Understanding Process Plant Schedule Slippage and Startup Costs

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PREFACE

In 1978 The Rand Corporation began a program of research into the causes of cost, schedule, and performance problems in pioneer process plants. Generally, the goal of this research has been to provide industry and government with improved methods for evaluating the commercial prospects of developing technologies. A large proprietary database covering information on more than 50 process plant development projects has been amassed. The database includes many projects that use standard technologies as well. These serve as a baseline against which the effects of unproven technology can be assessed. Detailed interviews with the engineering staffs of over 40 companies have been conducted to supplement the existing database. In addition, an extensive review of the literature has provided useful insights into this field.

The first report in Rand's Pioneer Plants Study series, E. W. Merrow, S. W. Chapel, and J. C. Worthing, *A Review of Cost Estimation in New Technologies: Implications for Energy Process Plants*, R-2481-DOE, July 1979, examined the problems routinely encountered in projecting realistic costs for advanced technologies. The second report, E. W. Merrow, K. E. Phillips, and C. W. Myers, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants*, R-2569-DOE, September 1981, developed methods for estimating total cost growth and expected initial performance of pioneer facilities. R. E. Horvath wrote a special report, *Pioneer Plants Study User's Manual*, R-2569/1-DOE, in June 1983 as a guide to those in government and industry wishing to evaluate their projects using the study results. The effects of certain management characteristics have been analyzed as well and reported in C. W. Myers and M. R. Devey, *How Management Practices Can Affect Project Outcomes*, N-2196-SFC, August 1984.

The goal of this study is to develop improved techniques for understanding and evaluating the extent of schedule slippage encountered during construction, and the time and costs of plant startup. It relies on the database developed for the Pioneer Plants Study augmented with additional project schedule and startup information. Additional interviews of plant engineers have been conducted to gain a better understanding of construction and startup faced by the process industries. The Rand Corporation's Private Sector Sponsors Program supported this research; supplementary support was provided from Rand's own research funds.

SUMMARY

This study explores major factors causing schedule delays and problems often experienced in constructing and starting up new process plants. The results of this research provide new insights into the problems firms across the process industries encounter in planning major plant developments.

The schedule established during project definition (or very early detailed engineering) for any major project gives the expected start and end dates for each phase of the project from engineering through construction and startup. Although the schedule may be revised during the project, it is the baseline against which the project's actual progress is evaluated. Startup is defined as the time between mechanical completion and the point at which the plant is turned over to the operating crew at the new plant, or the start of operating capability. Our analysis sought to explain the variation in construction schedule slippage, startup time, and startup costs (as a percentage of costs through mechanical completion).

Expected project length for construction and startup and total startup costs are especially critical in evaluating proposals to commercialize new technologies. Plant investment decisions often hinge on whether the project can be completed in time to meet a projected market demand in a timely and competitive manner. Unexpected delays can greatly increase capital requirements and reduce return on investment by postponing product sales. Delays can often spell the difference between being first in a new market and not being there at all.

This report quantifies the key factors driving construction and startup schedules as well as the costs of startup. Although our emphasis is on pioneer plants, the results should prove useful in understanding schedule slippage for fairly standard units as well.

The tools developed can be used as additional methods for evaluating planned construction and startup schedules. These methods use project and technology characteristics that are identifiable at any stage in a project's development once the schedule plan is established—even during project definition, before major financial commitments have been made. These variables reflect characteristics of the level of technological innovation embodied in a project technology and whether the plant uses solid materials as feedstock, coal for example.

The analyses described here indicate that each of these problems is explainable by a limited set of project characteristics. Specifically, the major factors explaining these outcomes are:

- *Construction schedule slippage* is strongly associated with poor project definition at the start of detailed engineering; planned long concurrency between detailed engineering and construction for pioneer plants; and the use of unrefined solid feedstocks.
- *Total startup time* can be explained by the number of commercially unproven process steps, the portion of the plant heat and material balances based on previous commercial units, and whether the plant processes an unrefined solid feedstock. In addition, placing responsibility for the project in a team composed of representatives from each of the corporate divisions, rather than dispersing project responsibility across these divisions, appears to result in better communication and shorter startups.
- *Startup costs as a percentage of total costs* are closely related to the number of new process steps, the extent of difficulty with materials handling issues (such as feed characterization, abrasion, solids handling, and waste handling) encountered during process development, and whether the plant processes an unrefined solid feedstock.

Management can make a substantial and quantifiable difference. Several factors critically affecting project schedules reflect strategic choices about how individual projects should be managed. Circumstances may encourage project (and corporate) managers to push a project into the field as rapidly as possible, even without the benefit of better project definition. Such strategies are not without substantial costs, however, at least in terms of the accuracy of schedule and cost plans. The management decision to invest in more thorough project definition before proceeding to detailed engineering usually results in more accurate estimates of construction time and project costs. The more that is known about the process design and specific site conditions at the time an estimate is prepared—whether for costs or construction schedule—the more accurate the estimate is likely to be. This is true for all projects.

Another aspect of management effects concerns the decision on when to begin construction relative to expected progress of detailed engineering. First-of-a-kind projects tend to overlap these phases more often than other projects. And in most cases, they pay a substantial penalty for doing so in terms of the accuracy of the construction schedule. Pushing a project—especially a pioneer plant—into the field early can prove more costly and take longer than expected. Fast-tracking by substantially overlapping engineering and construction often leads later to construction delays while engineering catches up.

Planned concurrency of eight months or more between these phases typically adds more than a half year to the actual schedule for first-of-a-kind facilities.

A third aspect of project management is how it is structured. Integrating the diverse (and sometime conflicting) perspectives of corporate R&D, engineering, and operations (or manufacturing) by making such a team responsible for its successful execution is associated with considerably shorter and smoother pioneer plant startups. Problems may be anticipated earlier and resolved more easily as a result, instead of plaguing the plant operators during startup.

Aside from project management, another implication of this analysis concerns innovation. The use of commercially unproven technology is a major factor explaining all three project outcomes. It is often not until startup that serious design problems are recognized; corrections then are usually costly and time consuming. Technological innovation can be particularly troublesome when coupled with either a lack of experience by the firm with building similar plants, or an inability to rely on previous commercial units in establishing the plant's basic heat and material (H&M) balances. It is not just the use of new technology that is important, but also the degree of technical advance attempted. Thus, plants involving only one or two new process steps typically experience shorter and less costly startups than those involving three or more new steps.

Furthermore, unrefined solid feedstock materials pose severe difficulties that result in longer than expected construction and startup and higher startup cost percentages. These plants also tend to be more innovative (in our sample at least) and suffer more problems with materials handling issues during development. In particular, raw solid feed plants tend to rely much less on previous commercial experience in calculating the H&M balances for the plant during design.

The analysis presented here and the resulting statistical models can be used as aids in project planning. For projects similar to those in the database, these models can be applied to estimates of project construction, startup length, and startup cost as checks on their accuracy. Such evaluations, moreover, can be performed with a minimal amount of data, all easily measurable at an early stage in the project's development.

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I. INTRODUCTION

Reasonably accurate projections of the time necessary to construct and start up a new commercial process plant are essential for many important industry and government decisions. Knowing how much additional capital may have to be infused to achieve steady operating capacity once construction has been completed is often just as critical. Major investment decisions as well as important public policy choices concerning whether and how to support the commercialization of new process technologies rely upon predictions of projects' commercial viability. Expected construction schedule and startup time and cost represent important components of such decisions. The soundness with which planners assess a project's commercial viability in large measure depends on how realistically such estimates predict actual time and costs.

Accurate planning for construction and startup is especially important because these phases represent the bulk of project expenditures and dictate market entry timing, respectively. Project cash flow requirements, contractor and labor force hiring, availability of product for sale, and, indeed, the very economic viability of the project can hinge on meeting construction and startup schedules. Delays distort corporate-level planning and reduce return on investment, especially when they occur late in the project, such as in startup, after most of the capital is already in place. Long startups mean delayed product sales and higher capital expenditures and can entail substantial redesign of the process technology involved.

Construction schedules and estimates of startup time and costs are often overly optimistic, especially when pioneer technologies are involved. Many large projects, some running in the billions of dollars, have been abandoned or faced cancellation because of long, drawn-out schedules, massive cost overruns, or the failure to start up quickly and operate successfully. Highly visible examples merely attest to the problem of placing too much confidence in early schedule and startup cost estimates that many companies and agencies face.

These problems are only more visible where public monies are involved, as in the case of some first-of-a-kind synthetic fuels plants. They are not unique, however. All planners concerned with commercializing new technologies confront these difficulties. But because of the potentially vital role synfuels might play in our nation's energy future, we need reasonable expectations about the costs of these and other new technologies. The extent of government involvement in such projects, and even the need for any public role, have been sharply questioned as the costs continue to push beyond competitive reach. Even when completed on time and budget, such new technologies commonly suffer difficult and prolonged startups.

