From Project to Process Management in Engineering: Managerial and Methodological Challenges.

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From Project to Process Management: An Empirically-based Framework for Analyzing Product Development Time

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While product development efforts are often viewed as unique configurations of idiosyncratic tasks, in reality different projects within an organization often exhibit substantial similarity in the flow of their constituent activities. Moreover, while most of the planning tools available to managers assume that projects are independent clusters of activities, in reality many organizations must manage concurrent projects that place competing demands on shared human and technical resources. This study develops an empirically-based framework for analyzing development time in such contexts. We model the product development organization as a stochastic processing network in which engineering resources are "workstations" and projects are "jobs" that flow between the workstations. At any given time, a job is either receiving service or queueing for access to a resource. Our model's spreadsheets quantify this division of time, and our simulation experiments investigate the determinants of development cycle time. This class of models provides a useful managerial framework for studying product development because it enables formal performance analysis, and it points to data that should be collected by organizations seeking to improve development cycle times. Such models also provide a conceptual framework for characterizing commonalities and differences between engineering and manufacturing operations.

(*New Product Development; Project Management; Process Management; Development Cycle Time; Processing Network*)

1. Introduction

> *I'm late, I'm late, for a very important date.*
> The White Rabbit, *Alice in Wonderland*

This paper presents an empirically-based framework for analyzing product development time in organizations that pursue multiple concurrent nonunique projects using shared resources. Our approach is premised on four hypotheses concerning development activities. First, while product development work is often discussed as if it were composed of idiosyncratic, unprogrammable tasks, in reality many tasks in product development are routine enough to allow their statistical characterization. Second, while projects are often managed as unique configurations of tasks, in reality different projects within a given organization often exhibit substantial similarity in the flow of their constituent activities. Third, while most of the planning tools available to managers assume that projects are independent clusters of activities, in reality many organizations must manage con-

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current projects that place competing demands on shared human and technical resources. And fourth, whereas uncertainty is an inherent characteristic of product development, current models and methods are essentially deterministic and do not account adequately for the impact of stochasticity on development cycle time.

We submit that a view of the development process as a "design production process" can provide a framework for better understanding organizations that pursue multiple concurrent nonunique projects using shared resources. Several business observers, including Blackburn (1991), Clark and Fujimoto (1989a), Rosenthal (1992), Stalk and Hout (1990), and Wheelwright and Clark (1992a, 1992b), have noted the increasing pressure on firms to accelerate their process of developing and launching new products. Our modeling approach explicitly quantifies project delays due to waiting for resources. Such an approach should be more accurate than existing tools in predicting project completion time and more effective in identifying opportunities for improving development cycle time. To test this hypothesis, we constructed a process model of a sample firm's product development activities. In this paper, we present this model, explore some of its implications through simulation experiments, and discuss potential uses of process models for improving development cycle time.

We model the product development organization as a stochastic processing network in which engineering resources are "workstations" and projects are "jobs" that compete for "service" from the workstations. At any given time, a job is either receiving service from a workstation or queueing for access to a resource. Our approach differs from previous studies of product development, which we survey in §2, in that it focuses on the management of resources as well as on the management of individual projects. This representation is in the spirit of queueing network models for manufacturing processes, but the product development environment has unique characteristics that lead to networks with different features than those traditionally associated with manufacturing. We elaborate upon these differences in §3, where we describe in detail the process models that we use. The subsequent sections are organized as follows. Section 4 describes the organization that was our host for this project. Section 5 describes the components of the model and specifies the data that we collected. Sections 6, 7, and 8 present our analysis. Section 6 discusses the first stage, "capacity analysis," which culminates in spreadsheets displaying resource utilization profiles. The underlying calculations compare the average demand of project-related work with the time available to resources. The second stage of analysis focuses on cycle time and is presented in §7. Section 8, which represents the third stage of analysis, considers several sample scenarios that suggest some ways to reduce development cycle time. Finally, §9 highlights the lessons that we learned in carrying out the project, points out some limitations of our study, and discusses future prospects for process modeling in product development environments. A companion paper (Adler et al. 1995) discusses in greater detail the methodological challenges.

Our objectives in this study were threefold. First, we wanted to test whether product development could be meaningfully represented within the framework of process models, "meaningfully," that is, from the dual perspectives of the practitioner and the theorist. We wanted to see whether there exist product development organizations satisfying the assumptions of a stochastic processing network sufficiently closely that the model could be validated against actual performance. Second, we wanted to see if we could build tools based on such a model that would be both useful to product development managers and theoretically interesting to researchers. Third, we hoped that this research effort would highlight major differences and similarities between engineering "knowledge work" and manufacturing operations.

We feel that our effort has successfully met all three goals: a process model can offer significant insights into a broad spectrum of product development organizations; our spreadsheet and simulation models appear to be promising practical and theoretical tools; and we have identified a rich framework for identifying the differences and similarities between manufacturing and engineering operations.

2. A Brief Literature Survey

The literature on project management and product development is voluminous, but little of it addresses the question of congestion in multi-project environments.

A brief survey of previous studies highlights the need for research that addresses this issue. Our survey begins with more general topics and progressively narrows its focus to process models.

A first body of research addresses information and task flows but focuses on the overall flow of tasks in single projects rather than on problems of queues within single or multi-project environments. For example, Cooper (1983) synthesizes the results of many field studies of product development, finding several key phases of new product development whose effective execution is critical to project success. He proposes a "flow" approach, in which management considers these phases in a systematic way to ensure that nothing is overlooked. Imai, Nonaka, and Takeuchi (1985) study five cases of recent product innovations in Japanese and American companies. They identify six critical factors that encourage efficient and innovative development: "top management as catalyst, self-organizing project teams, overlapping development phases, multilearning, subtle control, and the organization transfer of learning." But here, too, the unit of analysis is the individual project.

A second body of research is more attentive to the complex iterations that characterize most product development work. It attempts to describe the overall structure of these iterations but remains focused on individual projects. Concurrent engineering and design for manufacturability offer important opportunities for accelerating product development by reducing the number of such iterations, but most of the research has taken the individual project as its unit of analysis (see survey in Susman 1992). Clark and his colleagues (1987, 1989a, 1989b, 1991) highlight lead time as a critical performance measure in product development and analyze the coordination between development and manufacturing departments. In particular they consider the issues of simultaneous versus sequential performance of tasks and of the piecemeal release of information from upstream resources to downstream ones, but they do not discuss how these processes are affected by resource limitations. They analyze dedicated cross-functional project teams, but they offer no guidelines for assessing the associated trade-off between reduced congestion and increased cost.

Another group of studies is now emerging that highlights the importance of process issues in multi-project environments. Schonberger (1986) presents a case study of a group that tried to identify the obstacles to rapid project completion in their own organization. They found that careful recording of their work times highlighted bottleneck areas that subsequently they reduced or eliminated. Hayes, Wheelwright, and Clark (1988) develop a process-oriented framework for understanding the management challenges of product development. Of particular relevance to our research, they identify "manufacturing capability" as a key determinant of project performance (pp. 323–327). By manufacturing capability, they mean not only the manufacturing organization's readiness to ramp-up production, but also manufacturing's contribution to the earlier phases by speedily constructing high-quality prototypes. They stretch the concept to include the design engineering organization's internal "process capabilities" that allow for fast turnaround of key engineering tasks such as laboratory testing. This extension of the idea of manufacturing capabilities to the engineering organization leads naturally to the idea that engineering operations too can be organized according to JIT principles. But they do not develop the concepts needed to make this new approach operational.

Blackburn (1991) has begun to define the more specific concepts needed to flesh out a process view of project management. He compares product development to manufacturing with the aim of translating Japanese manufacturing philosophy into the product development setting. We make a similar comparison but with the different aim of importing modeling paradigms from manufacturing into product development.

Although recent behavioral research, as surveyed above, recognizes the impact of uncertainty and limited resources on development cycle time, current OR/MS models do not adequately handle the congestion that results when variability is compounded with capacitated resources in a multi-project environment. PERT (Project Evaluation and Review Technique) and CPM (Critical Path Method) methods (Dean 1985), which form the foundation for many project management models, depict an idealized flow of project activities in which activity times are essentially treated as deterministic and first attempts always succeed. Furthermore, PERT and CPM analyses often assume that resources are dedicated to a single project. However, activities involved in product development are inherently variable in both activity times as well as probability of success. Moreover, many product development organizations operate in a multi-project shared-resources setting. 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.

In order to account for the stochasticity of activity times, Kulkarni and Adlakha (1986) propose a Markov chain model whose state space is related to the structure of the network. The method, which assumes that activity times are exponentially distributed, allows numerical algorithms for evaluating the usual performance criteria such as moments of development cycle time. For more general distributions, Weiss (1986) presents stochastic bounds for the project completion time. Although these papers address the issue of uncertainty in the duration of activities, they still assume that the flow of activities is deterministic.

To study the phenomenon of repeated task cycles, Black, Fine, and Sachs (1990) propose a matrix method for deciding how to order the tasks of product design according to the flow of information among them. Eppinger, Whitney, Smith, and Gebala (1989) take a similar approach based on models of the design process in several organizations. These studies focus on how work flow should be structured to minimize the likelihood of iterations, but they consider neither the queueing effects created by the flow through this structure nor those created by multiple concurrent projects competing for resources. While they address the issue of how to organize work, we focus on analyzing work flow, assuming its structure is given.

A paper closer in spirit to ours is Taylor and Moore (1990). They take as their model a GERT (Graphical Evaluation and Review Technique) network, which is a generalized PERT network that allows probabilistic routing and repetition of activities via feedback loops (Neumann 1979). They use the simulation package Q-GERT (Pritsker 1979) to study a development organization with multiple research teams and multiple projects. However, since they assume that each team is dedicated to a single project at a time, their model does not include the resource contention and queueing effects that behavioral research suggests are endemic (Ancona and Caldwell 1992).

