FROM PROJECT TO PROCESS MANAGEMENT IN ENGINEERING: MANAGERIAL AND METHODOLOGICAL CHALLENGES

Paul S. Adler*
Department of Management and Organization
School of Business Administration
University of Southern California
Los Angeles CA 90089-1421

Avi Mandelbaum
Faculty of Industrial Engineering and Management
Technion
Haifa, Israel, 32000

Viên Nguyen
E53-353
Sloan School of Management
Massachusetts Institute of Technology
Cambridge MA 02139

and

Elizabeth Schwerer
Graduate School of Business
Stanford University
Stanford CA 94305-5015

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[*] The order of the authors' names is alphabetical

Abstract: Engineering product development efforts have often been studied as though they consisted of independent and idiosyncratic projects. In reality, however, many product development organizations do not rely on fully-dedicated teams, so their projects suffer delays when resources have to support more than one project concurrently. Moreover, in many product development organizations, projects often exhibit numerous similarities with previous projects. While PERT models allow the characterizations of independent and idiosyncratic projects, a more realistic model of development organizations would therefore represent them as stochastic processing networks in which engineering resources are "workstations" and projects are "jobs" that flow among the workstations. This paper describes the managerial issues involved in adopting such process approach to product development and the methodological issues in modeling development time with this approach. We identify these issues through a field-based research project.

INTRODUCTION

The motivation for the research reported here was the growing competitive importance of product development time. As argued by business observers such as Blackburn (1991), Clark and Fujimoto (1989a), Stalk and Hout (1990), and Wheelwright and Clark (1992a, 1992b), the intensification of global competition has created enormous pressures on firms to accelerate the process of developing and launching new products.

Our research was premised on two hypotheses concerning the product development process. First, while product development projects are often viewed as collections of unique activities, we believe that in reality different projects within a given organization often exhibit substantial similarity in the overall flow of constituent activities. Second, while most of the planning tools available to managers assume that projects are independent clusters of activities, we believe that in reality many organizations must manage concurrent projects that place competing demands on shared human and technical resources.

The conjunction of these two hypotheses suggests a proposition: a process view — that is, a view of the development process as a more or less repetitive "design production process" — can provide a framework for better understanding product development time in organizations with multiple concurrent non-unique projects that utilize shared resources. In particular, such a process view would allow us to estimate the delays projects are likely to experience as they wait for resources and to identify otherwise invisible opportunities to accelerate time-to-market.

This proposition can be restated in organization-theoretic terms: the degree of "structure" or "programmability" of engineering tasks is in part "enacted" rather than exogenously given (see Weick, 1977, on the concept of enactment). Whereas the naive researcher might take at face value an informant's description of engineering tasks as much less structured and programmable than manufacturing tasks, closer analysis might reveal the possibility of "reenactment" both in the weaker sense of the term — tasks that are interpreted as unstructured might reasonably be interpreted differently — and in the stronger sense — the real tasks can be reshaped to make them more structured.

Several previous studies have suggested that product development time could be significantly shortened based on a process approach (Hayes, Wheelwright and Clark, 1988; Schoenberger, 1986; Alexander, 1990), but they have not tested the idea by attempting to model realistically a sample firm's product development activities. The project described here sought to build such a model. Two other papers (Adler et al., 1992a and 1992b) describe the operational results. The research process itself also revealed important lessons concerning the technical methodological challenges of process modeling in engineering contexts. Underlying many of these methodological issues lay organizational challenges created by a shift from a project management to a process management viewpoint. These managerial and methodological issues are the focus of the present paper.

With the aim of better identifying and understanding these issues, this paper recounts the method by which we constructed a process model for a sample engineering organization and the challenges we encountered in this effort. The following section summarizes the formal characteristics of process models of the kind we envisaged. We then highlight several issues that we considered in choosing a research site and describe the organization that eventually became our host. The next sections discuss the issues we encountered in operationalizing and measuring the process model variables. A concluding section highlights the lessons learned.

THE CONCEPTUAL FRAMEWORK FOR PROCESS MODELING

The most commonly used tools for predicting product development times are descendants of PERT (Project Evaluation and Review Technique) and CPM (Critical Path Method) (Dean, 1985). But these techniques fail to account for two key phenomena that can slow project progress.

First, they depict an idealized flow of project activities in which activity times are relatively predictable and first attempts always succeed. Many product development organizations, on the other hand, face uncertainties in both activity times and number of activity repetitions. For example, proposed designs are often tested and iteratively redesigned and retested until specifications are met.

Moreover, the duration of prototype testing cycles may vary from one iteration to the next.

Second, typical PERT/CPM analyses, if they acknowledge resource limitations at all, assume that resources are dedicated to a single project at a time. Thus they fail to account for the congestion effects arising from contention for resources among concurrent projects. Although there are extensions of PERT/CPM techniques that acknowledge constraints on resources, they operate in a *static* environment where no new projects are introduced over time.

We posit that the product development organization can be viewed as a system whose activities can be described in terms of processes. This approach differs from previous studies of product development in that it focuses on the management of resources supporting multiple concurrent projects instead of focusing on the management of individual projects.