ANALYTICAL FRAMEWORK AND APPROACH

A body of Rand research has addressed these problems with particular application to advanced energy technologies, but with implications for all chemical process plant developments as well. An earlier report from Rand's Pioneer Plants Study (PPS) identified the sources of capital cost growth and related performance shortfalls, and developed methods that can yield more realistic expectations of ultimate costs and performance of first-of-a-kind process plants.[1]

This report emphasizes the problems of project construction schedule and the time and costs of plant startup. The analysis is based upon an expanded version of the database used in the earlier PPS research. This database contains proprietary details on many process plant projects undertaken in the United States and Canada since the 1960s. It draws on the experiences of private sector firms in the oil, chemical, and minerals processing industries. We have substantially expanded the database to incorporate further details on each project's schedule and startup and added many new projects. Many of the added plants involve fairly well-established technologies. These serve as a baseline against which we can assess the effects of technological innovation. Many plants also involve varying degrees of solids handling—a particular problem for plant performance shown in our earlier analysis.[2] The database enabled us to test a range of hypotheses suggested by the literature, in discussions with industry representatives, and by our own models explaining cost and performance estimation problems. The database is described in detail in the appendix.

The analysis reported here parallels the methods and approach taken in the Pioneer Plants Study. It relates characteristics of the project and technology, including their stages of definition, to the extent of schedule slippage encountered during construction, and to the time and costs of startup. The objective of this analysis was to develop quantitative estimating relationships that identify and explain the major sources of construction schedule slippage, startup time, and startup costs. As in the PPS, we have emphasized the explanatory role

[1] Merrow, Phillips, and Myers, 1981.

[2] Ibid.

of characteristics that can be identified and measured early during a project's development, before large sums have been committed or spent.

In this analysis, we developed methods for managers, planners, and estimators to use in evaluating and checking schedule and startup cost expectations. Our analysis revealed areas in which schedule and startup cost estimates can be substantially improved and ways to reduce schedule slippage and startup costs.

Our analysis holds direct implications for senior corporate management as well. We found that corporate and project management largely controls the extent to which a project meets it construction schedule and starts up smoothly. Individual firms use different approaches to project planning, scheduling, and execution. We examined aspects of this variation in attempting to understand their effects on project outcomes. These factors included how well the project has been defined before it proceeds to detailed engineering, the extent to which the construction phase is executed concurrently with engineering, and the structure of the project's management. These are essentially discretionary factors that reflect corporate decisions about how projects should be managed and executed. They also represent the major explanations for differences in the extent of construction schedule slippage experienced by most of the projects in the database.

PROJECT PHASES

Most development projects consist of five distinct phases: research and development (if appropriate), project definition (often including process engineering work), detailed engineering design, construction, and startup. We emphasized the longest and most costly phase of project execution, construction, and the subsequent time and costs required to start the plant and reach steady operations.

Figure 1 illustrates the average project schedule for the plants in the database. The length of each major phase (except R&D) is shown as a bar expressed in total elapsed months. Some slippage occurred in every phase, as indicated by the hatched portion of each bar. A portion of the average slippage during construction resulted from the effects of factors external to the project itself. These are shown as the lined portion of the construction phase bar, and involved such factors as unusually bad weather, labor strikes, materials shortages, or unanticipated regulatory changes. These are very unusual, low probability but high consequence events that generally cannot be planned for. They are examined in Sec. II and are not included in the statistical analysis of construction schedule slippage.

We collected information on the schedule definitions used by the firms providing the data. This allowed us to explore differences in how

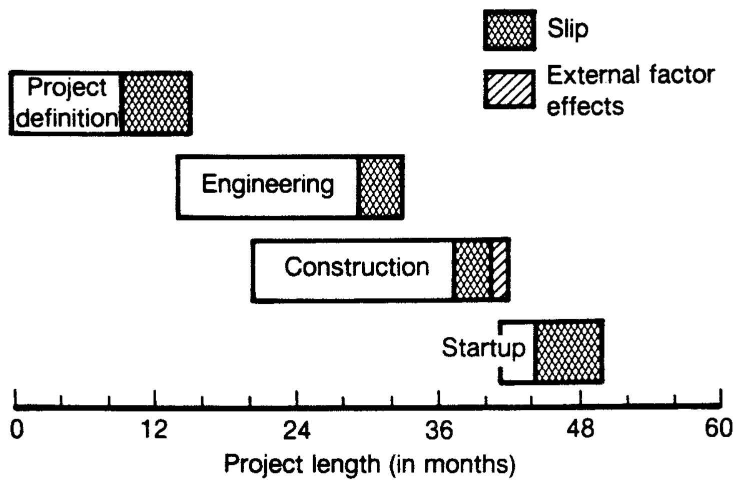

Fig. 1—Average PPS project schedule

firms defined the schedule phases. We found remarkable similarity in the way each company defined the phases and when the scheduling was done. This allowed us to measure slippage from a common planning point across all the projects in the database. For each phase from engineering through startup, the schedule was developed late in project definition or at the start of engineering. Thus, slippage is measured as the difference between the actual time elapsed and the planned time. We found that the following definitions sufficiently capture the small variety of interpretations and meanings in terminology across the companies:

Construction

- Period in months from foundation pouring through mechanical completion.
- Planned as of end of project definition.
- External effects removed.
- Analyzed slippage as the difference between actual and planned time in months.

Startup time

- Period from first production attempt to steady operations.
- Analyzed total actual time.

Startup costs

- Costs associated with startup time.
- Excludes lost sales and penalties.
- Includes expensed and capital costs.
- Analyzed as a percentage of capital costs.

The R&D and project definition phases are excluded from the analysis principally because the project schedule is established late in the project definition phase or very early during detailed engineering, and our analysis is concerned with the difference between the schedule time and the actual length of the subsequent construction phase. Also, some process plants, especially if they use a fairly well-established technology, do not have an R&D phase. Some projects do not even have a project definition phase. Our analysis of the construction phase examined the factors most likely to cause the actual time to differ (that is, to slip) from the planned schedule. For startup, we focused on the actual time required to reach more-or-less steady operating capability. Estimates of startup time and cost are exceptionally varied in their accuracy and usually extremely optimistic (see Fig. 1). In part, this stems from the lack of attention paid to this phase when schedule and cost plans are developed. Our analysis dealt with actual startup time and costs as a percent of the capital costs spent before startup.

Startup is a particularly important period for all projects. Startup problems can be viewed as the accumulation of all unresolved problems in the preceding phases. Some may be attributable to a poor definition and consequent engineering and construction errors, to insufficient process data obtained from the pilot plant operation, or to poor planning and project management.

Section II provides the results of the statistical analysis of construction schedule slippage, and Sec. III the analyses of plant startup time and costs. Section IV summarizes the primary lessons of the analysis for government and industry planners and suggests how the methods developed may be used to improve future planning and policy decisions. A detailed description of the process plant database is provided in the appendix.

II. UNDERSTANDING PROJECT CONSTRUCTION SCHEDULES

INTRODUCTION

Plant construction, from foundation pouring through mechanical completion, represents the longest of the four project phases. The detailed engineering and construction phases usually overlap somewhat, thereby reducing the contribution of construction time to the overall length of the project. Nonetheless, the time taken for construction is the critical component in project length. Yet construction scheduling "is probably the most ignored, compromised, and misunderstood part of all [project] specifications."[1]

This section presents the results of our analysis of construction schedule slippage. We first describe factors associated with the planned construction time to better understand the base against which slippage is measured. We then discuss our hypotheses and identify major correlates of construction slippage and conclude with a model that helps explain the extent of slippage encountered across the plants in the database. The results of our analysis demonstrate that a few management planning factors explain most of the variation in construction schedule slippage. The methods presented for evaluating construction schedule estimates are designed to broaden our understanding of the factors associated with schedule slippage. They are also intended to provide a means of evaluating construction schedule estimates for diverse types of projects with information that is available early during the project's development. We therefore emphasize management, project, and technology characteristics that are measurable well before construction begins.

Throughout this report, we refer to construction time as the number of months from the pouring of the initial foundation to the point of mechanical completion of the plant. Planned construction time is the number of months estimated to be spent during this phase when the schedule was initially established, which is usually during late project definition or at the beginning of detailed engineering. We evaluated construction schedules using a definition consistent across all the projects to establish the amount of time (in months) by which they slipped from a common point in each project's development.

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[1]Padgham, 1984, p. 1.

Planned Construction Time

Estimating the time required for plant construction can depend on many disparate and sometimes conflicting factors. State and local permit requirements, workforce quality and availability, peak labor requirements, equipment fabrication and delivery, general market conditions, corporate or project cash flow, vendor workload and availability, and other logistical issues may all affect how the construction schedule is developed and carried out. A critical path may be developed based on equipment items that must be obtained or tasks that must be done to avoid delaying subsequent progress. Identifying and planning for this path can also depend on factors like those listed above. Construction must be planned differently during periods in which equipment vendors face high demand than during slack periods. Similarly, skilled labor may be in short supply in an area, necessitating special planning and management.

