyze, the organization should be able to develop proven compatible capabilities in advance of the project, and product development should be cheap and fast, relying on low cost standards mechanism in the design and manufacturing phases (as in the ASIC case). Design-phase teamwork is costly over-coordination when fit could have been assured by standards that were developed in the pre-project phase. And if the organization leaves until the manufacturing phase the resolution of fit issues that could have been resolved earlier, time-to-market and development costs will suffer further.

It seems reasonable to hypothesize some curvilinearity in this relationship since the cost per design change increases exponentially as the project proceeds from conceptual design to detail design to prototypes to regular manufacturing (Hayes et al. 1988, p. 279). And just as in the novelty/interaction case, the curvilinearity is necessary if the theory is to predict the importance of design-phase producibility assurance efforts in cases of intermediate levels of analyzability.

It is interesting to note that while the proposition represented by the AA curve seems plausible when we look at the plans, mutual adjustment and team mechanisms in the different phases, the advantage of (design phase) design rules over (manufacturing phase) flexibility and of (pre-project) compatibility standards over (design-phase) design rules seems less obvious. This is because it is difficult to imagine there being much of analyzability problem without there being any novelty at all, and these three standards mechanisms are only viable in conditions of very low novelty. While the two dimensions of uncertainty are independent over most of their range, they collapse into one variable in conditions of very low novelty. This sets a limit to the value of the distinction, but does not undermine its usefulness in analyzing the broader range of situations.

As we shift our attention to projects with lower levels of product/process fit analyzability, fit can no longer be assured by working only with pre-established mental schemas, and these schemas must be enriched or transformed by their confrontation with the empirical reality of specific design drawings in the design phase or with the test of real manufacturing. As in the interaction dimension, the COP curve for less analyzable projects is thus translated upward and rotated clockwise: the advantage of the earlier-phase mechanisms progressively disappears (AA is replaced by BB). At very low levels of analyzability, coordination at earlier phases becomes more time-consuming than at later ones (BB is replaced by CC): in engine design for high-volume manufacture, for example, it becomes simply impossible to resolve all the fit problems without the benefit of extensive manufacturing experience.

We can again use this representation to analyze the impact of changing market and technological conditions. Increasing competitive pressure on time-to-market or development costs reduces the "effective analyzability" of the fit problems, and therefore translates the COP curve upwards and rotates it clockwise;

reliance on the later-phase mechanisms becomes relative greater. New technologies have a somewhat different impact on this dimension than on the interaction dimension, but again the impact is theoretically indeterminate. On the one hand, CAD/CAM strengthens the effectiveness of the earlier phases. Prior to CAD/CAM, it was technically impossible for the engineers to specify the thousands of constraints that aircraft tube routing had to satisfy, and even team collaboration of manufacturing engineers during the design phase would have not solved the problem, so a lot of the fit assurance effort took place after the design phase. But when CAD/CAM provided designers with a complete representation of the aircraft, they could analyze most of the tubing fit problems without recourse to a prototype and without involving manufacturing specialists during the design phase. This shift "upstream" in the overall distribution of the fit assurance effort was further reinforced because the availability of a direct CAD/CAM link encouraged the manufacturing department to better define their processes and to formulate explicit design rules; and CAD tools encouraged designers to be more complete in their specifications, avoiding another source of analyzability problems that tended to encourage over-reliance on manufacturing-phase mechanisms. On the other hand, CAD/CAM also facilitated reliance on later phases: CAD/CAM reduced the cost of manufacturing flexibility, and the ease of changing CAD drawings reduced the time required for processing ECs. So once again, the impact of new technologies on the relative effectiveness of the different coordination approaches was theoretically indeterminate and depended on the relative magnitudes of its different effects.

Discussion

This section (a) compares the model presented in the previous sections with other proposed models, (b) identifies some limitations of the underlying research, and (c) suggests some directions for future research.

The taxonomy presented here bears some resemblance to that proposed by Daft and Lengel (1986). These authors highlight the degree of interdependence and the cognitive difference between the departments as two factors creating, respectively, "uncertainty" and "equivocality" in interdepartmental relations. Daft and Lengel argue that while uncertainty can be managed by the communication of more information, equivocality can only be overcome by the use of "richer" communication media such as face-to-face dialogue. Their two dimensions of uncertainty can be viewed as a refinement of my "novelty" dimension, and as such could be incorporated into an expanded theory to explain better the choice of coordination mechanisms within a given phase. But Daft and Lengel do not focus on time-bound projects, and so they ignore what I have called analyzability, which is a form of uncertainty that would remain even after eqivocality had been successfully reduced by the appropriate bridging of cognitive frames. While equivocality can be reduced by face-to-face dialogue, analyzability is reduced by the creation of new information through the development of artifacts—design drawings, technical specifications, manufactured products—that are richer in information content. The cycle of interpretative rivalry can sometimes be broken only a new reality test.