The research reported here therefore sought to model the product development organization as a stochastic processing network. Exhibit 1 depicts such a network. For our purpose, a stochastic processing network consists of a collection of "workstations" or "resources," each of which is composed of one or more identical "servers" working in parallel. A workstation corresponds to a pool of employees, typically with the same title, who perform the same functions interchangeably. For example, two of the resources in our model are "process engineers" (a pool of two employees) and "manufacturing engineers" (a pool of five). The servers are the technicians or engineers who make up the pool. The organization processes projects, or "jobs," which consist of collections of tasks (such as "Product Prototyping" and "Product Testing") that are performed by specified resources in specified sequences. Certain tasks can be carried out in parallel while others must be performed sequentially. When several tasks may begin processing at the same time, we refer to the phenomenon as a "fork"; when a task may not begin until several other tasks have been completed, we call it a "join." The time required to complete a task is called its "processing time," or "activity time," and the intervals between the starts of new projects are called "interarrival times."

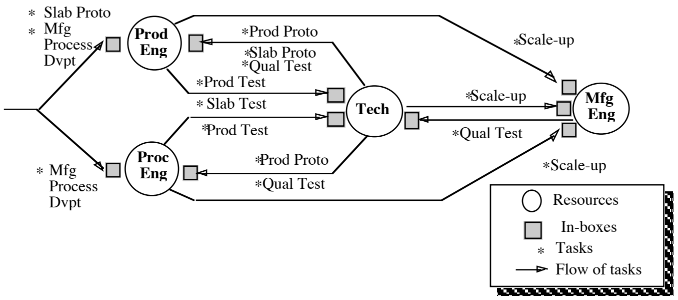

Exhibit 1: Processing Network Representation

The queue at each workstation (represented by shaded boxes in Exhibit 1) corresponds to the “in-box” of the resource. A complete description of the model must specify the service discipline at each station — that is, the rule by which the server chooses the next task from the queue. We implement our basic model using the “round-robin” discipline within priority classes. In this discipline, a free server takes the next top priority task in the queue and works on it for a pre-specified length of time. If he completes the task within the time period, the corresponding project moves on to a successor task, and the server continues with the next top priority task in the queue. Otherwise, the task returns to the end of the queue, its remaining processing time is updated to reflect the last round of service, and it waits until its next access to the server. When the queue is empty of top priority work, the station serves the second priority tasks in the same manner. Clearly there are other possible choices for service discipline, including first-in-first-out, last-in-first-out, or project with the earliest due-date first. We conjecture that the round-robin service discipline is a reasonable approximation of human response to important competing demands, and in Adler et al. (1992b) we explore the impact on project completion time of switching to a first-in-first-out discipline.

We can use PERT-style diagrams to illustrate constraints on the order in which tasks are executed. For example, Exhibit 2 is the PERT diagram associated with the processing network depicted in Exhibit 1 — these are parts of the product development process that will be described in the following section. Each job consists of seven activities. Activities “Manufacturing Process Development” and “Slab Prototype” can be performed in parallel (they represent a fork) and “Scale-Up” begins when activities “Product Testing” and “Manufacturing Process Development” are both completed (a join).

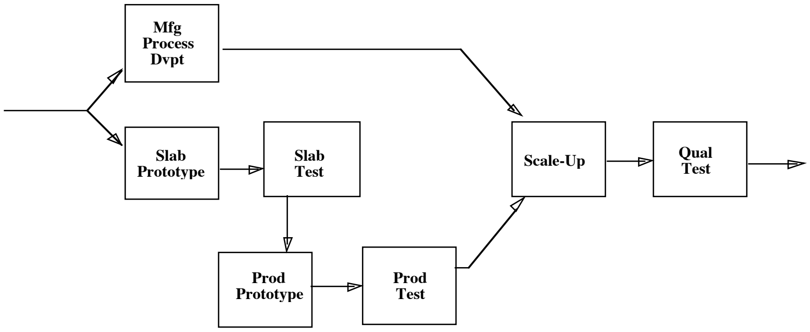

Exhibit 2: Traditional PERT Representation

The ease with which tasks fork is one of the features that distinguishes engineering from manufacturing tasks. Whereas a drawing and a CAD file can be reproduced to allow different engineers to work in parallel, manufacturing processes typically do not allow for a component or subassembly to fork into different parallel processes. Process models for manufacturing environments must allow for joins (as components and subassemblies come together), but they do not in general need to confront the greater modeling complexity of forking processes.

Alongside the technical difficulty of modeling forks there is a real management challenge: engineering organizations experience considerable freedom as to where to fork. In practice, there is considerable freedom in deciding the degree of parallelism that should be built into the engineering task flow. The technical pros and cons of forking at any given step are not always obvious and in some cases a range of possible workflow design options may be equally effective. This insight helps us understand why organizational politics and culture often weigh so heavily in shaping the roles that different firms assign to different engineering groups (for ex. design engineering and manufacturing engineering) in the product development process. Process modeling efforts such as the one we report here must rely on engineering assessments of the set of feasible alternative workflows, but such models can help compare the congestion effects associated with each alternative.

The processing network is stochastic because interarrival times, processing times, and precedence requirements may be subject to statistical variability. Although these quantities are random, they can be characterized via probability distributions. Projects are said to be of the same “type” if their individual precedence requirements, processing times, and interarrival times can be characterized by the same set of probability distributions.