Moreover, these factors are more likely to occur at times when the need to complete the project in the shortest possible time is highest. Growth in the general economy is often associated with new plant construction combined with labor and equipment bottlenecks of varying severity. The inverse of this relationship is also true. Forecast demand for a project's output may fall while demand for labor or vendor services also declines. Planned schedules may then be stretched out.

The schedule estimator often must operate without the benefit of very accurate forecasting of such events, however. Construction schedules (with attendant contractor hiring and equipment deliveries) are usually established many months and sometimes years before the first foundation is actually poured. The planned schedule may be calculated backward from a future date when the product must be available for market, because of contractual commitments or management directive. Often severe market or labor constraints are not yet sufficiently evident on the project horizon to alter construction schedule planning very much. Delays in engineering may push back the start of construction, or slow construction progress. These delays may allow new, unexpected regulations to take effect that may lead to further delays, or cause critical "weather windows" to be missed. These events cannot be easily anticipated and may severely distort the construction schedule. Where such unforeseen exogenous events occurred, we have tried to remove their effects from the actual schedule durations. (We do not know what effect, if any, premonitions of external factors may have had on the initial construction schedule plan, and we have not attempted to adjust construction schedule estimates.)

Table 1 shows the average planned time for detailed engineering and construction for the plants in the database. A wide range of estimated times is represented, with an average 16 months expected for detailed engineering and a year and a half for construction.

Planned Engineering Time and Construction Scheduling

Construction time is commonly estimated as a function of the expected effort to be spent during detailed engineering. Figure 2 shows the strong relationship between estimated construction months and estimated engineering months. The coefficient of correlation (Pearson's r) between these measures is 0.72, indicating that planned construction time can be predicted from the planned engineering time in many cases.

We cannot easily and certainly identify how the schedules were developed for these plants. However, the systematic patterns strongly suggest that very similar techniques were used to estimate them, despite the development by different firms and individuals.

Actual Construction Time

Because our primary interest lies in understanding how the actual time deviated from the expected time, we touch only briefly on the actual length. The average length of time spent between the first foundation pouring and plant mechanical completion was about 21 months. This varied between one very small project that took only five months and a very difficult and innovative development that required over four

Table 1

PLANNED ENGINEERING AND CONSTRUCTION SCHEDULES
(Months)

	Mean	Median	Standard Deviation	Range	Number of Plants
Detailed Engineering	16.1	15.5	8.3	4 to 42	48
Construction	18.4	18.0	6.9	4 to 32	51

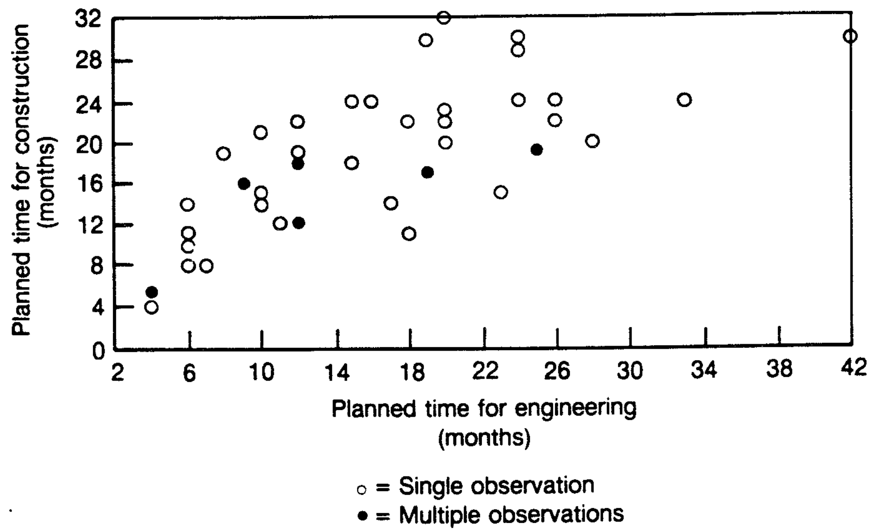

Fig. 2—Relationship between planned construction and engineering time

years. Two-thirds of the projects spent two years or less during construction; half took between 18 and 30 months.

Construction Schedule Slippage

Most of the projects were very close to their planned construction schedules. The average project slipped about two or three months, as Table 2 shows. Figure 3 shows the distribution of slippage across all the projects. In fact, five projects came in two or three months ahead of schedule, and 12 others experienced no overall delay at all. However, 10 projects suffered at least half a year's slippage; two slipped well over a year. As a percentage of planned time, the average project's construction schedule slipped about 18 percent. This outcome measure also varied widely. Over half the projects were within 15 percent of their planned schedule, but 15 slipped by more than 25 percent. The two slippage measures are closely related, with a correlation coefficient of 0.88.

Table 2

ACTUAL CONSTRUCTION SCHEDULE SLIPPAGE

	Mean	Median	Standard Deviation	Range	Number of Plants
In months	3.3	2	4.4	(-3) to 15	51
As % of planned time	17.7	11.8	24.2	(-14) to 88	51

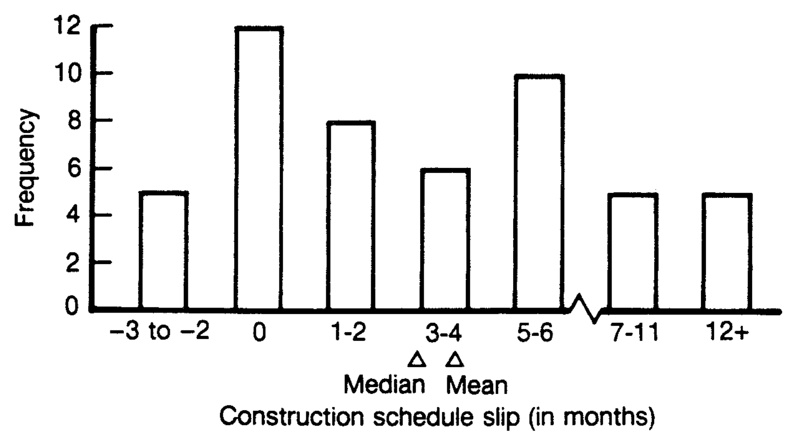

Fig. 3—Distribution of construction schedule slippage

Variable Selection Strategy

The most difficult task we faced in this analysis was trying to find the set of analyzable variables that could both explain slippage and be measured across the projects in the database. At first, there appeared to be no end to the list of potential causes of construction slippage. The available literature revealed little consensus on the major factors driving slippage. In fact, for each experienced industry staff member we spoke with, for each article on construction scheduling we reviewed, and for each project in the database, it almost seemed that there was a unique explanation for why a given schedule was or was not met. In the face of this wide range of potential explanations, we developed a strategy to focus our search for explanatory variables. This strategy had four criteria:

- First, the variable should measure a recurring factor in the literature and in our discussions with company personnel familiar with their projects. This was used to limit us to a set of commonly cited and recognizable factors hypothesized to explain slippage.
- Second, the variable should reflect a project characteristic that was readily measurable during the project definition phase, before the start of detailed engineering. This was used to maximize the usefulness of the analysis for project planning, when project authorization decisions and funding commitments are made.
- Third, the variable should represent an easily identifiable and changeable project characteristic and, to the extent possible, one that reflects corporate or project management discretionary decisions or strategy choices about how the project should be planned and executed.
- Finally, the variable must be contained in the process plant database.

This strategy led us to examine three types of variables: external factors, management planning characteristics, and a small set of technical project characteristics, such as new technology and feedstock type.

HYPOTHESIZED CAUSES OF CONSTRUCTION SCHEDULE SLIPPAGE

Statistical studies on the causes of project cost growth abound in the literature, yet there is a dearth of empirical research on the causes of construction schedule slippage, especially for process plant developments. (The Bibliography offers a range of published materials.) Most published articles describe problems and solutions from one or two projects in an anecdotal manner, or recommend preferred management approaches with little or no empirical evidence to support them. What literature exists typically posits one or more of the following hypotheses, each of which is addressed below using the PPS database:

- Project length and slippage are closely related to other project outcomes such as cost, cost growth, and performance.[2]
- External factors such as new regulatory requirements, late equipment deliveries, labor shortages, and the like are leading causes of delays in construction.[3]
- Technological innovation increases project length and schedule slippage.[4]

Relationship of Slippage to Other Outcomes

The interrelationships between project time and slippage, and other project outcomes, such as total cost, cost growth, startup time, and early plant performance that were identified in earlier research are also found among our 51 projects. Table 3 shows the correlations of total construction time and construction slippage (in months) with each of five major outcome measures. Plant performance during the second six months after the beginning of startup is measured as the average monthly percent of design capacity achieved. All five measures are significantly related to construction length as well as slippage. Longer construction time and slippage are associated with more costly plants, poorer cost estimates, longer startup and poorer early performance. Construction time and plant cost are causally related, of course, and unexpected construction delays can contribute significantly to cost overruns as well. To a large extent, however, poor outcomes such as construction slippage and cost growth stem from common sources, such as technical innovation, poor definition, and poor management, rather than from one another.