Our approach is similar to that proposed by Alexander (1990), who sketches a queueing network model of product development projects, discusses many issues of modeling and data collection, and suggests how principles of queueing theory could be used to identify bottlenecks. The present study contributes to this emerging body of research on the impact of congestion on project cycle-time in multi-project organizations. Processing network models are more general than those described above, and, we argue, provide new insights that justify the added modeling complexity. This paper focuses on testing this approach by applying it to data from real projects in a real organization.

3. The Conceptual Framework: A Process Model

We propose to model the product development organization as a "stochastic processing network" (Figure 1). 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 job title, who perform the same functions interchangeably. The servers are the technicians or engineers who make up the pool. The organization processes projects, which we will interchangeably call "jobs," and which consist of collections of tasks to be performed by specified resources in specified orders. When several of a project's tasks can begin processing at the same time, we refer to the phenomenon as a "fork"; when a task cannot begin until several other tasks have been completed, we call it a "join." The time required to complete a task is its "processing time," or "activity time," and the intervals between project starts are "interarrival times."

We use PERT-style diagrams to illustrate constraints on the order in which tasks are executed. For example,

Figure 1 Processing Network Representation

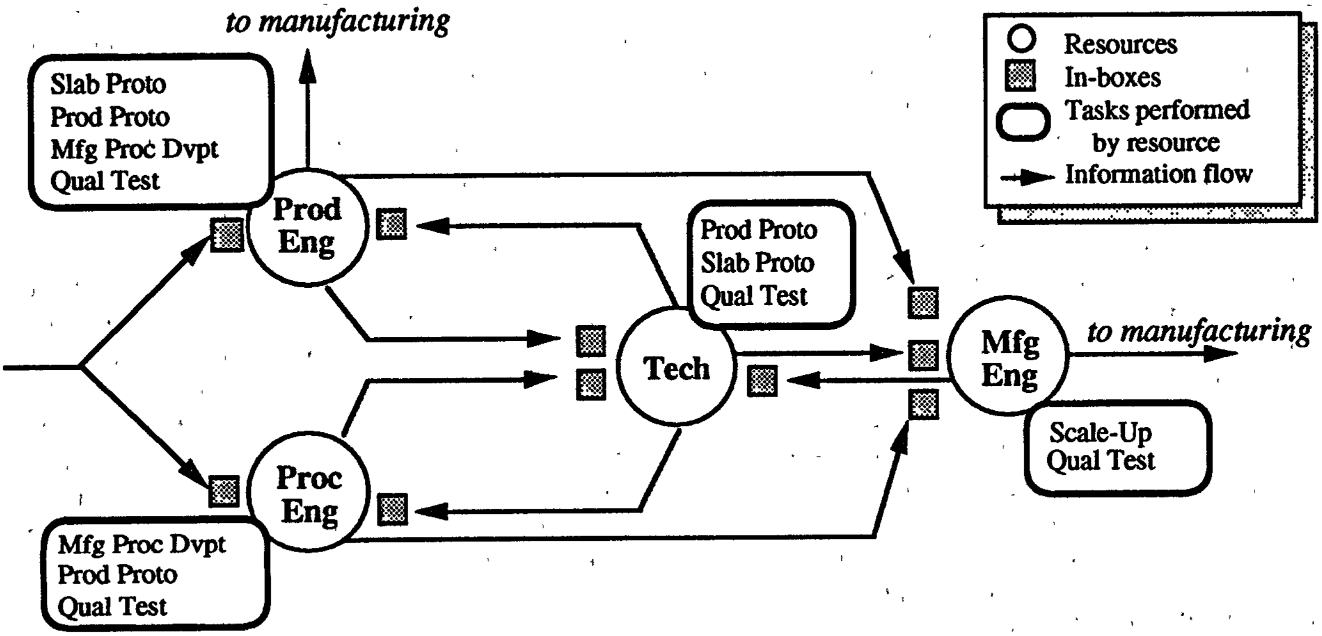
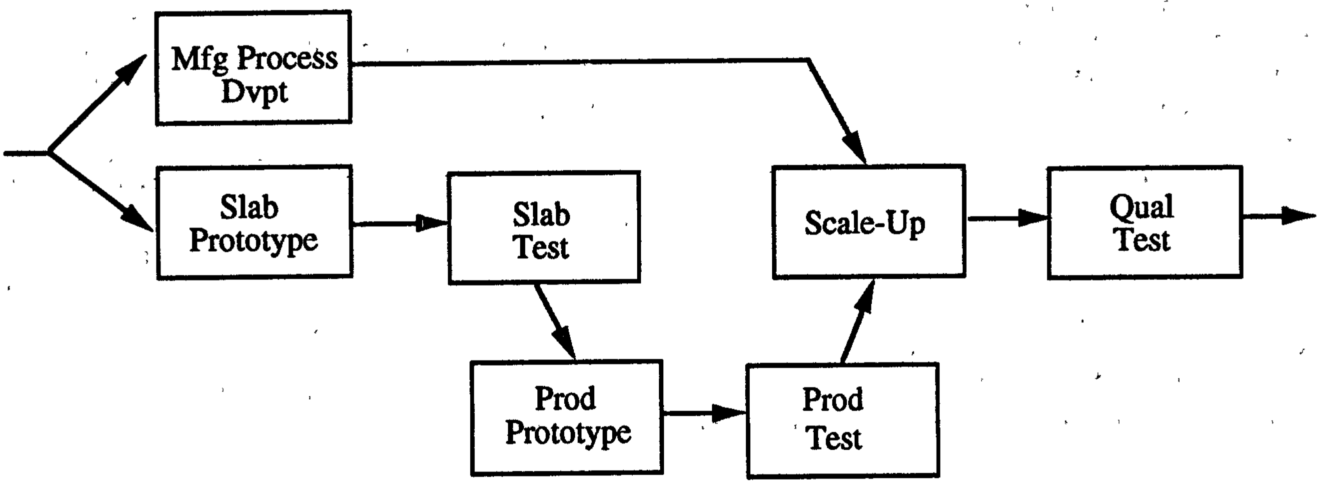


Figure 2 is the PERT diagram associated with the processing network depicted in Figure 1. Each job consists of seven activities. Activities "Manufacturing Process Development" and "Slab Prototype" can be performed in parallel (they represent a fork) and "Scale-Up" begins when activities "Product Testing" and "Manufacturing Process Development" are both completed (a join).

The processing network is stochastic because interarrival times, processing times, and precedence requirements may be subject to statistical variability. 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. In the sample organization we

Figure 2 Traditional PERT Representation



studied, we distinguished two types of projects, "new product projects" and "reformulation projects" (see discussion in §5).

When a new project is initiated, we say it "enters the network," whereupon it proceeds to the station(s) corresponding to its first task(s), forking as necessary into the appropriate number of tasks. In Figure 1, an incoming project forks into three tasks, and each task then proceeds to its corresponding workstation. The activity "Manufacturing Process Development" requires attention from both the product engineer and the process engineer; we therefore distinguish "process development by product engineers" and "process development by process engineers" as two different tasks. (For the sake of simplicity, we have left out several arrows and tasks from Figure 1 that appear in later figures and tables.) When a task arrives at a station, it joins the end of the queue and waits for one of the servers. When a task has received its requisite service, the project proceeds to the next task(s), again forking or joining as necessary. In the context of product development, the entities passed from one workstation to the next could be engineering drawings, work orders, or test results.

The queue at each workstation (represented by shaded boxes in Figure 1) corresponds to the "in-box" of the resource, and a complete model must also specify the service discipline at each station—that is, the order in which the resources work on the tasks in their in-boxes. Our basic model uses 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 she completes the task within the time period, the corresponding job 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. In conversations with members of the organization we studied we considered other choices for service discipline, including first-in first-out (FIFO) and project with the earliest due-date first. Our informants were most comfortable with the round-robin representation of their work discipline.

In summary, a complete specification of a processing network requires the following ingredients: the number of resources in the network and the number of parallel servers within each resource; the number of project types; and for each project type, a set of probability distributions characterizing the type's precedence requirements (i.e., the route that the project follows among its component activities), the processing time of each task, and the interarrival times of new projects.

This model clearly draws from queueing theoretic concepts and terminology and can be seen as a "generalized queueing network." Since Jackson (1957, 1963) introduced queueing networks as models of job shops, they have had a rich history of applications in manufacturing, communications, computer systems, and transportation science. The generalization of classical queueing networks to processing networks, which allow forking and joining, enables analysis of systems that are characterized by parallel as well as sequential processing (Nguyen 1993, 1994). Such models have been used, for example, to represent distributed database systems (Baccelli 1989). We hypothesize that stochastic processing networks can also be used to analyze product development organizations.

4. The Research Site: The Plastics Division at Chemicals Inc.

Our research site was an organization which we call the Plastics division at Chemicals Inc. in order to protect its anonymity. The Plastics division was a hospitable research site because both divisional and corporate management were eager to help us with our research; and management support was crucial because of the time and effort involved in collecting data. Division managers were interested in ways to accelerate their development cycle after losing several potential contracts to their principal competitor, a large Japanese firm with significantly faster product development.

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 making and testing product prototypes; manufacturing engineers, product managers, salespeople, and other staff members all made critical contributions to development projects. All these resources constitute workstations in our network.

Although the division considered its principal mandate to be the development of "new products," it also undertook "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 were rarely urgent; the plant might have several months' supply of the current material, and the potential cost savings from changing were typically small. Only rarely did circumstances force reformulation projects into top priority.

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. 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 urgency 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.

5. Constructing the Model

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. For each project type, the model required data on the frequency of new job starts (interarrival times), the tasks involved, the order in which they were executed (precedence requirements), and the time required to complete each task (processing times). Because we accounted explicitly for time spent on support and administrative duties, we also needed data on the time that each resource pool devoted to these activities. Recall from §3 that the model requires the entire *distribution* of these quantities and not only their averages. The final data set described below was collected in three half-day workshops with a group of Plastics division managers and employees representing most of the resource pools.