Underlying this framework are several assumptions, and as the history of our project revealed, these assumptions have significant methodological and managerial corollaries. First, we must assume that the organization's tasks and technologies are stable over time and that projects can be characterized by sets of probability distributions. We must further assume that there is a small number of identifiable types of projects and that projects within each type are similar in the sense that differences between their realizations can be attributed to stochastic variability.

THE RESEARCH SITE

In searching for a host, we found that the assumptions underlying process modeling and mentioned in the previous section did not fit all engineering environments. Since our model requires significant similarity among projects, it appeared to be ill-suited for groups involved in the basic research end of the R&D spectrum, where it would seem that projects are more idiosyncratic (although further research might usefully challenge this assessment). Similarly, our assumption of stable probability distributions seems inappropriate for groups whose technologies, products, or organizations change rapidly. Furthermore, the assumption that resources divide their time among competing projects is critical to our focus on the delay created by the contention for resources; in organizations that rely on dedicated teams as many software organizations do, problems such as underutilized resources may arise, but resource contention typically does not.

We eventually found a host in what we will call the Plastics Division of Chemicals Inc. This division offered several advantages as a research site. First, both divisional and corporate management were interested in understanding how they could accelerate their product development cycle, so they were eager to help us in our research. The Plastics Division had recently lost several possible contracts because their principle competitor, a large Japanese firm, had been significantly faster in developing new products. Their support was crucial to the success of our project because of the time and effort involved in helping us collect data. In addition, for several years the Product Development manager had been collecting time cards from his staff, and these could be retrieved for our use.

The Plastics Division at Chemicals Inc. made plastic parts. It accounted for some 7% of Chemical Inc.’s total domestic sales. Historically, the Plastics Division had sold primarily custom-designed products for the aerospace and defense industries. With the slow-down in defense contracts in recent years, the Plastics Division was shifting its focus to the automobile industry, an effort that coincided with that industry’s increased use of plastics. In moving away from defense and into a commercial market, the Plastics Division was increasingly concerned with cost and delivery issues and with high-volume production.

The staff of the technical department in the Plastics Division consisted of engineers and technicians divided into functional groups specializing in product design, process design, and applications. A technical services group supported these engineering groups by helping to make and test product prototypes. Finally, manufacturing engineers, product managers, salespeople, specifications specialists, and other staff members all made critical contributions to development projects. All these resources would constitute workstations in our network.

Although the group considered its principal mandate to be the development of new products, it also handled "reformulations" — projects to replace the materials in existing products — and it supported products on the market. New product development and support efforts were typically triggered by customer interest; reformulations arose either when a vendor discontinued a constituent material or when a better material became available. Reformulation projects usually had little urgency: the plant might have several months' supply of the current material, and the potential cost savings from using a different material was typically small. Only rarely did circumstances force reformulation projects into top priority.

Since the overall need for product reformulations was sensitive to the evolution of the materials market, the product development group's work tended to oscillate between new products and reformulations over periods of several years. Support activities, on the other hand, remained at a fairly stable level. When the Plastics Division restructured its engineering groups a few years before our study, the new manager of product development discovered that he needed to "clean up" operations and he therefore focused some 70% of the group's efforts on reformulations. The more recent Plastics Division strategy of targeting the automobile industry required a new line of products, so effort shifted back to new product development. At the time of our project, the Plastics Division wanted to strengthen its competitive position through lower costs, so the product development group expected to see an increasing proportion of reformulation projects in future years. (An important feature of our model was its ability to reflect the changing mix of work.)

Management assigned formal priorities to projects to help resources allocate their time. Typically, projects involving the development of new products were given priority 1 (the highest priority) whereas most reformulation projects were treated as priority 2. This priority system also affected project trajectories by communicating to resources outside the technical department how they should treat projects. Managers and engineers often expressed exasperation over the long delays that priority 2 projects suffered while waiting for attention from product managers or the manufacturing plant. If the priority reflected the true business importance of the project, then such delays might seem inevitable and even appropriate. Nevertheless, one project we studied had spread two person-months of work over 2.5 years, raising questions about inefficiencies due to mental set-up time, the opportunity cost of delay in getting the product to market, and the toll of prolonged management distraction. One purpose of our project was to quantify the delays arising from various management policies so that these costs could be evaluated more explicitly.

Once we began working with the Plastics Division to collect data, we realized that the host organization offered another important advantage. The group had recently defined a standard, five-phase procedure for product development. This procedure specified the activities that needed to take place in each phase and the conditions the project must satisfy before moving on to the next phase. This phase system proved essential to our data collection effort by providing a standard nomenclature and a common understanding of the specific tasks constituting the product development process.

OPERATIONALIZING THE FRAMEWORK

In this section, we describe how we operationalized our model's components. The development of each construct was associated with methodological challenges, many of which in turn pointed to important managerial issues.

Project types. To characterize statistically the projects at the Plastics Division, we asked our informants to identify major categories of projects according to the similarity of the projects' activity histories. This is generally the first step in systematizing any process, but unlike the explicit and formalized process plans in manufacturing operations, process plans in the Plastics Division, as in many product development organizations, were largely tacit. When asked to categorize types of projects using the activity flow configuration as a criterion, the Plastics Division's employees responded initially with rather ill-formed and inconsistent suggestions. Our question forced them to impose a taxonomy on their work portfolio, and it took several meetings to define an acceptable clustering.