As part of the data collection effort, firms were asked to describe the causes of any major delays encountered during construction. The reasons for construction delays mentioned by the firms providing data for our analysis span a wide range. Thirty-five of the projects answered open-ended questions about the causes of schedule slippage encountered, if any. Table 4 lists the answers relating to construction delays. Most projects cited multiple causes of construction schedule slippage. Many firms named external factors such as unusually bad weather, labor strikes or availability problems, or inordinate equipment

[2]See, for example, Baker et al., 1983, p. 690; Bauman, 1960, p. 59A; Harman, 1970, p. 29; Summers, 1962, pp. 160–161.

[3]See, for example, Baldwin et al., 1971, pp. 180–181; Budwani, 1982, p. 38; Rad, 1979, pp. 34–40; Tatum, 1978, p. 491.

[4]See, for example, Adams and Busch, 1981, p. 380; Doering, 1970, p. 90; Glennan, 1968; Mooz, 1978, p. 15; Perry et al., 1969, p. 6; and 1971, p. 4, 17; Ruskin and Lerner, 1972, p. 132; Schnee, 1972, p. 368.

Table 3

CORRELATIONS BETWEEN CONSTRUCTION TIME AND SLIPPAGE AND OTHER PROJECT OUTCOMES

	Total Construction Time		Construction Slippage	
Project Outcome	Correlation[a]	Significance	Correlation[a]	Significance
Construction slippage (months)	.76	.0001	—	—
Total cost (log)	.66	.0001	.34	.02
Cost growth[b]	-.38	.016	-.41	.008
Startup time	.26	.06	.29	.04
Plant performance (months 7-12)	-.37	.008	-.37	.009

[a]Pearson's r.

[b]Cost growth is the ratio of estimated costs to actual costs (as of early engineering), and thus lower values (less than unity) represent underestimation of actual costs.

shortages. Where the company provided an estimate of their effect on construction, we have subtracted it from the actual time and slippage. We have not adjusted for delays due to other causes, such as innovation.

Other frequently mentioned problems were delays in the engineering schedule—often resulting from starting construction too early and design modifications that held up construction progress. Use of new technology was usually cited as the cause of such changes, although some resulted from a failure to "freeze" engineering design before beginning construction. We will return to these problems shortly to analyze their actual effects on construction slippage.

Several qualitative studies have been conducted on delays in power plant construction projects. Based on surveys and interviews, they identify the leading causes of construction delays as design changes imposed by regulatory requirements, late delivery of components or materials, shortages of skilled labor, poor labor productivity, difficulty in financing, sharp declines in the growth rate of electricity demand,

Table 4

REASONS CITED FOR CONSTRUCTION SCHEDULE SLIPPAGE

Reason for Construction Delay (open-ended questions)	Number of Projects Mentioning
External factors	
labor strikes/problems	7
labor shortages	5
regulatory delays	5
very bad weather	6
cash flow restrictions	3
equipment shortages	9
Management planning factors	
engineering delays/excess concurrency	5
engineering design changes/evolution	13
poor definition/scope changes	5
poor management/planning/leadership	4

and increased project and process complexity.[5] A broader study on the causes of delay in the construction industry pointed to similar factors. Although contractors, architects, and engineers rank the major causes differently, they agree that the three most important factors are weather, labor supply, and subcontractors.[6] Generally speaking, except for project and process complexity, these are external influences on the project, and we have isolated their effects to point the bulk of our analysis toward factors more directly within corporate and project management control.

Based on a review of the available literature covering quantitative and qualitative studies of construction slippage, and our discussions with industry managers and estimators, we hypothesized that construction schedule slippage resulted from two types of causes: external factors, such as labor and equipment shortages, new regulations, and the like; and management planning factors, such as poor project definition or excessive concurrency. We further hypothesized that management planning factors are particularly important when associated with the introduction of innovative technology. Poor early project definition, for example, can be expected to result in considerable scope changes

[5]Budwani, 1982, p. 38; Tatum, 1978, p. 491.

[6]Baldwin et al., 1971, pp. 180–181.

later, delaying construction progress and resulting in cost overruns. Engineering delays may lead to long construction delays when the two phases have extensive overlap. But engineering design changes or evolution that are more common for innovative projects are especially troublesome when engineering is conducted in parallel with construction. We also investigated several technical project characteristics such as complexity, feedstock type, and measures of new technology. The factors that we examined as causes of construction schedule slippage are summarized below:

- External factors
  - low probability events; consequences vary
  - effects removed
- Management planning characteristics
  - degree of project definition at start of engineering
  - extent of concurrency between planned engineering and construction
  - contract type
- Technical project characteristics
  - complexity
  - feedstock type
  - new technology

Our analysis demonstrates that certain management planning factors explain most of the variation in construction schedule slippage, especially for pioneer plants.

EFFECTS OF EXTERNAL FACTORS ON CONSTRUCTION SCHEDULE

The effects of any external factors, such as labor or equipment shortages, strikes, unexpected new regulations, or severe weather, have been estimated and removed from the elapsed times shown in Tables 2 and 3. These effects are outside the estimator's ability to foresee reasonably, and are therefore treated as exogenous for our analysis. They have also been removed for purposes of the analyses presented throughout this report. Although these factors are often believed to be the major causes of schedule slippages,[7] especially during construction, *our data do not support this belief.* One or more of these factors may affect a project's schedule, but on average the typical project did not encounter problems with such events that were important enough to

[7]See Baldwin et al., 1971; Budwani, 1982; and Tatum, 1978.

delay construction. In fact, the effects of all external factors account for an average of one month's delay during construction for these projects. No other project phase was appreciably affected. Out of the 56 projects, only 10 suffered any external effects, for an average of about five months, or about 18 percent of their average construction schedule. Six of these ten faced more than one major external event.

Table 5 shows these factors in more detail. For the ten projects that encountered construction delays due to external factors, combinations of unusually bad weather, labor strikes or shortages, and material shortages or delays accounted for substantially all of the slippage. Overall, equipment shortages or delays and labor shortages had larger effects than unusually bad weather or labor strikes. Their effect was larger in months and they consumed larger proportions of the planned and actual construction schedule than any other problems. But when assessing external factors across all 51 projects for which construction schedule data are available, we find the effects to be rather small: All external factors combined accounted for about 16 percent of the average construction schedule delay and amounted to under 4 percent of the time spent during construction. For the ten affected projects, however, these external factors accounted for almost all (82 percent) of the slippage the projects experienced. We therefore conclude that such factors as bad weather, strikes, and labor and equipment shortages typically are minor factors contributing to construction schedule slippage, although they can cause a large effect when they do occur.

MANAGEMENT EFFECTS ON CONSTRUCTION SLIPPAGE

Based upon our earlier work[8] we investigated the effects of certain management practices on construction schedule slippage. Three variables were examined:

- Degree of project definition at start of engineering.
- Extent of planned concurrency between engineering and construction.
- Type of contract used for construction.

Each of these variables represents in large part a discretionary decision by project or corporate management about how the project should be executed. Depending on how quickly management wished to get into the field (or to market with the plant's product), the project would proceed into detailed engineering with more or less project definition

[8]See Myers and Devey, 1984.

Table 5

EFFECTS OF EXTERNAL FACTORS ON CONSTRUCTION SCHEDULE SLIPPAGE

External Factor	Number of Projects Affected	Average Months Delay	Average % Slippage[a]	Average % of Total Slippage[b]	Average % of Total Actual Time[c]
Unusually bad weather	6	2.2	11.9	38.8	8.7
Labor strikes	3	1.8	12.3	33.3	8.0
Labor shortages	4	3.8	19.0	60.2	12.5
Material shortages/delays	4	4.5	20.2	81.9	13.2
Totals	10	5.0	26.2	82.1	17.9
All Projects	51	1.0	5.1	16.1	3.5

[a]Months of external slippage divided by planned months.

[b]Months of external slippage divided by total months slippage.

[c]Months of external slippage divided by total actual months.

accomplished. And it may be expected to proceed into construction itself after some or most engineering was completed. Whether a cost-plus fee or fixed price contract was used depends in part on the availability of contractor services, of course. In periods of high construction activity, contractors may be less inclined to accept part of the project risk through fixed price contract vehicles. But fixed price contracts also require that a higher degree of project definition be completed prior to letting the contract for bid compared with cost-plus contracts. All of these factors reflect management choices. And they strongly related to the degree of success in meeting construction schedules for these projects.