5.1. Project Types

The 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. 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 organization's time. The remaining projects were more idiosyncratic. 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. We take these priorities to be exogenous characteristics of the projects. Reformulation projects were typically smaller than new product projects and required less than 4% of the resources' total capacity.

We based the data for job interarrival times on management interpretations of quarterly status reports for the few years preceding our study. Our informants estimated that recently there had been three priority 1 new product final design reviews per year, with approximately 5% more starts, or 3.15 per year. They also told us where in the activity flow uncompleted projects were typically terminated. Roughly 2.5 priority 2 new product projects and one reformulation project of each priority designation were initiated each year with none terminated.

5.2. 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. They ordered materials from other divisions, ran prototypes in the

Table 1 **Resource Characteristics**

Resource Name	Number of Servers	Server Capacity (hrs/week/server)	Resource Capacity (total hrs/week)
Product Engineers	4	55	225
Process Engineers	2	55	110
Product Technicians	5	50	250
Process Technicians	4	45	180
Technical Services	6	45	270
Application Engineers	4	45	180
Product Management	4	40	160
Manufacturing Engineers	5	45	225
Miscellaneous	6	40	240

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 legal issues, and relied on product management to coordinate and facilitate these activities. Our data gathering effort revealed wide differences in the quality of information available 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 were combined into a group called "Miscellaneous" which includes the following functions: Sales, Finance, Specifications, Logistics, and Quality Assurance.

We identified nine resources and further aggregated them into seven resources in the final simulation model. According to management estimates, average work weeks varied from 40 to 55 hours. The name of the resource, the number of parallel servers within each resource, and the average availability per week for each group are shown in Table 1. The first four resources, Product Engineers, Process Engineers, Product Technicians, and Process Technicians, constitute the core development resources. Collectively they handled approximately 65% of the product development work. Table 2 shows estimated fractions of time devoted to administrative and support activities by each resource group.

5.3. Tasks

To find a partition of the product development activities at the Plastics division, we turned to a five-phase procedure that had recently been developed there as a protocol for resolving development issues. Phase 1 ("Concept/Feasibility") was characterized by the intensive involvement of a few marketing and product development people who explored technical, manufacturing, and market feasibility. In Phase 2 ("Project Plan/Team") a full team was assembled and a project plan drafted. Phase 3 ("Product Development") signaled the project's critical challenges, as the team worked out the technical, legal, and marketing issues. Phase 4 ("Manufacturing Standardization/Launch") transferred the project from the development labs to full-scale manufacturing. It included the elimination of 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.

To simplify the data collection and the analysis, we focused on the first four phases (through Manufacturing Standardization/Launch), aggregating tasks in 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 features of product development that have not been explored in network models

Table 2 **Fraction of Time Devoted to Administrative and Support Activities**

	Product Engineers	Process Engineers	Product Technicians	Process Technicians	Technical Services	Product Management	Miscellaneous	Manufacturing Engineers	Application Engineers
Administrative	0.38	0.38	0.38	0.38	0.32				0.19
Support	0.01	0.01	0.01	0.01	0.30				0.30

of manufacturing operations, namely, forking, iterations among activities, continual transmission of information between steps, and resources who might juggle 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.

Working with the Plastics division staff, we identified 14 activities in Phase 3. Like the resources, the activities of the original model are further aggregated for the simulations. The complete model of the development process for new product projects consists of 17 activities whose names and descriptions appear in Table 3. Reformulation projects were usually smaller than new product development efforts, requiring only a subset of the activities shown in Table 3. We defined a "task" in §3 as an activity/resource pair (e.g. Review Patent/Product Engineer). Thus each activity corresponds to several tasks.

Table 3 Activity Descriptions

Activity Name	Activity Description
Phase 1	Identify customer expectations and project concepts, explore technical, manufacturing, and market feasibility
Phase 2	Form project team
Phase 3.	
Review Patent	Establish product liability position and file for patent
Mfg Process Dvpt	Determine process methods and equipment for all stages of production
Market Position	Determine competitiveness of product and establish market position
Make Slabs	Create samples of material in form of slabs
Test Slabs	Test slab prototype for conformance to materials requirements
Make Product	Make sample products from prototype materials
Test Product	Test product prototype for conformance to product requirements
Make Product—Mfg	Make product prototype in plant to uncover any manufacturing issues
Test Product—Mfg	Test manufacturing prototype for conformance to product requirements
Sales Strategy	Formulate sales strategy
Lead Customer	Identify lead customers and determine their needs
Product Specs	Identify product requirements and testing procedures
Field Trials	Test product with lead customer(s)
Agency Specs	Determine whether product is subject to government regulations
Qual Testing	Test product for conformance to all specifications
Phase 4	Complete customer trials, manufacturing scale-ups, product documentation, launch product

5.4. New Product Projects: Activity Times

Given the multidimensional heterogeneity of projects in the Plastics division, our informants found it impossible to estimate average processing times for most of the constituent tasks. We therefore asked them to consider their "portfolio" of recent projects and estimate the 10th and 90th percentiles of the task processing times. We estimate the associated average times using these data, via a flexible procedure described in §6 below. Prototyping tasks, however, were somewhat more standardized than the others, and our informants could estimate average times for them, which we take to be actual processing times. Members of the Plastics division estimated that prototyping activities were of relatively short and invariant duration and that the variability in times spent prototyping was due mostly to the number of repetitions. The task time data for new product development projects are shown in Table 4. An empty activity/resource box indicates that the resource did not contribute to the activity.

In Table 5, an entry of 1 indicates that the resource always was involved in the activity, and an empty cell implies that the resource never was. Fractional probabilities, however, can be interpreted in two diametrically opposed ways. On the one hand, such entries might be independent, indicating that the activity was not necessary for all projects. This is an appropriate representation of the activity "Phase 2." According to Table 5, only 30% of projects required application engineers to contribute to this activity, and independently of the application engineers' contribution, manufacturing engineers could expect to spend time on Phase 2 in 90% of the projects. On the other hand, some fractional probabilities reflected interchangeability among resources. When the probabilities in Table 5 indicate the average proportions of times that each resource was assigned exclusively to a task, we asterisk the corresponding entries and interpret their sum as the total probability that the activity occurred.

A second issue arises from this tension between in-

Table 4 Processing Times for New Products

	Product Engineers	Process Engineers	Product Technicians	Process Technicians	Technical Services	Product Management	Miscellaneous	Manufacturing Engineers	Application Engineers
Phase 1—10%	40		100			20	5		10
90%	300		450			125	100		100
Phase 2	40	20	10	10	10	10	5	5	5
	300	200	388	250	200	125	100	40	340
Review Patent	3		5						1
	200		100						5
Mfg Process Dvpt	200	150	20	40			5	5	
	700	2500	100	2000			10	40	
Market Position						20	5		
						100	25		
Make Slabs	17		30						
Test Slabs	23		30						
Make Product	30	14	15	23				15	
Test Product	20		20						20
Make Product—Mfg	15	8							
Test Product—Mfg	20		20			20	5		75
Sales Strategy	5					20	5		10
	100					100	40		100
Lead Customer	10	5				20			20
	500	50				100			500
Product Specs	10	5			5	20	50		5
	100	20			20	50	200		50
Field Trials	72	5				10			200
	700	20				20			700
Agency Specs	5						20		
	100						100		
Qual Testing	27	20	40	10	1000	10	10	25	10
	100	50	60	30	1500	20	50	50	60
Phase 4	400	350	60	100		200	5	100	50
	750	1000	100	250		400	200	1500	

terchangeability and specialization. Engineers and technicians—unlike machines which are their manufacturing counterparts—are capable of handling a wide variety of tasks beyond their formal functions in the organization. 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 and not of technical capability, it is up to the modeler to decide how much of this specialization to characterize as fixed versus variable. The entries in Table 6, which we obtained from interviews with our informants, indicate the maximum extent to which work can be reallocated between resources. A negative entry indicates a resource giving away some responsibility, and a positive entry reflects another resource accepting it. Our initial simplifying assumption was that the substitute resources work as efficiently as the original resources.

We do not include in our models any dependence among activities. One might wonder whether a longer-than-average Phase 1 was typically followed by a longer-than-average Phase 2—that is, if the complexity of the project made it difficult to resolve feasibility is-

Table 5 **Probability of Involvement—New Products**

	Product Engineers	Process Engineers	Product Technicians	Process Technicians	Technical Services	Product Management	Miscellaneous	Manufacturing Engineers	Application Engineers
Phase 1	1		1			.1	.1		5
Phase 2	1	1	1	1	1	1	1	.9	.3
Review Patent	1		.9						.3
Mfg Process Dvpt	9	1	1	1			.9	1	
Market Position						1	9		
Make Slabs	1		1						
Test Slabs	1		1						
Make Product	.25*	1	1	1				.75*	
Test Product	.75		1						1
Make Product—Mfg	1	1							
Test Product—Mfg	1		1						1
Sales Strategy	.5*					1	1		.5*
Lead Customer	.5*	1				1			.5*
Product Specs	1	1			9	1	1	9	
Field Trials	.5*	.1				1			.5*
Agency Specs	5						5		
Qual Testing	1	1	1	1	1	.9	.9	.9	1
Phase 4	1	1	1	1		1	.1	1	1

sues, was it also difficult to formulate a process plan? Or was the opposite scenario more representative: if the development group spent more time resolving Phase 1 issues, did that up-front work facilitate the downstream task of formulating process plans? The organization we studied did not keep the detailed data necessary to include such correlations in the model.