Our categorization criteria for project types required that each type occupy a substantial amount of resource time and that each have some structural features distinguishing it from other types. Some dialogue with our Plastics Division informants was needed to operationalize this general specification, and in the process, our research team was forced to clarify our own understanding of engineering process modeling. Through this dialogue, we identified three main features of a project: the assigned priority, the characteristics of the final product, and the nature of the development effort as reflected in the constituent activities and their precedence relationships. The assigned priority affected the service discipline applied to the project. The characteristics of the product determined the technical requirements and hence influenced the development activities. Finally, the nature of the development effort determined the required resources and activity sequence.

Following the suggestion of our key contact at the Plastics Division, we focused our study on a family of products we will call plastic parts. This product family accounted for over 80% of the engineering organization's time. The other family was made up of more idiosyncratic projects developing more complex systems. As in the broader class of all products, plastic parts work included both new product developments and reformulations, and these projects could be assigned either priority 1 or priority 2.

In summary, our model consisted of two project types — new products and reformulations — and two priority levels for each. Our decision to isolate these four types of projects accomplished two goals. First, it allowed us to explore how various project characteristics affected the product development cycle. Second, with these two categories of projects, we managed to capture the bulk of the Plastics Division’s time. In combination with support activities and administrative duties (which the group also treated as priority 1 work), they accounted for virtually all of the group’s time.

Resources. The core resources were the product and process engineers and technicians who dedicated their time to product development, but this “development group” relied on several other resource pools. For example, they ordered materials from other divisions, ran prototypes in the manufacturing plant, requested tests from the technical services group, sought marketing and sales advice about the concerns of the lead customer, consulted with the specifications group about possible legal issues, and relied on product management to coordinate and promote these activities.

Our data gathering effort revealed wide differences in the quality of information available to us on these resources. Considering these information gaps, we distinguished resources that satisfied the following two criteria: the group had potential impact on project process, and its activities were adequately documented. Those groups that potentially affected the rate of project completion but that did not satisfy the latter requirement are combined into a group called “Miscellaneous” which includes the following functions: Sales, Finance, Specifications, Logistics, and Quality Assurance.

An interesting methodological issue emerged in how to reflect the fact that resources may be both specialized and adaptable. Engineers and technicians, unlike their counterparts in manufacturing environments — machines and equipment — are capable of handling a wide variety of tasks beyond their formal functions in the organization. For example, during busy periods at the Plastics Division, the development group might turn some of its work over to engineers with nominally different functions, such as manufacturing or applications engineers (who normally dealt with factory and customer implementation issues respectively). Since specialization is often a matter of organizational choice rather than of technical capability, it is up to the modeler to decide how to characterize this specialization as fixed versus variable. We discuss this issue in greater depth in the next section.

We identified nine resources. According to management estimates of resource availability (number of work hours per week per server within each resource), average work weeks varied from 40 to 55 hours depending on the resource. However, our simulation experiments (reported in Adler 1992b) later led us to recognize the need to allow for "crunch" periods with significantly higher levels of overtime.

Tasks. To find a partition of the product development activities at the Plastics Division, we turned to the phase procedure mentioned earlier. This procedure described five sequential phases of the development process, specifying a standard protocol for resolving the key issues in each phase. Phase 1 ("Concept/Feasibility") was characterized by the intensive involvement of a few marketing and product development people who simultaneously explored technical, manufacturing and market feasibility. In Phase 2 ("Project Plan/Team") a full team was assembled, and a project plan was drafted. Phase 3 ("Product Development") signaled the project's peak effort, as the team worked out the technical, legal, and marketing issues in detail. It was here that the development group expected to face the project's critical challenges. Phase 4 ("Manufacturing Standardization/Launch") marked the transfer of the project from the development labs to full-scale manufacturing. It included a concentrated effort to eliminate any remaining technical wrinkles, and it closed with the product launch. Finally, Phase 5 ("Continuous Improvement") represented ongoing refinements while the product was on the market. Each phase consisted of approximately a dozen issues to be resolved.

Although the phase procedure provided a detailed characterization of the relevant issues, it did not identify the discrete tasks that were required to resolve these issues. Something that appeared as a simple item to check off in a phase review meeting might require several distinct tasks by independent resources, or it might represent an issue that would be addressed several times as a project progressed. In the words of one of our contacts, "the phases are defined by objectives, not by activities." When a modeler defines a cluster of possible project steps as an activity, she assumes that this cluster can be viewed as a single entity across a spectrum of projects. However, the degree to which an employee aggregates activities in his description of a process depends on both his knowledge of the details of others' work and his knowledge of the function of his own work in the entire project. Thus any model of an engineering organization will depend on individual judgment — and this to a greater degree than in manufacturing. Our informants found it useful that our study forced them to characterize their tasks more explicitly than they had done before.