Project Definition

The extent to which the project has been defined on an actual site contributes materially to the accuracy of cost estimates made at each point during the project's development.[9] The accuracy of schedule plans prepared during (or near the end of) the project definition phase should reflect the extent of definition as well. Other things being equal, better defined projects as of the time of schedule development should experience less slippage. Greater understanding of the conditions—including local labor and materials costs, hydrology, and regulatory requirements—specific to the actual plant site should greatly improve the schedule planning as well as its timely execution.

This hypothesis is strongly supported by these data, as Fig. 4 illustrates. The level of project definition at the start of detailed engineering (when most schedules were developed) is related to the construction schedule slippage experienced. These measures correlate at 0.37. Many projects were quite thoroughly defined when detailed engineering began; others were not. This difference reflects a deliberate decision by project or corporate management to proceed in the absence of more complete understanding of the site and process design.

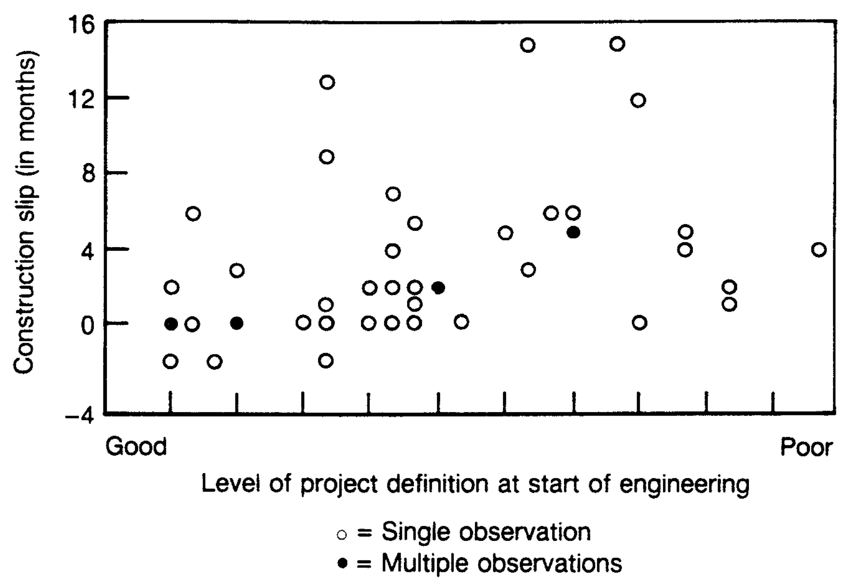

Fig. 4—Relationship between construction slippage and project definition

[9]See Merrow, Phillips, and Myers, 1981, Sec. IV.

Contract Type

The type of contractual scheme for a project's construction phase reflects another important management decision. Where possible, firm fixed-price, or lump-sum, contracting methods are generally preferred. The contractor accepts part of the project's risk and certain responsibilities in such an arrangement. The contractor in essence agrees to complete the job *as defined* within a specified time and cost. The problem in choosing a contract type often lies in how well the job can be defined, and therefore executed. Contract type also reflects to some degree to the level of uncertainty surrounding the project at the start of construction. Uncertainty may be perceived to be too great in cases where important technical or site-related issues remain to be resolved, for instance. In such cases, contractors may refuse to bid on a fixed price basis. The alternative contract type usually involves a reimbursable arrangement, often with a percentage fee. Under such a cost-plus contract, the project owner or sponsor retains responsibility for any risks stemming from remaining uncertainties.

Because the level of uncertainty typically is higher when new, unproven technology is being demonstrated commercially for the first time, or when the project scope has not been thoroughly defined, cost-plus contracts should be more common in such instances. Table 6 supports this view by showing the average number of commercially unproven process steps and the average level of project definition accomplished by the time the schedule estimate was developed for each type of contractual arrangement. Projects that used fixed price contracts (or, more precisely, that were able to use them) were less innovative and had somewhat better project definition. The correlations between cost-plus contracting and the number of new steps and level of project definition are 0.33 and 0.46, respectively.

For these same reasons, problems that delay construction are more likely. And lacking contractual means to assure cost and schedule goals are met, additional delays can become even more likely. Table 7 demonstrates that cost-plus contracts are associated with only slightly greater average construction schedule slippage, however. It also shows that the effect of cost-plus contracting on construction slippage is almost entirely for pioneer plants.

Planned Engineering-Construction Overlap

The construction phase for a typical project begins as soon as practical, while detailed engineering continues. Usually a short time after engineering has started, plot plans and other drawings are sufficiently detailed to permit ground work and foundation-laying to begin.

Table 6

INNOVATION AND PROJECT DEFINITION BY CONTRACT TYPE

Primary Type of Construction Contract	Average Number of New Steps	Average Level of Project Definition[a]
Fixed-price	0.7	3.6
Cost-plus	1.7	4.1
Other	1.3	3.4

[a]2 to 8 point scale: high values indicate lack of process engineering and site definition.

Table 7

CONSTRUCTION SLIPPAGE BY INNOVATION AND CONTRACT TYPE
(Months)

Primary Type of Construction Contract	Standard Plants	Number	Pioneer Plants	Number	All Plants	Number
Fixed price	3.4	7	0.0	2	2.7	9
Cost-plus	1.2	13	5.5	22	3.9	35
Other	1.0	2	1.0	5	1.0	7

Procurement has probably already begun by this time. As construction progresses, engineering produces the drawings necessary for the next stage of plant construction. Such concurrency means that should engineering slip substantially, construction may also suffer. Waiting for engineering to catch up can be a major cause of delay in construction schedules; it was cited by several project managers as a particular problem they confronted during their projects. Sometimes a high priority is placed on "getting into the field" very quickly, often for market reasons, and construction begins earlier than it normally would. In those cases, the engineering schedule has less flexibility or room for delay, because construction is dependent on engineering progressing as planned. Small delays at the wrong time in engineering can lead to costly slips in construction. In the end, a project that is rushed into the field prematurely could take longer to reach market than if it had not been fast-tracked.

Of course, some overlap or concurrency between detailed engineering and construction is normal. For the projects in our database, Table 8 shows the average planned overlap was about eight months. This means that on average, engineering was expected to last another eight months after the start of construction. In four cases, however, engineering was expected to be completed by the time construction began, while in 11 other projects, engineering and construction overlapped a year or more.

Measured as a proportion of expected total engineering time, this average eight-month overlap represents over 40 percent of the estimated engineering schedule. In other words, the typical project began construction field work when detailed engineering was believed to be about 56 percent complete (measured as a fraction of time only).

Table 8

PLANNED ENGINEERING AND CONSTRUCTION OVERLAP

Expected Concurrency Between Engineering and Construction Phases	Average	Median	Standard Deviation	Range	Number of plants
In months	8.2	7.0	6.4	(-4) to 24	51
As percent of planned engineering time	44.3	47.9	31.3	(-100) to 92	46
As percent of planned construction time	39.4	37.5	32.8	(-100) to 111	51

This varied considerably, however. Often, as we shall see, engineering was not as far along as was believed. Viewed as a percentage of planned construction time, the initial 40 percent of the construction phase was expected to overlap with the last part of detailed engineering for the average project in the database. The cases ranged from those where engineering was expected to be completed before construction began to some where the two phases were planned to be executed essentially simultaneously.

Construction Slippage and Planned Engineering-Construction Overlap

Rushing into the field before sufficient engineering work has been completed has been hypothesized as a major cause of construction slippage. We examined this notion using the experience of the projects in our database. Construction can be delayed while waiting for engineering (drawings and the like) to catch up. Five projects specifically mentioned this type of situation as a cause of construction delay. These five projects planned to execute between 40 and 92 percent of the engineering schedule after the start of construction; an average of less than 28 percent of the planned engineering schedule had been completed by the beginning of construction. The planned engineering-construction phase overlap averaged nearly a year. Some of the comments offered are instructive:

- "Project schedule did not allow for complete engineering before start of construction."
- "Delays in defining the process led to starting construction in the winter."
- "Engineering was a bottleneck. Construction was ahead of drawings and continuously expedited design."
- "The urgency of the schedule caused design to proceed with many 'holes' that later created major complications."

Only one of the projects that cited excessive engineering-construction concurrency managed to expedite engineering sufficiently to keep construction on schedule. (This was also the only one of the five where the firm had experience building similar units.) The other four suffered slippage of between three and seven months.