5.5. New Product Projects: Precedence Constraints

The activity flow diagram presented in Figure 3 is a translation of the phase system into a PERT-like diagram. 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. Figure 3 represents the following process flow: a new project begins at Phase 1 and then proceeds to Phase 2. The completion of Phase 2 triggers the start of several (possibly) simultaneous Phase 3 activities. Product engineers and technicians begin prototyping, and product engineers, and technicians simultaneously develop the manufacturing process, getting information from the product engineers

Table 6 **Maximum Permissible Pooling (hours per project)**

	Product Engineers	Process Engineers	Product Technicians	Process Technicians	Technical Services	Product Management	Miscellaneous	Manufacturing Engineers	Application Engineers
Phase 1	−66		66						
Phase 2	38	−38							
Make Slabs	−6 8		6.8						
Test Slabs	−9.2		9 2						
Make Product	−9	−4.2	9	4 2					
Test Product	−6		6						
Make Product—Mfg	−12	−6.4	12	6.4					
Test Product—Mfg	−16		16						
Phase 4	415	−415		−115					115

about special product requirements and sharing their own cost and feasibility results. 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 iterations among activities. For the sake of simplicity in our model, we include only those loops that our informants believed occurred with significant frequency.

Figure 4 displays the process flow diagram for reformulation projects. These require significantly fewer activities than new product developments. In particular, our model bypasses Phases 1 and 2, and Phase 3 contains fewer activities.

To completely characterize iterations, 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. Our informants found it

Figure 3 **Process Flow Diagram—New Products**

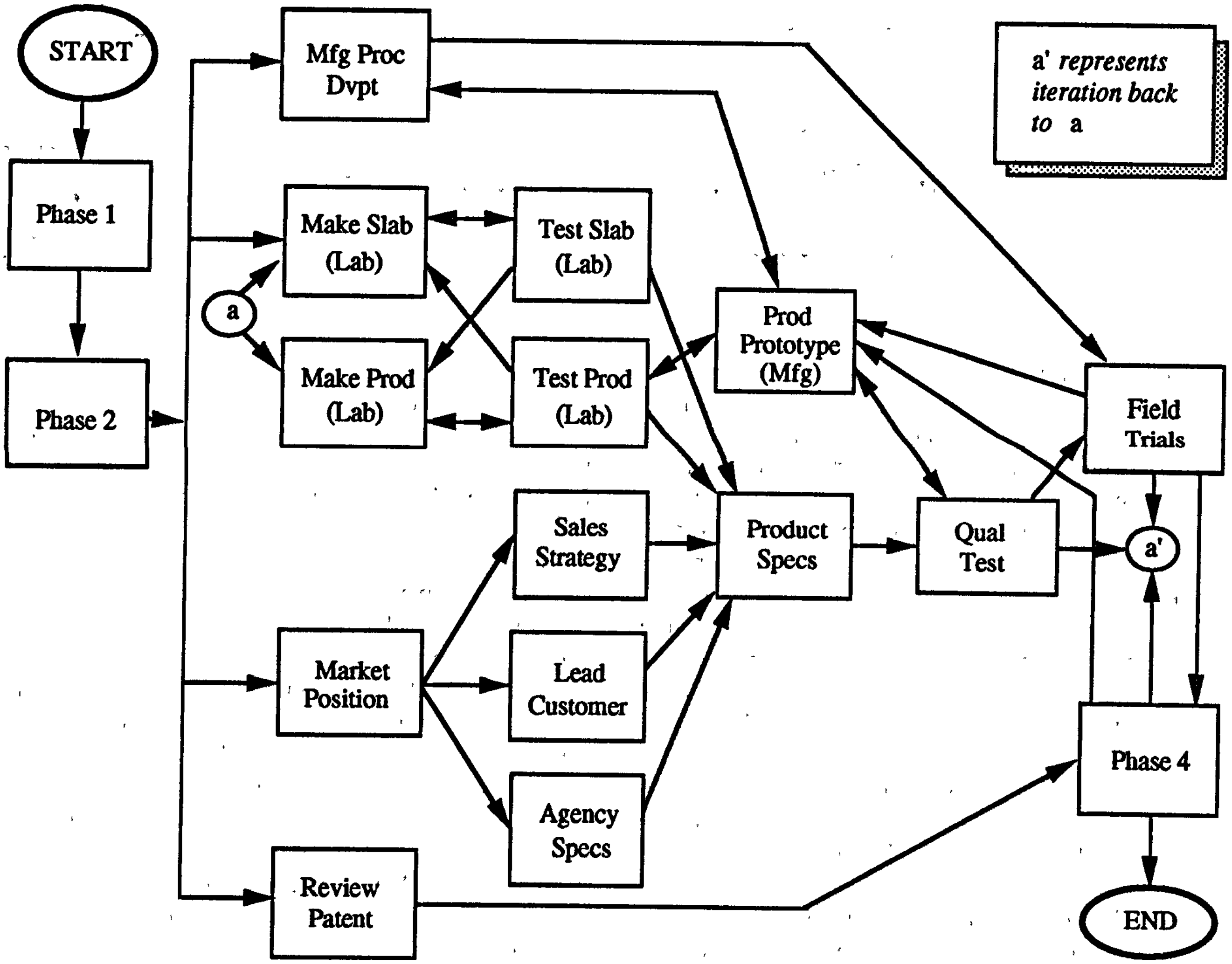
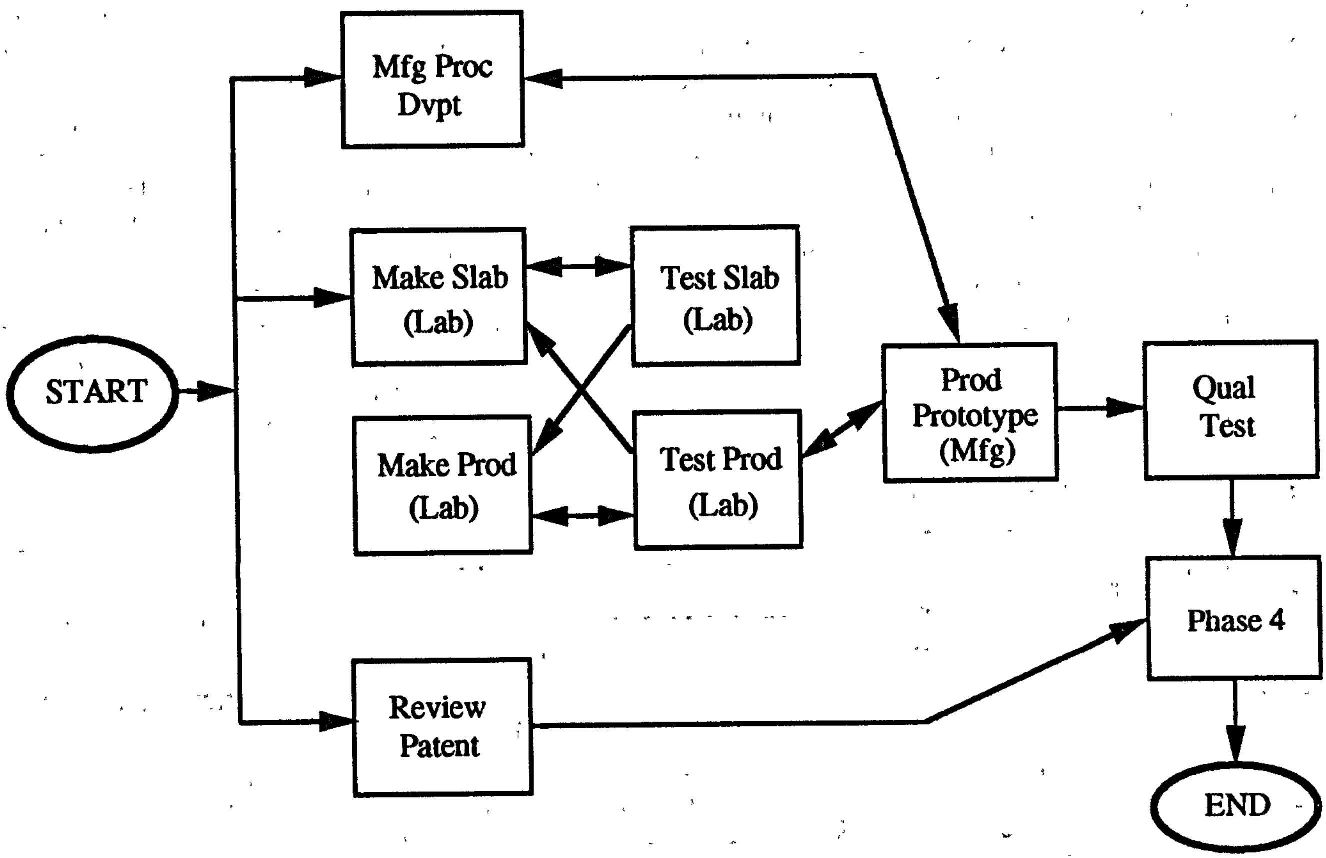