We considered several trial representations before arriving at a collection of activities that the Plastics development group found satisfactory. To simplify the data collection and the analysis, we decided to focus on the first four phases (through Manufacturing Standardization/Launch), aggregating Phases 1, 2, and 4 into one "activity" each and specifying Phase 3 (Product Development) in greater detail. We chose to highlight Phase 3 of the development process because it contained the bulk of project work and because it illustrated some interesting network features which distinguish product development from manufacturing, namely, forking, iterative looping among activities, continual transmission of information between steps, and resources who potentially juggled several activities at once. Phase 3 later proved to be a felicitous choice for the additional reason that it marked the time of crispest activity definition.

Our model of the development process for new product projects consists of 18 activities. Each of these activities may require attention from several resources. We therefore developed an "activities-resources map" to display the involvement of resources in each of the 18 activities (see Exhibit 3). A "task" corresponds to an activity/resource pair (e.g. Review Patent/Product Engineer). Thus while each task is performed by exactly one resource, each resource can be responsible for several tasks.

Reformulation projects tended to be smaller projects than new product development efforts, requiring fewer resources and fewer person-hours to complete. Often they skipped Phases 1 and 2 entirely and began with Phase 3.

Precedence Constraints. Simultaneously with our effort to identify tasks, we asked our key contact at the Plastics Division to translate the phase system into PERT-like diagrams illustrating the flow of activities. We wanted to find abstract representations of projects that our informants could regard as both meaningful and realistic, and we needed many rounds of discussion to identify a satisfactory flow diagram.

	Prod Engr	*Proc Engr*	*Prod Tech*	*Proc Tech*	*Tech Svcs*	*Prod Mgt*	*Misc*	*Mfg Engr*	*Appl Engr*
Phase 1	X		X			X	X		X
Phase 2	X	X	X	X	X	X	X	X	X
Rev Patent	X		X						X
Mfg Proc Dvpt	X	X	X	X			X	X	
Mkt Position						X	X		
Make Slabs	X		X						
Test Slabs	X		X						
Make Product	X	X	X	X				X	
Test Product	X		X						X
Make Prod-Mfg	X	X							
Test Prod-Mfg	X		X						X
Sales Strat	X					X	X		X
Lead Customer	X	X				X			X
Product Specs	X	X			X	X	X		
Field Trials	X	X				X			X
Agency Specs	X						X		
Qual Testing	X	X	X	X	X	X	X	X	X
Phase 4	X	X	X	X		X	X	X	X

Exhibit 3: Activities–Resources Map for New Product Projects

The activity flow diagram presented in Exhibit 4 reflects the resulting model of the process flow. Activities are shown in boxes and arrows indicate precedence among activities; if several resources were involved in an activity, we assume that they could execute their tasks in parallel. An “ideal” project would have only forward arrows: that is, a downstream activity would never be followed by an upstream activity. Exhibit 4 represents the following process flow: a new project begins at Phase 1 and then proceeds to Phase 2. Its completion of Phase 2 triggers the start of several (possibly) simultaneous Phase 3 activities. Product engineers and technicians begin activities in the prototyping cycle: making and testing material samples (“slabs”) to refine the material formulation, making and testing product prototypes in the lab to explore product geometries and to study the material’s behavior, and finally making product prototypes in the plant to uncover manufacturability issues. Product engineers, process engineers, and technicians simultaneously develop the manufacturing process, getting information from the product engineers about special product requirements and sharing their own cost and feasibility results.