Figure 5 shows the relationship between construction slippage and planned engineering-construction overlap for all 51 projects. The two variables appear to be unrelated to each other until the planned concurrency reaches eight months or so. After that, slippages increased in direct relation to the number of planned concurrent months. Those 23

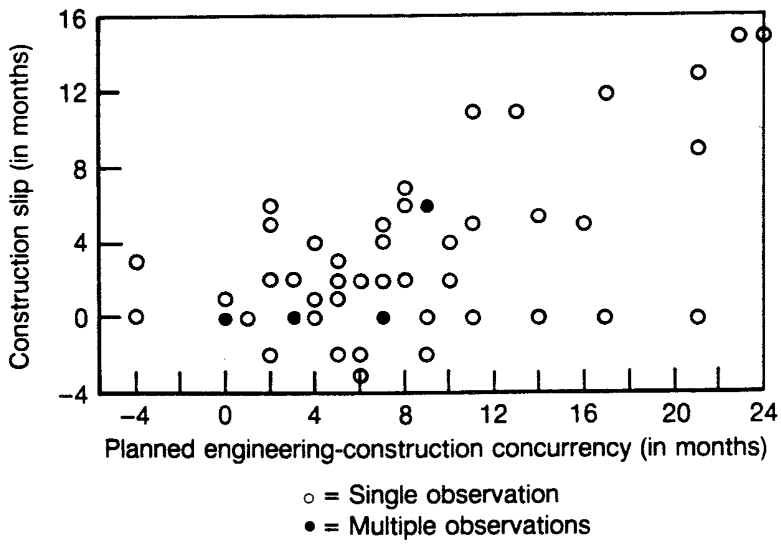

Fig. 5—Construction slippage and planned engineering-construction overlap

projects with planned concurrency of eight months or more planned to complete only about a third of the scheduled engineering time before the start of construction. For the other 28 projects, just the opposite was true: Almost three-quarters of the scheduled engineering time was expected to be finished before construction began. Table 9 summarizes this relationship. The evidence suggests that planning more than about seven months of concurrency between engineering and construction is associated with substantial slippage in construction.

This relationship is especially pronounced for first-of-a-kind facilities. In fact, two-thirds of the projects with planned concurrency between engineering and construction of eight months or more were pioneer plants. It is the innovative plants that suffer the greatest penalty for excessive overlap. Figure 6 demonstrates this relationship clearly.

Table 9

CONSTRUCTION SLIPPAGE AND PLANNED ENGINEERING-CONSTRUCTION OVERLAP

Planned Engineering-Construction Overlap	Average Months Slippage	Range	Number of Plants
Less than 8 months	1.2	(-3) to 6	28
8 months or more	5.5	(-2) to 15	22

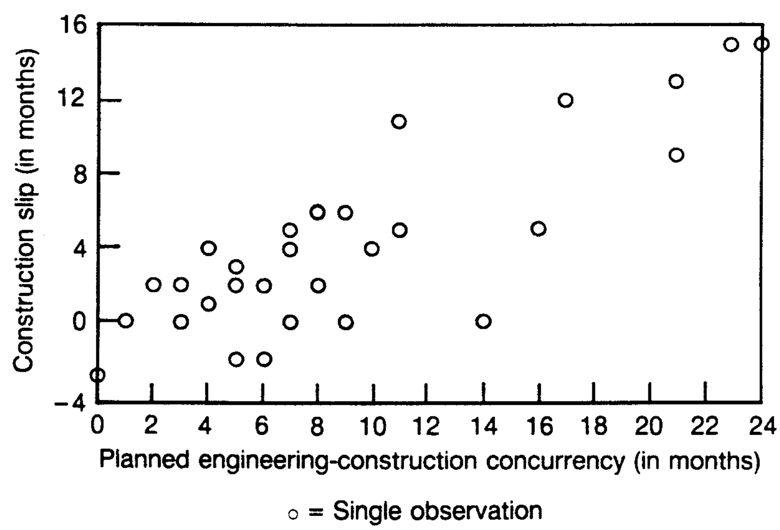

Fig. 6—Pioneer plant construction slippage and planned engineering-construction overlap

CONSTRUCTION SLIPPAGE AND TECHNICAL PROJECT CHARACTERISTICS

Besides external factors and management approaches, we also investigated the effects of certain technical project characteristics. These variables were suggested by our review of the literature and by experienced industry personnel; they included measures of plant complexity, the primary type of feedstock, and the level of technology innovation. We found that construction slippage was moderately related to complexity, measured as the number of process steps or blocks in the plant; to the use of unrefind solid feedstock; and to pioneer technology. These relationships are shown in Tables 10–12. Table 10 shows that the seven plants that used raw solid feedstocks, such as mineral ores or tars, experienced an average of seven months delay during construction, or more than twice the average for the plants that used other feedstock types. This factor proved to be one of the most useful predictors of the extent of construction schedule slippage, even after other such factors as project definition and planned engineering-construction overlap are accounted for. As will be seen below, an indicator for raw solid feedstock plants is used as an explanatory variable in the regression model for construction slippage.

Table 10

MATERIALS PROCESSED AND CONSTRUCTION SCHEDULE SLIPPAGE

Type of Material Processed	Average Months Slippage	Range	Number of Plants
Liquids or gases	2.9	(-3) to 13	18
Solids--not as feedstock	1.9	(-2) to 12	14
Refined solid feedstock	3.3	(-2) to 11	12
Raw solid feedstock	7.0	0 to 15	7

As we would expect based on earlier research, pioneer plants typically experienced greater construction schedule slippage than did plants that used commercially proven technologies. First-of-a-kind facilities averaged more than twice as much slippage as the standard units, as Table 11 indicates. Finally, Table 12 shows the correlation between schedule slippage and plant complexity to be a weak 0.27, which, although statistically significant, cannot be called a major influencing factor.

Table 11

TECHNICAL INNOVATION AND CONSTRUCTION SCHEDULE SLIPPAGE

Plant	Average Months Slippage	Range	Number of Plants
First of a kind	4.3	(-2) to 15	29
Standard unit	1.9	(-3) to 11	22

CONSTRUCTION SCHEDULE SLIPPAGE REGRESSION ANALYSIS RESULTS

Table 12 also lists the correlations between slippage and several other factors that have already been discussed. Construction delays other than those due to external factors are associated with poor project definition, long overlap between planned engineering time and the construction phase for pioneer plants, and unrefined solid feedstock plants. These factors were introduced in various combinations as independent variables in successive ordinary least squares (OLS) linear multiple regression analyses in an attempt to identify the best fitting explanatory model (the one that minimized predictive error and maximized predictive power, and did so robustly without undue influence being exerted by one or two outlying observations). The final regression model is shown in Table 13.

Construction schedule delays are directly related to three important factors:

Table 12

CORRELATIONS BETWEEN CONSTRUCTION SLIPPAGE AND PROJECT CHARACTERISTICS

Characteristic	Correlation	Significance
Complexity (block count)	.27	.05
Output capacity (log)	.09	--
Pioneer plant (yes/no)	.33	.009
Cost-plus construction contract	.27	.02
Planned engineering-construction overlap	.60	.0001
for pioneer plants only	.73	.0001
Planned overlap as percent of planned construction time	.45	.001
Level of project definition	.37	.01
Unrefined solid feedstock	.37	.009

-- not significant.

- Poor project definition at the start of engineering when the schedule is developed.
- Long planned concurrency between detailed engineering and construction for pioneer technology plants.
- The use of unrefined solid plant feedstocks.

The model suggests that for projects like those in the database (which encompasses a wide range of plant types), the construction schedule developed near the end of project definition will slip more than two months if the process involves an unrefined solid feedstock; if it is a pioneer plant, it will slip about a week and a half for every month of planned overlap with engineering; and it will slip as much as seven months more, depending on the level of project definition accom-

Table 13

REGRESSION MODEL OF CONSTRUCTION SCHEDULE SLIPPAGE

Variable	Coefficient	t-statistic
Intercept	-3.147	-2.5
Level of project definition at start of detailed engineering (2=full; 8=none)	0.969	3.2
Planned engineering-construction overlap (pioneer plants only)	0.419	7.1
Unrefined solid feedstock (yes/no)	2.212	2.0

R^2 = 0.65

Standard error of estimate = $\pm$ 2.57

Number of projects = 47

plished when the schedule was developed (around the start of detailed engineering).

The model captures about two-thirds of the variation in construction schedule across the 47 projects for which complete data were available, with a standard error of ± 2.5 or so months. This again suggests strong similarities in the factors driving construction delays across the projects and their sponsoring firms. These results also indicate that most construction slippage is predictable using very limited information available well before construction actually begins.

To a large extent, the results also point to key independent factors that drive construction delays and that could in many cases be avoided with appropriate planning. In particular, this analysis highlights the need for scheduling flexibility when planning to commercialize new technology for the first time. The statistical analysis suggests several conclusions for project scheduling:

- The choice of building facilities that involve unrefined solid feedstocks brings with it the likelihood of a certain amount of unexpected delay during construction.
- The management decision to invest in more thorough project definition before proceeding to detailed engineering usually results in more accurate construction scheduling.
- The decision about when to begin construction relative to the expected progress of engineering should be made more carefully for pioneering ventures. Pushing such a project into the field early can prove costly because it will probably take longer to complete in the end than expected.