Figure 4 **Process Flow Diagram—Reformulations**

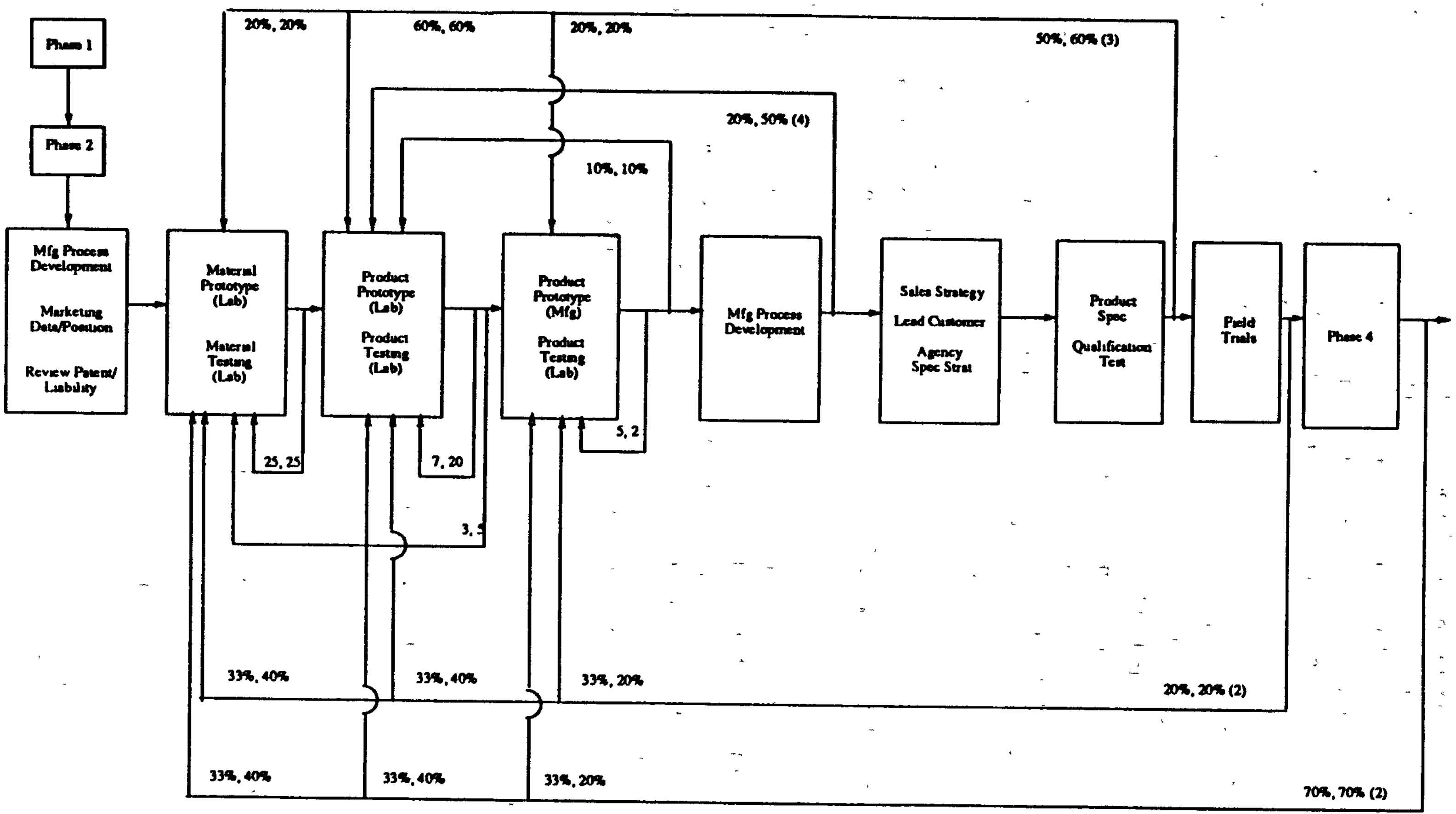


difficult to identify the range of possible configurations they encountered, so instead we asked them to classify 11 recently completed projects according to the complexity of the iteration structure (2 projects were simple, 5 medium, and 4 complex). We developed profiles for each class as we describe below; and then we used the weighted average of the resultant profiles for our model. Implicit in this approach was the assumption of dependence among different iterations in a project. In reality, it appears that some project iterations were probably independent of one another and others negatively correlated; but we only gathered piecemeal indications of this correlation.

We collected two forms of data for the iteration structure. For "inner" prototyping iterations (involving the making and testing of materials and products), which were typically repeated many times, we estimated the "expected total number of iterations per project." This form of data reflects an expectation of strong negative correlation among nested levels of iterations. For "outer iterations," which occurred much less often, we collected data in the form of "probability of iterating," sometimes with a maximum number of times that an activity could be executed. We treat this maximum as a global maximum and treat visits before the maximum number as independent.

Figure 5 displays data on the iteration structure in new product development projects. Activities within a cell are assumed to proceed either in sequence (i.e., there is no chance of iterating between each other) or in parallel. Arrows indicate the direction in which activities flow; "forward" arrows indicate that an activity is successfully completed and the project moves on to successor activities, and "backward" arrows indicate that a number of activities must be repeated. Numbers accompanying backward arrows describe the likelihood of repeats. Percentages indicate the probability of iterating, and integers denote the expected number of times

Figure 5 Iteration Structure for New Products



Iteration structure of "easy" project follows history of a baseline project. Data: Average, Difficult.
(Distribution of projects: Easy, 18%; Average, 46%; Difficult, 36%)

that an activity is executed. Figures in parentheses indicate the maximum number of times that an activity can be executed. Each pair of numbers corresponds to data for medium and complex projects, respectively. Following our informants' recommendation, we use a baseline project as the profile of a simple project.

5.6. Reformulation Projects

Table 7 summarizes the average work content of each activity in reformulation projects. These figures were obtained from an internal study at the Plastics division. Unlike the figures that we presented for new product projects, the numbers in Table 7 correspond to "aggregate" data: that is, these numbers are the *total* number of hours required for each task, accounting for the total number of times that tasks are carried out and weighted with the probability of involvement of each resource.

6. Analysis, Stage I: Capacity

Our first stage of analysis estimates divisional capacity utilization by comparing the average demand of project related work with the time available to the resources. For each resource, we calculate its percentage utilization—the ratio of the average rate at which the resource receives work to the rate at which the resource can complete it—by means of a spreadsheet (part of which is shown as Table 8). These first-order performance measures can be used to identify under-staffed resources, determine probable project bottlenecks, and estimate the maximum rate at which the organization can take on new work. By varying key parameters in the spreadsheet, management can examine their influence on the average load for each resource.

The top row of Table 8, labeled "NP Hours," shows the total amount of time that each resource group spends on an average new product development project. The second and third rows of Table 8 compare some spreadsheet-generated measures with actual data that is available for the Plastics division. Although the division did not keep track of the time spent by individual resources on individual activities, it did record the total hours spent by various groups on recent projects. Thus, we can see that our estimate of 3,910 hours spent by the four development resource pools on an average project is not too far from the division estimate of 4,408. However, we appear to overestimate significantly the time spent by technical services on an average project, and in particular it appears that we may be attributing to them work actually performed by the development group. This kind of analysis can point to differences between the way our informants conceived of their work and the way it actually occurred, or between the nominal functions of resources and the roles they actually performed. For example, it appears that technical services was chartered to do a significant amount of routine testing that was often done by the development group. Technical services was often a project bottleneck, so development engineers often did their work themselves. The fourth row of Table 8 shows the amount of time resources spent on an average reformulation project.

In Table 9, we show percentage utilizations when resources share their work with others according to a

Table 7 **Processing Times for Average Reformulation Project**

	Product Engineers	Process Engineers	Product Technicians	Process Technicians	Technical Services	Product Management	Miscellaneous	Manufacturing Engineers	Application Engineers
Review Patent	*	*	*	*					*
Mfg Process Dvpt	23	39	3	56			*	*	
Make Slabs	41	41	41	41					
Test Slabs	42	42	42	42					
Make Product	45	54	45	54				30	30
Test Product	40	48	40	48				30	30
Make Product—Mfg	5	5	5	9				20	
Test Product—Mfg	2	2	2	4	160			10	
Phase 4	50	64	19	25	8	67	12	54	129

* Less than one hour of work content.

Table 8 **Utilization Profile**

	Product Engineers	Process Engineers	Product Technicians	Process Technicians	Technical Services	Product Management	Miscellaneous	Manufacturing Engineers	Application Engineers	TOTAL
NP Hours	1485	946	1005	474	1085	400	130	319	767	6611
Marginals				3910	1085			319	767	5762
True Values				4408	458			169	780	
RF Hours	242	294	189	280	169	67	13	175	189	1618
					Percent Utilization					
					Priority 1 Work					
New Products	40	50	24	16	24	15	3	8	25	
Reformulations	2	6	2	3	1	1	0	2	2	
Admin	28	28	30	344	28				17	
Support	1	1	1	11	27				27	
Subtotal Priority 1	70	85	57	54	80	16	3	10	71	
					Priority 2 Work					
New Products	33	42	20	13	20	12	3	7	21	
Reformulations	2	5	1	3	1	1	0	1	2	
Subtotal Priority 2	35	47	21	16	21	13	3	8	23	
TOTAL	106	131	78	69	101	28	6	18	94	

variable reallocation level set in accordance with the maximum permissible pooling level defined in Table 6. In this example, process engineers allocate 60% of the permissible amount to product engineers and 100% to technicians, while product engineers allocate 80% of the permissible to technicians. By hypothesis, reallocation happens with perfect efficiency, so tasks take no longer when performed by substitutes, and the total number of person-hours does not change.

The utilization figures in Table 8 and 9 reveal that in order for some resources to complete all of their priority 1 and 2 work, they must maximally reassign work to other resource groups. One possible explanation is that since engineers estimated most of our numbers, they may have systematically overestimated their own contributions at the expense of their technicians'. Another possibility is that the group simply took on more work than it could handle, completing it in last minute stints of overtime not included in our model.

Constructing a utilization profile required converting the 10th and 90th percentile activity time estimates into averages. We weighted the estimates by 0.9 and 0.1, respectively. It was necessary to skew the distribution in this way in order to arrive at a reasonable estimate of total hours per project. Although this was initially a disturbing finding, we think it may point to significant negative correlation in the activity times: a given project may have one or two "sticking points" that take abnormally long to complete, but working through them facilitates other activities.

We also adjusted the durations of later iterations of the prototyping cycle in response to an informant's comment that our estimates for the number and duration of the prototyping loops were unreasonably high. This, too, is most likely due to negative correlation. The average slab prototyping effort did indeed take 21 iterations (as our spreadsheet implied), but each iteration was unlikely to take the product engineer the number of hours required by the first iteration.

7. Analysis, Stage II: Cycle Time

Unlike the first-order capacity analysis presented in the previous section, which uses only information regarding *average* processing times and *average* new start rates, the second stage of our analysis incorporates the un-

Table 9 **Utilization Profile with Pooling**

	Product Engineers	Process Engineers	Product Technicians	Process Technicians	Technical Services	Product Management	Miscellaneous	Manufacturing Engineers	Application Engineers	TOTAL
NP Hours	1300	606	1462	543	1085	400	130	319	767	6611
RF Hours	242	294	189	280	169	67	13	175	189	1618
					Percent Utilization					
					Priority 1 Work					
New Products	35	32	35	18	24	15	3	8	25	
Reformulations	2	6	2	3	1	1	0	2	2	
Admin	28	28	30	34	28				17	
Support	1	1	1	1	27				27	
Subtotal Priority 1	65	67	68	56	80	16	3	10	71	
					Priority 2 Work					
New Products	29	27	29	15	20	12	3	7	21	
Reformulations	2	5	1	3	1	1	0	1	2	
Subtotal Priority 2	31	32	30	18	21	13	3	8	23	
Total	96	98	98	73	101	28	6	18	94	

certainty of the development process. Interarrival times, activity times, and number of iterations are subject to variability. The next section specifies the additional assumptions necessary to specify this model and shows how simulation can be used to identify trends, develop qualitative insights, and test system improvement suggestions.