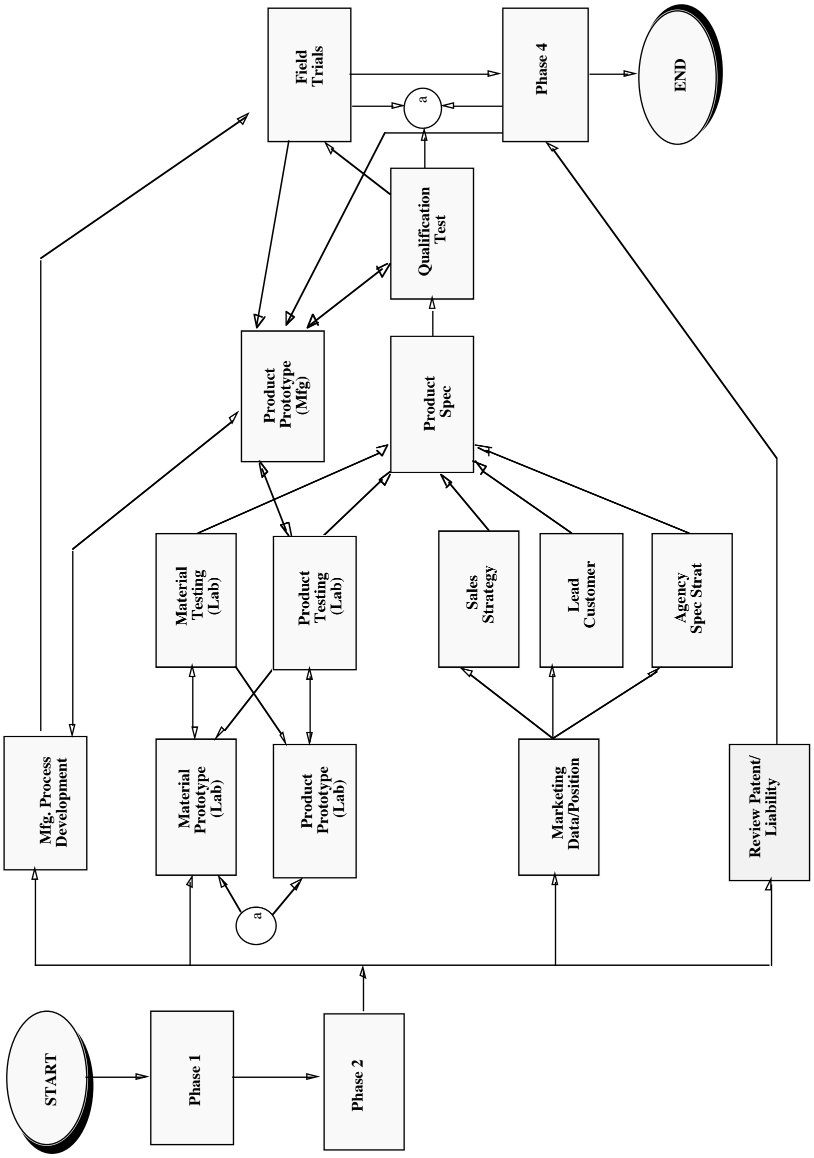

Exhibit 4: Process Flow Diagram – New Products

At the same time, people in sales and product management begin the activities shown in the lower-left corner of the flow chart. These activities initially have little impact on the technical side of product development, but ultimately the two groups negotiate through the interface of the product specifications effort. When a final product and set of specifications are defined, technical services performs a comprehensive set of qualification tests to ensure that the product meets these specifications. If all goes well, the new product proceeds on to field trials, to the phase 3 (design) review, and ultimately to the full manufacturing scale-up and launch of Phase 4.

The proliferation of reverse arrows in the flow chart illustrates the phase system's purpose of systematizing checks. Since these "activities" were really objectives, each of them could be regarded as a decision box indicating whether earlier issues needed to be revisited before the project moved on. For the sake of simplicity in our model, we included only those iterations that our Plastics Division informants believed occurred with significant frequency.

The process flow diagram for reformulation projects was simpler. The process typically bypassed Phases 1 and 2, and Phase 3 contained fewer activities, although there were sometimes just as many iterations between slab and product prototyping with the introduction of a new material. Our model reflected this relative simplicity.

THE CHALLENGES OF DATA COLLECTION

The preceding section discussed the key variables of our model and how we arrived at operational definitions for them. In order to derive quantitative conclusions from our model, we needed statistical data characterizing its components. For each job type, we required data on the frequency of new job starts (interarrival times), the tasks involved and the order in which they were executed (precedence requirements), and the time to complete each task (service times). Because we accounted explicitly for time spent on support and administrative duties, we also needed data on the time that each resource devoted to these activities. Moreover, our model requires the entire distribution of these quantities and not only their means.

Lacking an appropriate data base, we began this data collection effort by asking our informants at the Plastics Division to estimate averages for a recent new product project — Project X — which had enjoyed high visibility in the group and had been well documented. We intended this preliminary exercise to provide a baseline from which we could ask our informants to generalize to probability distributions for the entire portfolio of new product projects.

We collected our data in three half-day workshops with a group of Plastics Division employees representing most of our resource pools. These meetings proved to be rich data-gathering efforts because they raised fundamental issues about our model — for example, would our informants find it meaningful to assign probability distributions to events that they viewed as essentially unique? We had extensive conversations about some of our simplifying assumptions, sometimes resulting in further aggregation of activities in the flow diagram, and sometimes highlighting complicating issues that might affect the validity of our results. For example, we learned that the boundaries between phases were not hermetic: some phase 3 activities actually began in phases 1 and 2, and some continued into phases 4 and 5. Our sources emphasized a similar phenomenon at the level of activities within phase 3: many pairs of nominally sequential activities actually overlapped or involved significant passing of information back and forth. (Although we have not included this continual release of information in our model, we think it is a feature of product development that should be explored in future research since it involves a critical trade-off between the value of early communication and the risks of basing work on incomplete information.)

A further issue we considered in these workshops was how to deal with project delays caused by resources outside of the division (and hence beyond divisional control). For example, the product development group relied on manufacturing to run "scaled-up" production of prototypes in order to test the newly designed products in the actual plant. These production runs often proved to be a bottleneck in the development process, but since we did not know the actual procedure for scheduling them, we did not incorporate them in our model.

After collecting specific data for Project X, we turned to the task of generating distributional data for a portfolio of new product projects. The following discussion describes the main methodological and managerial issues we encountered.

Interarrival times. We based our data for job interarrival times on management interpretations of quarterly status reports for the few years preceding our study. Our informants also characterized for us the distribution of project terminations for those projects that were never completed. Typically these terminations occurred toward the end of Phase 3 when engineers determined that no feasible solutions existed for the remaining problems inhibiting scale-up or launch.

Activity times. Using our baseline new product project as a reference and "reality check," we asked for 10th and 90th percentile estimates of the times necessary to complete the activities. That is, we expected that 10% of all occurrences of an activity took less time than our low estimate and 10% took more time than our high estimate. We characterized the prototyping activities according to the experience of the baseline project, since these activities were of relatively short and invariant duration.