APPLICATIONS OF CONSTRUCTION SLIPPAGE MODEL

Figure 7 illustrates three applications of the model for projects at different levels of project definition, innovation, and planned engineering-construction concurrency. A plant employing liquid, gas, or refined solid feedstock is used for these examples. Hypothetical Project A is well-defined by the start of detailed engineering, with a rating of 3. (The project definition scale ranges from "2" for full site definition and completed process engineering work to "8" for no site definition and conceptual process engineering.)[10] Project A uses a commercially proven technology. The model predicts that this project will stay pretty much on schedule (absent any external factor effects). Project B involves a first-of-a-kind technology. The project definition level is comparable to that of Project A and has a rating of 3 as well. An overlap of only six months is planned between engineering and construction. The model predicts that Project B will slip about two months during construction. Project C illustrates the effects of poor definition and planned long concurrency between engineering and construction. This project also represents a pioneering technology being commercialized for the first time. The model predicts that Project C will slip by more than seven months during construction.

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[10]See Merrow, Phillips, and Myers, 1981, for further discussion of this factor and its measurement.

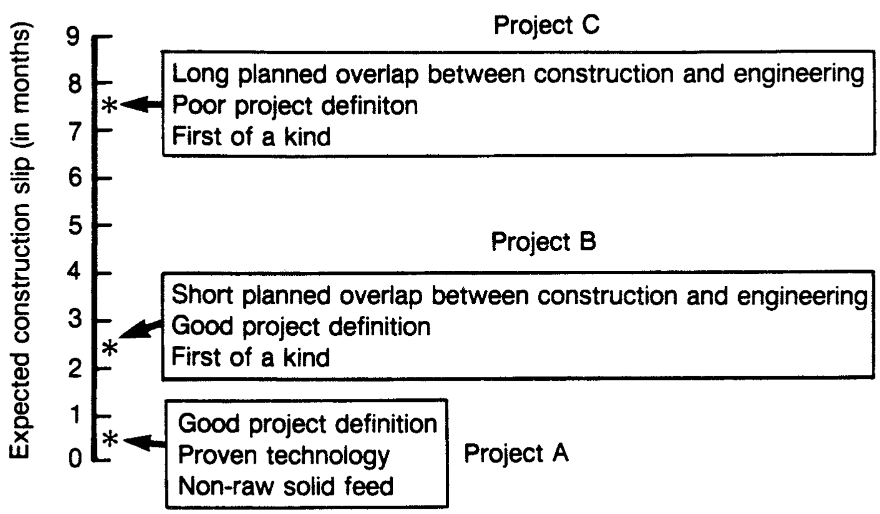

Fig. 7—Illustration of construction slip model applications

III. UNDERSTANDING STARTUP TIME AND COSTS

INTRODUCTION

Startup is a critical period for any new process plant. The economic viability of a project often hinges on the speed and costs of getting the plant up and operating after mechanical completion. As with schedule slippage during the construction phase, delays of any kind reduce the return on investment, and any unforeseen problems that occur during startup usually cause delays. For example, if a major equipment item fails it may have to be replaced, requiring unexpected capital expenditures, but also delaying startup until the replacement equipment can be procured and installed. Problems arising from discrepancies between engineering designs and the plant as actually constructed may emerge only during startup, and then require expeditious resolution under adverse conditions. For an innovative plant, the most important process test and evaluation occurs during startup. For all plants, startup represents the ultimate proof that the design and construction were competently executed. Errors in earlier phases unobtrusively cumulate, only to emerge during startup—and often with a vengeance. Delays in startup are usually more critical than they are during construction because they postpone the time when any return can be made on the capital investment already in place. Meanwhile, raw materials may be wasted and market commitments or opportunities missed.

The problem is that startup time and costs are often much higher than expected, especially for pioneer plants. Startup time is usually assumed to be brief. Startup costs are typically estimated as a small percentage of total projected capital requirements. Almost universally, they are assumed to be minimal, and in many cases trivial compared with the investment through mechanical completion. For plants constructed as near duplicates of existing facilities, the startup effort usually poses no special difficulties, and these turnkey cost assumptions may be reasonable.

Experience with pioneer plants, however, suggests that these assumptions are rarely satisfied when trying to estimate startup time and costs for innovative facilities. Startup is often a difficult period for these plants and may last for many months. A major portion of capital cost growth often occurs during startup efforts for technically advanced plants. Frequently, it is not until construction has been completed and startup attempts begun that the need for additional or modified equipment to make the plant operate is recognized.

There are many explanations for prolonged and costly startups. For example, the need for a clean-up step may not become clear until the plant is mechanically completed and started because uncertainties in the new technological process lead to greater than expected waste handling difficulties. The unexpected costs involved can often result in considerable cost overruns—amounting to a major share of the total capital requirements. These difficulties can also greatly delay plant operations. Failure of the process developers to communicate adequately with the design engineers could result in critical design flaws that become apparent only during startup. And if R&D personnel are not present during startup, these and other design problems may not be readily solved by an operating crew not yet intimately familiar with the new process.

Based upon our review of the literature and discussions with experienced process industry personnel, we hypothesized that long, costly startups are associated with:

- First use of new technology.
- Materials handling difficulties, often involving solid feedstocks.
- Project management approach and handoff problems.

We found startup costs and time to be primarily a function of the level of technological innovation, measured in several ways, and secondarily related to material handling difficulties, the use of unrefined solid feedstocks, and the failure to employ a management team approach that involves R&D, engineering, and operations personnel from the project's outset.

DEFINING STARTUP TIME AND COSTS

Although the purpose of the startup period, "to get the money back into the bank as soon as possible,"[1] is clear enough, its definition is not always as obvious. To measure the startup of different plants on a consistent basis, standard definitions of startup period and startup cost have to be established. To do this, we asked each firm providing project data to explain their company's definitions of startup, reviewed published literature, and consulted accounting industry standards. Substantial agreement on the general analytic components of startup emerged from this process.

[1]Matley, 1969, p. 110.

Startup Period

Startup time can be measured more easily than its costs. The startup period begins with the introduction of feedstock following the end of construction and preoperational testing, and continues until fairly steady performance is achieved and the startup crew turns the operating plant over to the regular operating staff. Feldman suggests that this endpoint can be measured in three distinct ways:

> The beginning of "normal" operations [and thus the end of startup] may be defined differently for each project: as operations at certain percent of design capacity, as a specific number of days of continuous operation, or as the capability for making a specified product purity.[2]

Firms take various approaches in defining the startup period for pioneer plants. For accounting purposes, many companies specify a set of circumstances that must be achieved before the plant is considered officially operational. This approach also provides a specific goal for the startup personnel. Many times, especially with innovative technologies, a prespecified startup period is redefined as the startup team learns more about the limitations of the process. In these instances, the end of the startup period may be justified on grounds other than those cited by Feldman.

Because much of our emphasis will be on pioneer plants, many of which are slow to attain design capacity (or never achieve it), our definition of startup time cannot rely on design performance as its endpoint. Instead, we have used the point at which the plant achieves some degree of steady operations or is turned over to the operating crew as a reasonable cutoff point. This criterion provides a clear termination date for startup for most projects.

Startup Costs

There is general agreement on what constitutes startup costs, but as these examples suggest, it may not be as easy to measure them:

> The time, manpower, and materials needed to bring a plant up to design conditions result in costs beyond those needed solely to construct the plant and to operate it routinely after it is built. These are plant startup costs, which are often defined as those plant-associated costs incurred after construction in excess of 'standard' production costs needed to bring the unit to budgeted levels of production rate, quality, and operating costs.

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[2]Feldman, 1969, p. 419.

> Startup costs are those costs incurred between the end of construction and the start of normal operation, less estimated standard costs (i.e., costs that would have occurred during an equal period of normal operation).[3]

Measuring startup costs is largely an accounting problem involving three elements: *capitalized costs* (e.g., for installation of major new equipment items), *expensed costs* (e.g., for startup personnel) and *normal operations costs* (e.g., for raw materials and operators).[4] Company policy in the face of changing tax laws often blurs the distinction between capitalized and expensed costs, however, and we need not depend on this distinction for analytic purposes. The important distinction is between standard, or normal, operating costs, and "only those costs directly related to getting a new production facility into operation."[5] Because operating costs can vary widely from one type of plant to another, and these costs may be incurred during the startup period as well, ideally they need to be removed from the total costs of startup for purposes of analyzing startup costs alone. We have obtained most startup costs for the plants in the database excluding lost feedstock, missed sales, and operating costs.

We must first understand how firms deal with startup costs, both in estimating them and in accounting for any actual costs incurred. Many firms did not include an allowance for startup in their capital cost estimates for the projects in the PPS database; startup costs were not charged to the project's capital budget. Instead, they often are included as part of the plant's initial operating budget and therefore represent expensed rather than capitalized costs. Because expenses are fully deductible for tax purposes during the year in which they were incurred, whereas capital costs must be amortized over several years, there is an understandable incentive to try to expense rather than capitalize as much of startup as possible. Company policies in this regard vary widely, however, and also vary over time in the face of changing tax laws.