The information necessary to build a simulation model of the Plastics division is contained in §5. However, instead of using all of this information, we simplify the model by aggregating activities and resources. To create a simulation model at the level of detail provided in §5 (and *a fortiori* to experiment with such a model) would require an overwhelming amount of computer time, and we believe it would only marginally improve our insight. Our simulation model is intended to capture the spirit of the product development process at the Plastics division without actually mimicking all levels of interactions. (Section H of the XCELL manual (Conway 1990) discusses the virtues of keeping simulation models small and simple.) All simulations were performed using the simulation software SIMAN (Pegden 1990). Each simulation run took approximately 80 minutes of CPU time on a MicroVAX 3800.

7.1. The Simulation Model

Resources. The simulation model aggregates the nine resources shown in Table 1 into seven composite resource pools. First, product engineers and process engineers are grouped into a single resource called product development (PD) engineers. Second, the product technicians and process technicians are combined into a pool called product development (PD) technicians. Third, we replace the miscellaneous group, which previously was composed of several groups including the specifications department, *solely* by the specifications group (i.e., all other groups in the miscellaneous category have been deleted from consideration). This aggregation, which coalesces several resources into a single group, creates pools of interchangeable resources that were not treated as interchangeable in the original model. Such aggregation hides inefficiencies and results in more optimistic predictions of system performance. However, because the pooled resources have comparable levels of utilization, our estimates of system performance should not be strongly biased.

Finally, we allocate additional capacity to resource pools that belong in the technical group of the Plastics division (these include product development engineers and technicians, application engineers, and technical services). These resources typically work extra hours when projects are backlogged or when deadlines approach; the maximum number of hours that these resources work during those critical periods are 60 for product development engineers, 55 for product development technicians, 60 for application engineers, and 55 for technical services. The simulation models report the fraction of time that each resource pool must work its maximum overtime.

Activities and Precedence Constraints. In addition to aggregating resources, the simulation model also groups together several activities as shown in Table 10. For example, all activities related to marketing and sales such as "Review Patent" and "Identify Lead Customer" become a single activity called "Marketing." Moreover, we coalesce all prototyping activities into a single activity called "Prototyping." In general, any subset of a network can be replaced, without much sacrifice in accuracy, by a single node if the node's processing times and routing instructions are defined to approximate closely the processing times, queueing times, and routing of the subnetwork. A simplified model can determine the most significant nodes, and subsequent studies can examine these individual nodes in greater detail.

Figure 6 depicts the simplified flow of activities in new product projects. The simulation model treats all routing as "Markovian," meaning that the future route of a job is not affected by its processing history. As indicated in Figure 6, the probability of repeating a prototyping activity is 0.75, and the probability of returning to prototyping after manufacturing scale-up is 0.60. Thus, the average number of times manufacturing scale-up and prototyping are carried out are $(1 - .60)^{-1} = 2.5$ and $2.5 \times (1 - .75)^{-1} = 10$, respectively.

Table 10 **Activity Descriptions—Simulation Model**

(Aggregated) Activity	Subactivities
Phase 1	Phase 1
Phase 2	Phase 2
Prototyping	Manufacturing Process Development, Make Slabs, Test Slabs, Make Product, Test Product
Marketing	Review Patent, Market Position, Sales Strategy, Lead Customer, Agency Specs
Mfg. Scale-Up	Manufacturing Scale-Up
Specs	Agency Specs
QualTesting	Qualification Testing
Phase 4	Phase 4

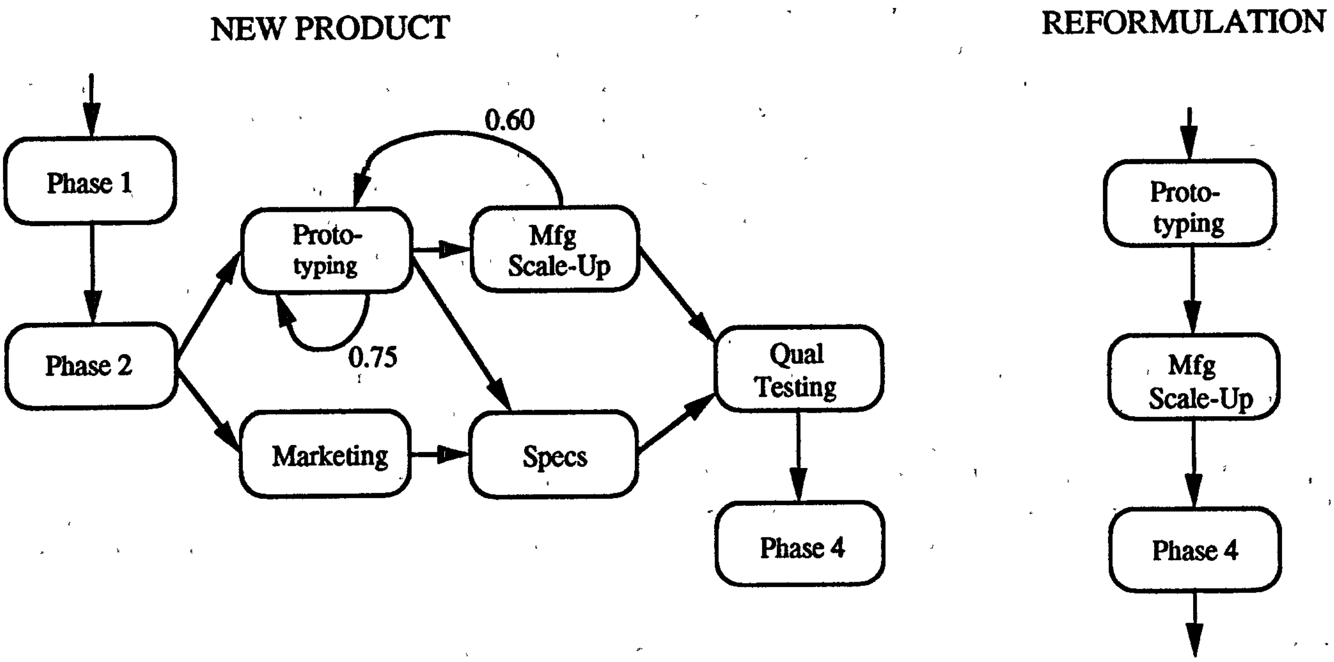
Also illustrated in Figure 6 is the flow of activities in reformulation projects. As discussed in §5, reformulation projects constitute a very small fraction of project-related work, and we collected only summary data for this type of project. Consequently, we do not model reformulation projects at the same level of detail as new product projects, and, in particular, Figure 6 shows no iterations among activities.

Task Times. The simulation model assigns time to an activity/resource pair only if the resource's contribution (in hours) exceeded a pre-set level of significance; otherwise, the resource spends zero time on the activity. In addition, it models all task times as exponential, despite the fact that we collected some distributional information in the form of 10th and 90th percentile information. Simulation experiments revealed that system performance did not vary significantly with different distributional forms for several key activities (e.g., prototyping and manufacturing scale-up). We conjecture that other sources of uncertainty dominate processing time variability in determining cycle-time performance.

We took support and administrative times from Table 8 when such figures were available; otherwise, we estimated them based on the roles of the resources and the nature of their work. (For example, because the manufacturing engineers' primary responsibility was to the production and manufacturing operations, they spent the bulk of their time on activities outside the product development arena. The model reflects this in high support times.) We found it necessary to reduce the administrative times for several resources to obtain reasonable performance measures. This modification is partially justified by noting that administrative duties may be curtailed in critical situations. Vacations may be postponed, meetings skipped, and training activities rescheduled. The model takes activity times for both support and administrative activities to be exponentially distributed. Support activities arrive according to a Poisson process, and administrative activities arrive deterministically.

Pooling. Section 6 notes that an important characteristic of the product development environment is the

Figure 6 Activity Flow Diagram—Simulation Model



possibility of pooling work among various resources, and the spreadsheet analysis indicates that some resources had to maximally reassign work to other resource groups in order to have enough capacity. The simulation model allows product development engineers to reassign part of their work to product development technicians whenever there are more than five ongoing projects. Work can be transferred from PD engineers to PD technicians only in Phase 1, Prototyping, and Manufacturing Scale-Up. For each of these activities, at most 30% of the engineers' work can be given to technicians.

Service Discipline. The service discipline at each workcenter is assumed to be the "round robin" discipline described in §3 with service segments equal to two weeks.

7.2. Simulation Results

Table 11 shows various statistics obtained from the simulation. The performance measure of primary interest in this paper is *project completion time* or *project cycle time*. It is the amount of elapsed time from the "beginning" of the project until the "end" of the project. New product projects begin with concept generation and feasibility studies (Phase 1), and they end with the product launch (Phase 4). Reformulation projects begin with prototyping activities and end when the product is launched (Phase 4). A second performance measure is the number of unfinished projects in the organization.

To calibrate our models, we compared our findings with figures provided by the Plastics division. Our host was able to provide us with detailed timelines for priority 1 new product projects from which we computed average project completion times. Such records were not available for other types of projects, and for these projects we relied on estimates by the manager of the Plastics division.

Table 11 shows that the simulated average completion time of priority 1 new product projects is 84 weeks, compared to the figure of 82 weeks reported by the Plastics division. Both simulated and reported figures indicate that the Plastics division required on average more than three years to finish priority 2 new product projects.