The present analysis can also be compared to Allen and Hauptman's (1987) discussion. There the focus was on factors that could affect the relative benefits of project and functional organization in R&D. This reflects my interaction dimension. But Allen and Hauptman do not address the relative benefits of these organizational forms in the different phases of product development. Their analysis of the interaction dimension highlighted three key factors: subsystem interdependence, project duration, and rate of technological change. It seems plausible that all three are reflected in novelty as I have defined it.

Several possible limitations of the present study should be mentioned. First, my analysis may have been biased by the sample's industry, age or size composition. While this composition has, I earlier argued, some benefits, it is possible that the range of coordination mechanisms was truncated or that the kinds of forces that shaped the selection of mechanisms were somewhat idiosyncratic. I have since had the opportunity to study the design/manufacturing coordination problem in several other industries and in firms with no CAD/CAM integration experience (see Adler 1992a, b), and have not found reason to change the taxonomy or the model, suggesting that a reasonable degree of theoretical saturation has been attained. A possibility that cannot as yet be entirely eliminated is that Japanese firms that are renowned for extraordinary product/process fit assurance may use mechanisms that I have not identified; but the available documentation suggests rather that Japanese firms are distinctive only in the degree of discipline with which they implement the optimal coordination mechanisms (see, for example, Langowitz and Wheelwright (1989)).

Second, both the testing and the practical utility of the organizational design approach developed in this article depend entirely on our ability to construct valid and reliable measures of fit novelty and analyzability. Daft and Macintosh (1981) show how this can be done for the uncertainty and equivocality experienced within units. Future research will need to test whether it can be done for interdepartmental coordination issues.

Future research should lift the assumption of a pre-existing departmental specialization of product design and manufacturing. As a result of their experience with joint teams and transition teams. Company H was planning to revise this division of labor to create a single staff of "product engineers" who would assure both product design and manufacturing engineering functions. Dean and Susman (1989) discuss an intermediate solution which maintains the difference in types of jobs but puts both types of engineers under a common manager so as to minimize conflicts of priority and culture. We need more research to elucidate the complex mix of technical and organizational factors at work in these innovations.

The second type of research suggested by the present study would address the complex organizational processes through which in practice the nature of interdepartmental interdependence is identified and coordination mechanisms adopted. The exploration of this process could draw on theoretical perspectives such as organizational politics, strategic choice, organizational learning, social construction, and institutionalization. In these perspectives, however, the properly technical considerations are often ignored in favor of an exclusive focus on the role of political, symbolic and cognitive forces in shaping organizational arrangements. We need to synthesize these perspectives with the contingency-theoretic approach to develop a more balanced process model of changing forms of interdepartmental interdependence and coordination (for a step in this direction, see Adler (1992a, b)).

A third and related research issue arises if we lift the assumption of an exogenously given degree of fit uncertainty. In most of the preceding analysis, analyzability has been presented as an intrinsic characteristic of the project's fit problems, but I have also indicated that CAD/CAM technology can enhance analyzability through its simulation capabilities. Other pre-project efforts can be deployed to enhance effective analyzability, such as job rotations, the development of manufacturability databases, and various mechanisms for capturing learning from previous projects. Similarly, some companies facilitate the producibility assurance effort by reducing fit novelty: they can do this by constraining designers to use only components listed in an "approved parts" database, and allowing components onto this list only when their producibility characteristics have been thoroughly documented. These strategies should be studied in future research (see Adler (1992a, b) for further discussion).

This article has focused on project interdependence in a single dyad: the design/manufacturing dyad. Future research should attempt to develop a more general theory by comparing this project dyad with others such as R & D/marketing (see for example, Bonnet 1986, Gupta et al. 1985, Souder 1980) and software developers/users (see for example, Leonard-Barton 1992).

With the relative decline in popularity of contingency theory as an overarching paradigm, the issues it traditionally focussed on—in particular, those surrounding interdepartmental coordination—have become less central to organizational research. This shift in focus should not, however, be read as a sign that our current level of understanding of these issues is adequate. In a period during which so many U.S. firms are being challenged by foreign competitors in areas so directly related to the management of interdepartmental relations, it is to be hoped that research efforts on these issues will be renewed.

Acknowledgements

This research was supported by McKinsey & Co. Their financial, logistic and conceptual assistance is gratefully acknowledged. Managers and engineers at the companies surveyed graciously provided not only data but also their valuable insights. They must unfortunately remain anonymous. Duane Helleloid and Elaine Rothman provided extensive research assistance. This draft has also benefitted from comments by Bryan Borys, Kim Clark, Robert Hayes, Jim Jucker, Reuven Regev, Robert Sutton, Steven Wheelwright, and the referees.