In addition to individual task times, we also collected estimates of the total time devoted to activities across all resources. This entry provides some indication of the correlation among activity times of the different resources. For example, time estimates given for the activity “Field Trials” show a 10% chance that product engineers contributed more than 700 hours to this activity and also a 10% chance that application engineers contributed more than 700 hours to it. However, the total estimate indicates that the 90th percentile of time spent on this activity by all resources was only 700 hours. Thus if one of the two resources spent a large amount of time on the activity, then the other resource necessarily devoted less time to it: the two task times (Field Trials/Product Engineers and Field Trials/Application Engineers) were negatively correlated. On the other hand, the time an engineer devoted to a particular activity is likely to have been positively correlated with the time her technician spent on it. Such correlation has important implications for project management as well as for process models, but it did not appear to be a quantity that our informants could confidently estimate without records of actual project histories.

We encountered similar difficulties in accounting for dependence among activities as in accounting for dependence among tasks. One might wonder whether a longer-than-normal Phase 1 is typically followed by a longer-than-normal Phase 2 — that is, if it was difficult to resolve feasibility issues, will it also be difficult to formulate a process plan? Or is the opposite situation more representative — if the development group spent more time resolving Phase 1 issues, will it be more straightforward for them to formulate process plans? Our model assumed that the two activities are independent. To answer empirically the question of dependence among activities, we would need a joint distribution of all the tasks that compose a product development effort; but the engineering organization we studied did not keep the detailed data necessary for such analysis. It is important to note that in general tasks may be neither perfectly independent nor perfectly correlated.

Likelihood of Iterating. We found that the likelihood of iterating was the most difficult part of our model to specify. To completely characterize it, we would need to describe not only the number of times that activities occurred, but also the order in which they occurred, and we would need probability distributions over both of these differentiating features.

The workshop participants found it difficult to discuss the range of possible configurations that they encountered or to identify characteristic patterns, so we needed to take a simpler route. We asked the engineers to classify 11 recently completed projects according to the complexity of the iteration structure (2 projects were simple, 5 medium, and 4 complex); we developed profiles for each class; and then we used the weighted average of the resultant profiles to analyze the organization’s overall performance.

Implicit in this approach was the assumption of dependence among different iterations in a project. It appears that in reality some project iterations were independent of one another, and others were negatively correlated; but we could generate only piecemeal indications of what form of data collection might prove most revelatory.

We gathered two forms of data for the iteration structure. For prototyping iterations (those involving the making and testing of materials and products), which were typically repeated many times, we collected "expected total number of iterations per project." This form of data reflected an expectation of strong negative correlation among nested levels of iterations. It also reflects our finding that our informants were typically not well informed on the iteration phenomena outside their domains; we considered it best to ask each informant only for estimates of the numbers of iterations she herself performed. For "major" iterations involving several activities, which occurred in fewer projects and were less numerous when they did occur, we collected data in the form of "probability of iterating," sometimes with a maximum number of times that an activity could be executed. We treated this maximum as a global maximum and treated visits before the maximum number as independent. This raises the following interpretive question: when the maximum is reached, should we assume that further visits to the activity will always succeed, or should we allow the possibility of failure (representing project termination)? We made the first, simpler assumption.

Resource Availability. Finally, we required data that quantify the capacity of the resources. We easily estimated the number of people in each resource pool and the average hours they worked in a week. The time cards enabled us to estimate fractions of time devoted to administrative and support activities by each resource group. An internal study gave us estimates of the average work content of each activity in reformulation projects.

The final kind of data characterizing resource capacity pertains to their functional flexibility. The interchangeability described in the preceding section can be attributed to our choices of resource and activity partitions: either the resources involved have some overlap of function or some set of tasks that we aggregate into a single activity could actually be differentiated. A qualitatively different kind of interchangeability occurs when one resource is over-burdened and turns his work over to someone else. We reflect this phenomenon by partially reallocating the work of over-used resources. Based on conversations with our informants, we estimated the maximum extent to which this reallocation could occur. In some situations, one might imagine that the new person is less well qualified for the task, and that as a result the process time and likelihood of error are increased; but we left this issue for future research.

CONCLUSION

In other papers, we have summarized the operational results from our analysis of this model (reported in Adler et al. 1992a and 1992b); here we focus instead on what we believe we have learned about the features that distinguish the product development process from other types processes. Exhibit 5 presents a two-dimensional typology of processes. The first dimension contrasts more and less repetitive operations — from this point of view, product development resembles other “professional/creative” activities in that it is much less repetitive than mass production manufacturing operations or routine clerical operations.

		Nature of key inputs and outputs	
		material	information/ knowledge
Degree of Repetitiveness	high	CRAFT	CLERICAL
	low	MASS PRODUCTION	PROFESSIONAL/ CREATIVE

Exhibit 5: Four Types of Processes

The second dimension contrasts processes whose key inputs and outputs are material and processes that are essentially concerned with information and knowledge.

We can use this taxonomy to classify the characteristics of product development that we identified, to summarize our degree of success in modeling each characteristic, and to sketch future research prospects.

A first group of process characteristics might appear in any type of process, but are not usually critical outside the professional/creative type of process:

- “Servers” in any process might exhibit some load responsiveness, but unless the focus of the study is overtime scheduling, this feature is not likely to be important enough to warrant incorporating into models of processes outside the professional type.
- Iterations are a key feature of some product development environments and some other professional activities, but are not usually a major concern for other

types of processes (note, however, the exception of semiconductor fabrication studied by Chen *et al.*, 1988).