For reformulation projects, the simulated completion times are five months for priority 1 projects and one year for priority 2 projects. These numbers are somewhat lower than the figures estimated by the manager

Table 11 **Simulation Results**

	Simulated Average	90th Percentile	Actual Average	PERT Prediction	Actual-to-PERT Ratio
Project Cycle Time					
New Products					
Priority 1	84 weeks	130 weeks	82 weeks	76 weeks	1.08
Priority 2	200 weeks	350 weeks	>3 years	76 weeks	>1.97
Reformulations					
Priority 1	21 weeks	32 weeks	6–9 months	16 weeks	1.50–2.25
Priority 2	55 weeks	90 weeks	1–3 years	16 weeks	3.13–9.38
Number of Concurrent Projects					
New Products					
Priority 1	5	8	6	—	—
Priority 2	10	16	8	—	—
Reformulations					
Priority 1	<1	1	1	—	—
Priority 2	1	2	3	—	—

of the Plastics division. Although reformulation projects were formally assigned either priority 1 or 2, in reality they were generally treated with less urgency than new product projects of the same priority. Only when they needed to be expedited were they elevated to priority 1. Consequently, priority 2 reformulation projects were often treated as "priority 3." This informal resetting of priorities may partly explain the biases in the simulation results: the simulated completion time for priority 2 reformulation projects is shorter than the actual project cycle time, whereas simulated priority 2 new product projects take longer to complete than reported by the Plastics division.

Figures 7–8 show histograms of the simulated project cycle time for the two types of projects. The 90th percentiles of project completion time, which can be deduced from Figures 7 and 8, are significantly longer than the corresponding averages; for example, while priority 1 new product projects are completed in 84 weeks on average, 10% of them take more than 2.5 years. It is clear from these figures that it is not enough to measure *average* project completion times; information concerning the *distribution* of project completion times must also be considered.

To measure the impact of variability and congestion on cycle time performance, the last column of Table 11 shows the ratio of the actual average project completion time (which appears in the fourth column) to the project cycle time predicted by PERT (fifth column). This number, the "actual-to-PERT" ratio, compares the

Figure 7 **Simulated New Products Project Completion Time**

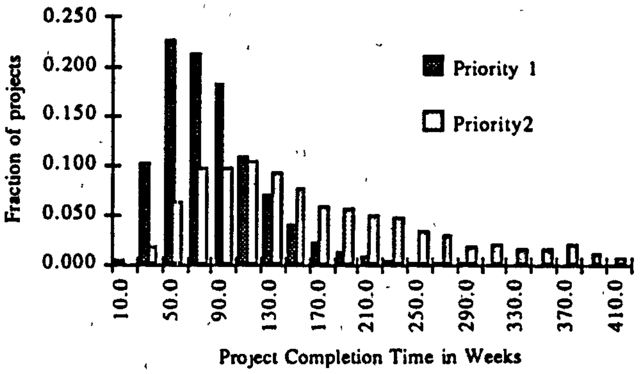
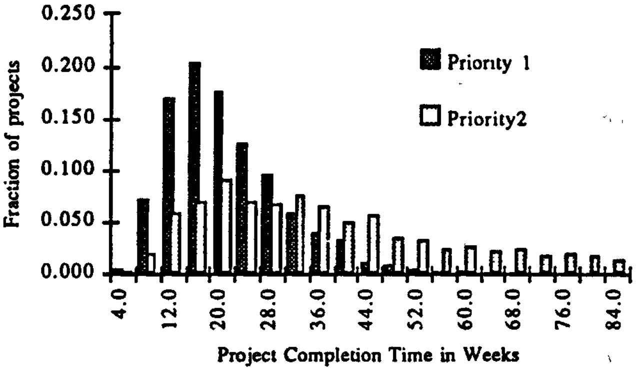


Figure 8 **Simulated Reformulations Project Completion Time**



amount of time that a project spends waiting for resources to the amount of time it actually spends being processed. For example, Table 11 indicates that an average priority 1 new product project suffers relatively little from congestion, as less than 10% of its time is spent idle waiting for resources. A priority 2 new product project, on the other hand, spends (on average) more than half of its time waiting to be processed. Priority 2 reformulation projects, which are less time-intensive than new product projects, suffer even more from congestion. They spend approximately twice as much time waiting for resources as they do being processed.

The last four rows in Table 11 compare the simulated number of concurrent projects in the Plastics division with the figures estimated by its manager.

Finally, Table 12 shows the fraction of time that each resource pool in the core technical group must work its maximum overtime. These numbers appear to be quite high for some resources—PD engineers work 60-hour weeks more than 65% of the time. On the other hand, PD technicians put in a maximal work week less than six weeks a year. As noted in §6, the data seems to misrepresent the allocation of work between engineers and technicians.

The "average" project completion times and "average" number of unfinished projects were obtained by simulating the models until "steady-state" and taking the long-run averages as performance measures. In computer simulation runs, this took approximately 2,000 years of simulated operations. The steady-state criterion may be inappropriate in a setting such as product development where reorganizations typically occur several times before such a steady-state is reached. On the other hand, the difficulty here may be artificial, insofar as it reflects our inability to specify the relevant initial conditions for the system. If we were able to collect data concerning the present distribution of workloads, i.e., the number of projects currently in the system and the amount of work remaining to be done on each project by each resource—then simulation could answer practical questions such as "how will the system perform over the next five years?" In the absence of such information, we simulate the systems long enough for them to accumulate a reasonable amount of work, and we approximate the performance measures by their steady-state values.

8. Analysis, Stage III: What if?

Given a working simulation model of the product development organization, the researcher can start to explore questions like: Where is the most beneficial place in the organization to add a new engineer or technician? How would cycle time be reduced if fewer projects were taken on, or their starting times were more strategically determined? We investigate several such possibilities in this section.

8.1. Adding Resources: Where Are the Bottlenecks?

Table 13 displays average project completion times under three scenarios in which engineers are added to one or more resource pools. In Cases 1 and 2, one employee is added to technical services and product development engineering, respectively, amounting to roughly a 3% increase in the total resource pool. In Case 3, one additional person is added to each group of technical services, product development engineering, and applications engineering, amounting to a 9% increase.

Because product development engineers are most heavily utilized, we expect from queueing principles that

Table 12 **Fraction of Time Spent in Overtime**

PD Engr	PD Tech	Appl Engr	Tech Svcs
0.65	.0.11	0.35	.46

Table 13 **Project Completion Times with Additional Resources**

		New Products				Reformulations			
		Priority 1		Priority 2		Priority 1		Priority 2	
Case	Added Resouces in	Weeks	% Change	Weeks	% Change	Weeks	% Change	Weeks	% Change
Base	–	84		200		21		55	
1	Technical Services (3%)†	82	2%	185	8%	20	5%	50	9%
2	PD Engineering (3%)	81	4%	150	25%	20	5%	43	22%
3	Technical Services, PD Engineering and Applied Engineering (9%)	80	5%	141	30%	20	5%	41	25%

† Percent increase in total resource pool.

they will be the best resource to augment. The simulation results in Table 13 bear out this expectation. The results in Case 2 indicate that investment in well chosen resources can yield disproportionally large reductions in cycle-time. On the other hand, Table 13 shows that adding a resource to an "uncritical" resource pool may have virtually no impact on cycle-time performance, as in Case 1.

A final resource allocation decision (that is, whether and whom to hire) would require economic analysis comparing the savings resulting from shorter development cycle times to the cost of an additional employee, including the extra coordination effort implied by the addition of new people (Brooks 1975). The data we present in these simulation studies could serve as one (otherwise elusive) element of such an economic analysis.

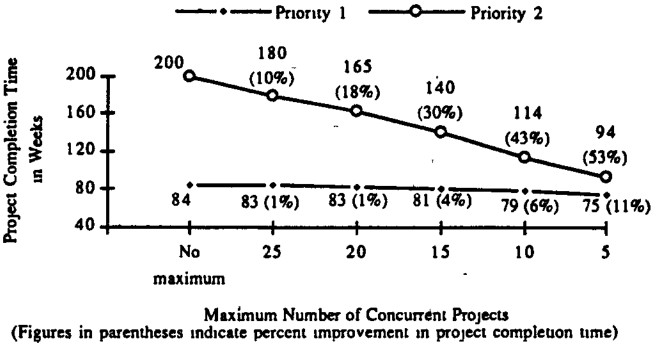
8.2. Input Control: Capping the Number of Projects or Operating as a Pull System

In the base case simulation, the product development organization had more than 20 unfinished new product projects 10% of the time, and the number of ongoing projects could reach 40. Using our simulation model, we considered two "input control" policies: one in which the organization does not bid for new product projects when the level of unfinished projects rises above a pre-set cutoff level, and a second in which new product projects are not begun until existing ones are finished. (Because reformulation projects support established product lines, we assumed that the organization could not decline these projects without great cost.)

Figure 9 shows the average new product completion times for both priorities and for cutoff levels ranging from 25 to 5 projects. Our simulation results show that while priority 1 project completion time is not reduced by much, priority 2 projects, being the primary victims of congestion, benefit greatly from this control policy.

The improvement in completion times comes at the cost of projects lost as a result of the input control policy. For example, with a cutoff level of 20 projects, an average of 4% of potential new product projects are lost, and average completion time for priority 2 new product projects is reduced by approximately 18%. Thus, input control policies look particularly attractive if

Figure 9 **New Products Project Completion Time with Input Control**



(Figures in parentheses indicate percent improvement in project completion time) management can select projects according to their probabilities of success.

This simple control policy reduces cycle time not only by decreasing the amount of work in the system but also through the more subtle yet more powerful variability reduction that comes from restricting the total number of jobs allowed in the network at a time. In light of this, we consider a "pull policy" in which the number of concurrent projects in the organization is kept at a constant level so that the development organization initiates a project only when another project has been completed. In order to implement a pull system, the product development organization must always have projects "on the shelf" waiting to be processed. The manager of the Plastics division confirmed that in his organization worthwhile product or material ideas emerged frequently enough for this to be feasible.