Appendix: The Contexts

This Appendix gives a brief overview of the tasks and technologies that link design and manufacturing functions in the types of organizations we studied. We also characterize the cultural and political contexts of these interdepartmental relations.

There are typically about 2,500 hydraulic tubes per aircraft. The traditional product development process began with a begin-point-to-end-point engineering specification: the task of defining a precise route for the tube and its brackets was left to the "mock-up" (prototype) department, since tubes compete for space with structural elements and other sub-systems (electrical, fuel, etc.). Given the enormous complexity of aircraft design, it was virtually impossible for design engineers to develop more precise specifications because of these multiple interdependencies. Mock-up was such a key stage in the development process that most airframe manufacturers have a vice president for that department.

Mock-up department workers ("plumbers") fitted flexible wire into the full-scale model aircraft and thereby established the more detailed tubing specifications. Mock-up generated sample tubes and "tube bend cards" describing this configuration. The cards were sent back to the design engineers, who used them to generate official production release drawings. The sample tubes and the bend data cards went to the tooling department to generate tooling. When production orders were released, the fabrication shop used the sample tubes, the data cards and the tooling to bend the tubes needed by the assembly function. (This description is, of course very simplified; Rutledge (1986) identifies no less than 68 discrete tasks involved in this sequence.)

While mock-up resolved many of the producibility problems associated with the design specifications, there were typically a considerable number of engineering changes generated when the tubing tooling reached the assembly department. It often took several production aircraft until the final specifications for tubing were stabilized. Indeed, informants at Company B indicated that even after the three mock-up cycles traditionally required for a new generation plane, the percentage of tubes that fit the first production aircraft without further modification averaged between 10% and 20% (the other three aircraft companies confirmed that these results were representative of their own experience too.) Requests for design changes by the assembly group would go to mock-up, which would then initiate a new iteration.

CAD/CAM technology made possible a new product development process and a new division of labor in aircraft tubing activities. If all the other structural and subsystems elements were visible to them on their CAD workstations, design engineers could fully specify the tubing routes and brackets. This specification could be accessed electronically by the mock-up staff, whose numbers could be considerably reduced since they were only necessary for resolving residual space conflicts. The design database could then be accessed directly by fabrication, where the specifications were directly downloaded into a numerically controlled tube bender. The NC benders were faster and more accurate; they also eliminated entirely the need for error-prone data reentry, expensive special tools and fragile sample tubes.

Apart from the changes associated with CAD/CAM integration, stand-alone CAD and CAM systems also transformed the routines of the participating departments:

- CAM enhanced manufacturing repeatability, accuracy and productivity, and ancillary tasks such as materials handling, tube cutting and deburring were often automated.
- CAD enhanced drafting repeatability, accuracy and productivity. Computerized design databases facilitated the standardization of parts and thus helped minimize the variety of fittings, thereby reducing design time and manufacturing complexity. Computer-Aided Engineering [CAE (in this article, I subsume CAE under the more general category of CAD)] added analytic capabilities that simplified sophisticated design analyses such as Finite Element Analysis.
- CAD/CAM systems offered considerable possibilities for simplifying the elaborate administrative and control system for cost estimation, lot release, shop orders, materials and performance tracking.

The total effect of these changes in technology was still unclear, since few of the sampled companies had had a chance to use the full panoply in a new-generation aircraft. But at Company B, their most recent major modification programs showed a "first-time-fit" ratio—the proportion of tubes that fit the first new production plane—averaging 98%, as opposed to traditional, pre-CAD/CAM ratios for comparable projects that averaged 55%. (Again, the other three companies confirmed that they experienced similar improvements.) The Northrop B2 Stealth bomber program claimed to have entirely eliminated the need for mock-up aircraft and to have gone directly from electronic drawings to production (flyable) aircraft (Harris, 1988).

In the PCB case, the traditional product development process began with the design engineer who hand-sketched a schematic and indicated the components to be used. This schematic passed to a design and drafting technician (titled "PCB designer" or "drafter" depending on the organization) who developed a proposal for component placement and wire routing. (In aircraft tubing, no such division of labor between engineering and design/drafting had emerged.) After several review and revision cycles between engineering and design/drafting, manually-created drawings and mylar masks ("artwork") for printing were transmitted to the fabrication and assembly (component insertion) departments. Each department in turn referred to these documents to generate (manually) the specific drawings and documentation that it required. New board development often required several time-consuming prototype iterations to resolve both design and producibility issues.