- Similarly, flexible pooling might appear in some other types of processes (in the guise of multi-skilling, for example), but it has not been a major point of focus in previous modeling research. In contrast, it appears to be a rather important feature of engineering and other professional environments.
- The possibility of terminating projects in mid-course is an important characteristic of the product development process; any of the other three types of projects might also manifest "yield" problems, but these have not often been the focus of process modeling efforts.
- Interdependencies between phases is a phenomenon that our project skirted because of the added data collection and modeling complexity it would have introduced. But future research might usefully focus on the topic, since difficulties experienced at any one phase often have downstream repercussions. This seems particularly salient in engineering activities, but semiconductor manufacturing experiences similar interdependencies.

A second group of characteristics does not appear in mass-production manufacturing operations, but may appear elsewhere:

- The uncertainty of task times is likely to be a key issue only in less repetitive processes, whether material-intensive or information- and knowledge-intensive.
- Rapidly changing technologies and product mixes are also characteristic of less repetitive processes. Modeling is useful in these contexts primarily to identify key transition planning issues, but the newness of technologies or products may also lead to insurmountable uncertainty concerning the tasks to be accomplished.
- Forking only appears in a very limited form in material processes (disassembly operations), but is common in any process in which the emergent product can be duplicated, for example using a photocopier.

And finally, a third group of characteristics seems specific to product development and other professional/creative processes:

- Flexible forking — the fact that there is a certain element of management discretion in where to fork — is likely to be a central issue only in knowledge-intensive processes, since the routine nature of clerical information-processing allows managers to determine with much less ambiguity the optimal process flow.
- The incremental release of information to downstream resources would appear to be a potentially important feature of product development (see also Clark and Fujimoto, 1991), but we did not explore it in this project. It could perhaps be modeled effectively with the benefit of more detailed information on the impact of the incomplete information on downstream activities.
- Informal lateral sharing of information is potentially important in knowledge-intensive forking-intensive processes; this issue too we have left for future

research. More detailed precedence diagrams might suffice to capture the essential issues here.

- The interdependencies between activities within a given phase would appear to be an important feature of product development. More detailed data would facilitate modeling this characteristic, but the low degree of repetitiveness makes it difficult to accumulate enough data to form reliable estimates.

It is perhaps not surprising that our model of the product development process was relatively successful for the first category of characteristics, less successful in the second category, and in general unsuccessful in the third. Modeling the product development process will require a more sustained effort by a larger community of researchers.

REFERENCES

Adler, P. S. and B. Borys, "'Tools, Not Weapons': An Inductive Study of Engineers and Formalization," unpublished, 1992.

Adler, P. S., A. Mandelbaum, V. Nguyen, E. Schwerer, "From Project to Process Management in Engineering: An Empirically Based Model," unpublished, 1992a.

Adler, P. S., A. Mandelbaum, V. Nguyen, E. Schwerer, "From Project to Process Management in Engineering: Results of a Simulation Model," unpublished, 1992b.

Alexander, R., "Scheduling and Resource Allocation Methodologies for Fast Product Development in a Multi-Product Environment," unpublished master's thesis, Sloan School of Management, Massachusetts Institute of Technology, 1990.

Blackburn, J. D., "New Product Development: The New Time Wars," in *Time-Base Competition: The Next Battleground in American Manufacturing*, J. D. Blackburn, Ed., Business One Irwin, Homewood, 1991.

Chen, H., J. M. Harrison, A. Mandelbaum, A. van Ackere, and L. M. Wein, "Empirical Validation of a Queueing Network Model for Semiconductor Wafer Fabrication," *Operations Research*, 36 (1988), 202-215.

Clark, K. B., and T. Fujimoto, "Lead Time in Automobile Product Development Explaining the Japanese Advantage," *Journal of Engineering and Technology Management*, 6 (1989a), 25-58.

———— and ———— , *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*, Harvard Business School Press, Boston, 1991.

Dean, B. V. (Ed.), *Project Management: Methods and Studies*, North-Holland, Amsterdam, 1985.

Hayes, R. H., S. Wheelwright, and K. B. Clark, *Dynamic Manufacturing: Creating the Learning Organization*, Free Press, New York, 1988.

Schoenberger, R. J., *World Class Manufacturing: The Lessons of Simplicity Applied*, The Free Press, New York, 1986.

Stalk, G., Jr., and T. M. Hout, *Competing Against Time*, Free Press, New York, 1990.

Weick, K. E., "Enactment Processes in Organizations," in *New Directions in Organizational Behavior*, B. M. Staw and G. Salancik, Eds., St. Clair Press, Chicago, 1977, 267-300.

Wheelwright, S. C., "Time to Market in New Product Development," *ICL Technical Journal*, November (1989), 625-646.

Wheelwright, S. C. and K. B. Clark, *Revolutionizing Product Development*, Free Press, Free Press, 1992.

Wheelwright, S. C. and K. B. Clark, Creating Project Plans to Focus Product Development, *Harvard Business Review*, March-April 1992, pp. 70-82.