Table 14 compares the performance of the push (or "open") system and the pull system when the number of concurrent projects is fixed at different levels. It reveals the possibility for trade-off: the more projects that resources must handle concurrently, the more projects they can complete each year, but the longer it takes to complete each individual project. But relative to the base case, the pull system with five concurrent priority 1 new product projects delivers better cycle-time performance for all project types while completing as many or more projects per year.

Table 15 highlights this point by comparing priority 2 new product completion times for three systems that have approximately the same throughput rate: (i) the push system (ii) the push system with input control, where the maximum number of concurrent projects is set at 25, and (iii) the pull system with the number of concurrent projects set equal to five. Despite a slightly higher throughput rate, the pull system outperforms the other two systems by eliminating the variability due to (uncontrolled) arrivals of new projects. In queueing theoretic language, the pull system is a closed processing network, the natural analog of the manufacturing models proposed in, for example, Solberg and Spearman (1977), and Woodruff and Hopp (1990).

8.3. Tradeoffs of Cross-training: Effects of Pooling

Because product development engineers are much more heavily utilized than product development technicians, we examine the consequences of allowing more shared work between these resources. In the simulation experiments described here, we assume that engineers reassign a portion of their work to technicians whenever the number of ongoing projects exceeds 5. Whereas we previously assumed that 30% of the engineers' work could be performed by technicians, we now explore the effect of varying this amount of transferable work. These results provide one measure of the potential benefits of cross-training.

Figure 10 shows the average completion times for new product projects with pooling levels ranging from 10% to 70%. The numbers in parentheses are percentage reductions in cycle time resulting from giving an additional 10% to the amount of work that PD engineers can reassign to their technicians. For example, by in-

Table 14 **Project Completion Times and Throughput Rates in a Pull System**

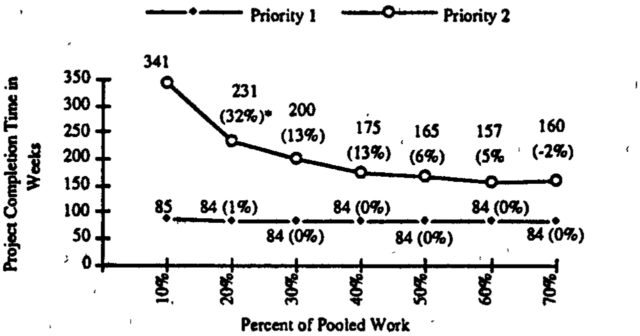
	Average Cycle Time (Weeks)				
	New Products		Reformulations		
Number of Concurrent Projects	Priority 1	Priority 2	Priority 1	Priority 2	Priority 1 New Product Projects Completed per Year (Throughput Rate)
Open System	84	200	21	55	3.0
5	82 (2%)*	173 (14%)	20 (5%)	47 (15%)	3.1 (+2%)†
3	78 (7%)	114 (43%)	20 (5%)	30 (45%)	1.8 (−41%)
1	77 (8%)	94 (53%)	19 (10%)	24 (56%)	0.7 (−78%)

* Percent improvement in project completion time over open system.
† Percent change in number of priority 1 new product projects completed per year over open system.

Table 15 **Comparing Priority 2 New Products Project Completion Times**

System	Project Completion Time: Average	Project Completion Time: 90th Percentile	Throughput Rate
Open	200	350	3.0
Input Control (25)	180	290	2.9
Pull (5)	173	270	3.1

Figure 10 **New Products Project Completion Time with Pooling**



*Incremental change in cycle time associated with an incremental 10% increase in pooling

creasing the fraction of pooled work from 20% to 30%, average priority 2 completion time is reduced by 13%. (Again, note that the impact on priority 1 cycle time is negligible.) The graph in Figure 10 suggests that the expected incremental benefit of additional pooling diminishes as the amount of shared work increases. Indeed, as engineers reassign more work to technicians, the engineers gain slack time while the technicians become busier. Eventually product development engineers cease to be the bottleneck.

We make the simplifying assumption that no loss of efficiency results from pooling. In general, transferring work from engineers to technicians could result in increases in either processing times or in the likelihood of errors. Although our hosts shared this expectation, they were not able to quantitatively estimate these effects for us. Nevertheless, combining this observation with the insight gained from Figure 10, it should be clear that there is an "optimal" level of pooling beyond which cycle time increases.

8.4. The Importance of Priority Coordination

An often-addressed topic in the product development literature is the benefits of organizing different functions under one manager (we call this a "centralized" system), rather than letting them operate independently under different managers (which we call a "decentralized" system) (Wheelwright and Clark 1992b). The Plastics division operates under the centralized structure. In this organization all functions involved in product development activities (e.g., product development engineers, product management, and marketing) are grouped under one manager. Consequently, projects are assigned the same priority across all groups—at least, in principle. Conversely, if the "lowest common manager" were higher in the reporting hierarchy, projects would likely be accorded different priorities in different groups.

To examine the consequences of the decentralized organization, we analyze a system in which manufacturing engineers and product management treat all project-related work as low priority compared to their support activities. Project completion times, shown in Table 16, are much longer for the decentralized system. Manufacturing engineers and product management play relatively small roles in the product development process in terms of both absolute number of hours contributed and percentage of time dedicated to project related work. But when these groups do not treat project work as first priority, project completion times can suffer by 35%.

9. Conclusion

When we began this project, we hypothesized that process management would offer opportunities to improve product development in a wide class of businesses and that process modeling would prove to be a valuable tool supporting that effort. We believe that the results

Table 16 **Project Completion Times with Lack of Priority Coordination**

System	New Products: Priority 1	New Products: Priority 2	Reformulations: Priority 1	Reformulations: Priority 2
Centralized	84	200	21	55
Decentralized	95	190	24	53

reported in the previous sections are sufficiently positive to encourage further research along these lines. The hurdles we encountered along the way, however, are also valuable research results. Here we discuss these hurdles under two headings—technical constraints and organizational impediments.

From a technical point of view, development process modeling encounters some difficulties inherent in the differences between product development engineering and repetitive manufacturing operations. Whereas manufacturing produces many identical units of a few different products, the task of the engineering organization has the inverse structure: it produces a few different product designs using many possible engineering and support activities. For manufacturing, repeatability is of the essence, and the constituent activities have to be rigorously standardized. In the engineering case, the product design effort aims at the optimal unique solution, and the group performs the required activities in whatever order, combination, and form are necessary to reach that goal. (Of course, customized manufacturing job shops look a lot like engineering from this perspective.) In this technical setting, a process perspective seems antithetical to the very essence of product development engineering, and the difficulties we encountered in building a process model have helped us better understand the distinctive nature of engineering. Our research was designed to test the hypothesis that the conventional view of engineering work as essentially nonroutine is sufficiently false—in other words, that there is enough repetitiveness in at least some engineering organizations—to make a process model possible and useful. We believe the results reported in the previous sections support our hypothesis.

Second, even if a process view is feasible, another technical difficulty lies in the intrinsic complexity of process modeling. Many managers are familiar with the enormous complexity of manufacturing process plans, and they justifiably worry that the burden of creating, maintaining and exploiting "engineering process plans" would outweigh any benefits. As we discuss in Adler et al. (1995), we found that the construction of the model itself, rather than being a burden, was probably the most directly useful part of our research. The act of explicating the work process, establishing a common task nomenclature, and abstracting the process for people in different technical functions gave our contacts a broader understanding of their organization and pointed to some immediate process improvements. However, we hope that this project has also shown that the particular insights of a stochastic processing network justify the modeling effort. In particular, given a working simulation model, management can explore the implications of changes to their organization and to the way they structure their work.

A third technical impediment that surfaced only occasionally in our project might prove to be an interesting subject for future research. Our approach takes the project as the unit of analysis, but in reality projects belong to streams: new products are often generated as variants of old ones. For example, dialogue with new customers often leads the product development group to adapt product specifications in order to broaden their potential customer base. If our collection of project data proved difficult, it was in part because the engineers and managers tended to view the organization's work as composed of such streams, rather than as a set of discrete projects.

If we are right and a process approach could be a powerful management tool, why has it not been attempted before? Our project also led us to several insights about the specifically organizational impediments that account for engineering management's traditional focus on discrete projects rather than on ongoing processes.

First, engineering managers have tended to concentrate on the unique features of each project, a point of view that is rooted in the assumption that the effectiveness of an engineering project depends most critically on creativity. It is natural that the culture of engineering should highlight and celebrate the distinctive and novel challenges in engineering work. In many engineering organizations, however, there is considerable cross-project commonality and a high ratio of routine to nonroutine activities. In such contexts, projects can be managed as variants of previous projects, and effectiveness depends not only on the creativity with which the truly creative parts of the project are conducted but also on the efficiency with which the routine parts are conducted. As product development time becomes a more salient competitive factor, management needs to shift its attention from an exclusive focus on creativity and product features and to consider as well the efficiency of the product development process.

A second organizational impediment for engineering managers is the lack of requisite data. It is difficult to determine what data ought to be gathered; moreover, unlike manufacturing operations, there is no unobtrusive way to collect the data that process modeling would require. Nevertheless some organizations do collect time cards from engineers, and if the organization has a consistent nomenclature of activities, then times can be collected for projects and activities, thus opening the way to systematic process modeling. In the future, as more engineering work is done on CAD / CAE workstations, the opportunities for unobtrusive data collection will grow.

Finally, and perhaps most fundamentally, the reluctance to develop process models might stem from an image of engineers as "autonomous" professionals who should not be told how to do their jobs. Indeed, process models might connote an organization so regimented as to preclude creative innovation. We believe, however, that if process management is presented and implemented as a means of enhancing effectiveness—not as a club to make engineers work harder but as a tool that helps them work smarter—then it will be embraced by such professionals. Our experience at the Plastics division supports this hypothesis. We found a high level of support for our project, and the engineers were very cooperative throughout our time-consuming data collection effort. It is appropriate that we close this article by thanking them.

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