CAD/CAM technology made possible important changes in PCB development. The organization developed producibility guidelines or rules to be coded into the design software, facilitating the assessment by designers of the manufacturing costs and quality implications of their design choices. Instead of receiving drawings and mylar, the fabrication department could access the design database directly, using it to automatically generate more accurate artwork, board profiling and drilling programs, and connectivity test programs. The assembly department could draw on the design database too, to semi-automatically generate automatic component insertion programs and functional tests. Automatic insertion programming that used to take 72 hours per board now took only 5 hours at Company E for PCBs of similar degrees of complexity. The design data could also be used to generate process plans and other manufacturing documentation. At Company F, for example, the automation of manufacturing process plan preparation reduced the time required from 160 hours per average board to 50 hours, and the planned integration with the design database was expected to allow a further reduction to 2 hours.

As in the aircraft case, these benefits of integration combined with the important benefits of the stand-alone CAD and CAM systems. Design automation meant that the schematic could be generated on a CAD workstation, allowing for functional simulation even before routing was established, and as a result fewer prototype iterations were necessary. The schematic was then directly accessible by design/drafting, which had at its disposal interactive CAD programs for optimizing placement and routing and for automating drafting. Layout and drafting could now be done in 2 weeks rather than 8 weeks for boards of similar complexity (Company H). Timing tests could then be conducted before any prototypes were manufactured. The combined result of improved accuracy and simulation led to a reduction of the average number of revisions per drawing from 0.51 to 0.33 at Company K. In PCB manufacturing as in aircraft tubing, quality and efficiency were enhanced and various ancillary tasks such as materials handling were automated, and the administrative control system could be greatly simplified. The time required to process an Engineering Change notice fell from 12 weeks to 3 at Company G.

Apart from this task and technology context, it is useful to describe the cultural and political setting. We should note first that there was not much difference in degree of formalization between defense and commercial airplane companies, despite complaints commonly expressed by the defense contractors. The complexity and reliability requirements of the product forced a high level of formalization. The only major distinction was that defense aircraft have more stable designs; commercial aircraft went through more major modification/upgrades, and customers of commercial aircraft typically requested many minor, customer-specific modifications.

The ubiquitous overriding characteristic of the cultural and political setting of both PCB and airplane activities was the disparity of power and prestige between manufacturing and design. The clearest expression of this informal hierarchy was the fact that as recently as 1980, in all of the eight PCB organizations on which I collected this data, not only were design and manufacturing engineers not at the same average pay levels, but they were not even on the same pay curves. In 1987, five out of eight still did not have common pay curves. Of the three that had moved to common curves, one still had a lower maximum for manufacturing and another did not include manufacturing in profit sharing plans. Only one organization seemed to have equalized compensation and hiring norms. Aircraft pay curves were generally similar across functions, but a multiplicity of other symbols and prerequisites communicated the same message of inequality: amount of office space, time to participate in professional activities, etc.

The hierarchy expressed in these "artifacts" of organizational culture reflected and reinforced a hierarchy in values (Schein 1984). The status hierarchy in PCB engineering was almost universally in the following, descending order:

(1) circuit design,
(2) board design,
(3) mechanical design,
(4) assembly engineering,
(5) fabrication engineering.

At Company F, the status differentials were summarized by one manufacturing engineer tersely: "Design engineers are God around here." The grass patch separating the engineering building from the manufacturing building was commonly referred to as "the moat." In aircraft, a similar hierarchy of status and organizational influence distinguished design engineering and manufacturing engineers.

These forms of inequality were the heritage of an earlier epoch in which manufacturing engineers were often promoted from the shop floor while design engineers all had college degrees, and in which competitive success in these industries depended much more on product sophistication than on manufacturing cost or quality. The competitive context has changed significantly in recent years for both aircraft manufacturers and virtually all the PCB organizations surveyed, putting a much greater premium on manufacturing performance. In every sampled company, manufacturing engineering skill requirements were being upgraded: for example, the proportion of degreed people among the manufacturing engineers in Company E grew from 40% to 68% between 1980 and 1986, and from 15% to 100% from 1976 to 1986 in Company H. This explains the fact that several organizations—most noticeably Companies A, B, E, H, I and K—had tried to overcome the functional disparities of pay, power and prestige.

But change has been painfully slow. This could be seen in the very variable degrees of enthusiasm that the design engineers showed towards producibility design rules. At one extreme, the design engineers at Company L pushed manufacturing to develop them, since they were under severe time-to-market pressure and when their PCB designs respected those rules they could be assured of fast prototype cycles and a fast transition to mass production. At the other extreme, at Company F, one engineer described the design rules as "an anvil around our necks" and analysis of the previous 12 months' design releases revealed that over 50% of the PCB designs violated at least one design rule. It was hard to avoid the impression that many design engineers used CAD/CAM to avoid contact with low-status manufacturing: the manufacturing manager at Company I asserted that "We never used to see any design engineers in the plant; and now they have their design rules, we see even less of them."

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Accepted by Arie Y. Lewin; received November 1990. *This paper has been with the author for four revisions.*