To understand and predict all costs to startup, however, regardless of this accounting problem, we have obtained additional information on startup expenses for most plants in the database to augment the data we have for the capitalized portion of startup. The capitalized portion of startup costs dominate, in any event. The expensed portion exceeded the capitalized portion of startup costs in only five instances. In our analysis we have included all costs of startup, capitalized and expensed. In most cases, this distinction was not important because

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[3]Malina, 1980, p. 167.

[4]Operating costs are also expensable charges.

[5]Feldman, 1969, p. 418.

almost all major startup costs were capitalized. In fact, an average of almost 80 percent of the total costs of startup represented charges to projects' capital budgets. Where capitalized startup costs were incurred, they usually represented expenditures for replacing or redesigning major pieces of equipment.

THE STARTUP PROBLEM

Table 14 shows the distribution of startup time and costs, in addition to startup costs as a percentage of capital spent through mechanical completion for the plants in the database. In the analyses that follow, we will examine the factors driving two project outcomes: actual time for startup and all startup costs as a percent of capital costs through mechanical completion. These represent our two dependent variables.[6] The data in Table 14 evidence the wide variety in startup time and costs encountered among these plants. Startup required anywhere from practically no time at all to over two and a half years. Startup costs, including both capitalized and expensed portions,

Table 14

SUMMARY STATISTICS ON STARTUP MEASURES

Measure	Mean	Median	Standard Deviation	Range	Number of Plants
Months of startup	8.0	4.0	8.9	0 - 30	53
Startup costs as % of capital through construction	5.5	3.6	6.1	0 - 20	51

[6]Information is missing on the startup time and costs for three of the 56 plants in the database. Startup costs are not available for another two facilities. In addition, four cases with startup costs ranging from 26 to over 60 percent of capital through mechanical completion posed a special problem: Separately and together, they exerted a distorting influence on our analysis (measured, for example, by Cook's Distance statistic). Further investigation confirmed that the costly difficulties these units encountered warranted their inclusion in the analyses as unusual but not completely exceptional projects. We therefore set the value of startup costs for these four plants to 20 percent. This value is about one standard deviation above the next lower value and permits us to retain these four plants in our analysis without having them unduly distort the results.

amounted from nothing to over $150 million (in mid-1980 dollars), and ranged up to 20 percent (or more) of the capital already spent through the end of construction.

Our analysis of startup time deals with the actual time required to reach (more or less) steady-state operations, or the point at which the plant was accepted by plant operations. Startup efforts sometimes continued almost indefinitely. In these cases, we have limited our startup time measure to 30 months or less to avoid having these outliers unduly influence or distort our analysis. And unlike the preceding examination of construction schedule slippage, we do not focus here on the difference between actual and planned startup time. We do this because startup schedules tend to assume very brief and smooth startups, even for pioneer facilities. This assumption often proves adequate for established technologies that process primarily liquid and gas feedstocks, as we will see. In other cases, however, such plans are overwhelmed by long, drawn-out efforts to start the plant. Actual startup time is generally a better measure of the startup schedule than startup slippage. This is further indicated in Fig. 8, which shows the weak relationship between actual and planned startup time. (Single observations are indicated by the hollow points, multiple observations are indicated by the solid points.) The solid line represents a regression line fitted to the observations.[7] If planned startup time predicted actual startup time on a one-for-one basis, the line would approach a 45° slope and the points would cluster closely to the line. The line is fairly flat, indicating that knowing the planned startup time tells us very little about the time actually required.

UNDERSTANDING STARTUP TIME

Here we discuss several relevant characteristics of projects that suffered long startups and compare them with projects that started up smoothly and quickly. Startup delays are costly and usually indicate an inability to reach timely performance goals. We direct particular attention toward technologically innovative plants and on those using solid feedstocks because those projects tended to have the greatest difficulty in meeting startup and early performance expectations. We investigate the effect of using a project management team that integrates representatives from R&D, engineering, and operations. We then present the results of a linear multiple regression analysis that identifies the significant independent factors explaining the time

[7]The equation took the form $\hat{y} = 2.7 + 1.8x$, where $\hat{y}$ is the predicted startup time and x is the planned startup time.

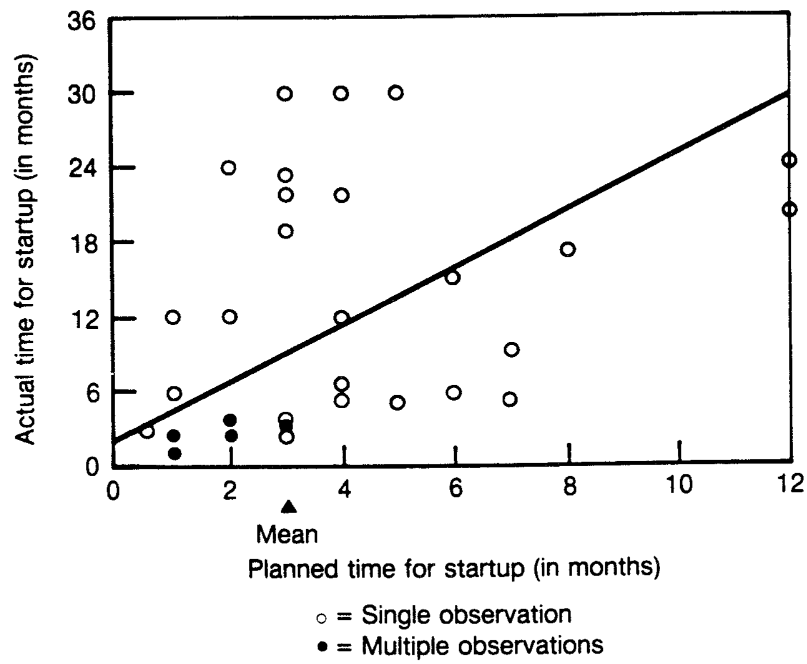

Fig. 8—Relationship between actual and planned startup time

needed for plant startup. In part because unexpected delays in startup are usually associated with higher than expected startup costs, many of the results presented here parallel the results reported on the following analysis of startup costs.

Startup Delay and Plant Performance

Delays in startup are strongly related to poor plant performance. To a large extent, they are measuring the same phenomenon when a plant is experiencing early operational problems. Generally, the longer it takes to reach performance capacity, the greater the unexpected time and costs required for startup. Table 15 portrays the level of design capacity achieved during each three-month period following the beginning of startup, according to the amount of startup time required. Performance for all plants improved over the course of the first year after startup, with most operating at nearly 80 percent or better by year's end. Plants that started up within the first month were operating at

Table 15

AVERAGE PERCENT OF DESIGN CAPACITY ACHIEVED AFTER STARTUP

Months of Startup	Months 1-3	Months 4-6	Months 7-9	Months 10-12
0 - 1.5	70	79	84	91
2 - 3	40	55	74	80
4 - 12	38	62	73	80
13 - 30	10	22	30	35

an average of more than 70 percent of capacity within a few weeks. Plants that required up to a year for startup operated at a somewhat lower rate until the end of the year, when they reached an average of 80 percent of design. But the units that failed to achieve startup within the first year were on average operating at only about one-third of capacity in the second half of the year. Average improvement for these units was slow through the year. Two of these plants were unable to produce any output during the first year.

Because startup time and early plant performance are closely related, we expect that the factors driving performance shown in earlier PPS research should strongly influence plant startup. These factors included the number of commercially unproven process steps, the portion of the heat and material balances based upon previous commercial units, and materials handling difficulties, reflected in process development and use of solid feedstocks.[8]

PROBLEMS ENCOUNTERED DURING STARTUP

Startup is a period of minor equipment debugging and process adjustments for all plants. Many plants encounter more serious problems, of course, including equipment breakdowns and failures in the process design. Equipment problems appear to be the most common cause of startup difficulties and delay. Holroyd, for example, found

[8]See Merrow, Phillips, and Myers, 1981, Sec. V.

that 61 percent of startup problems were related to equipment deficiencies, 10 percent to design inadequacies, 16 percent to construction shortcomings, and 13 percent to human error. Finneran, Sweeny, and Hutchinson (1968) found that equipment problems accounted for over half of all startup troubles. Gans (1976) reported that equipment failures were responsible for three-quarters of all startup delays, with another 20 percent attributable to inadequate equipment and the remainder to process failures.

Equipment problems in general are fairly easy to resolve provided replacement units are readily available and the problem stems from improperly manufactured equipment rather than design failures. Design failures, however, stem from causes fundamental to the process itself and are more difficult to remedy. When the process fails to perform as expected, it usually reflects inadequate understanding of the process itself, especially when new processes or equipment are involved.[9] It may result from incomplete R&D, overreliance on small-scale units or theoretical modeling, or inadequate communication among process developers, designers, and operators. Faulty process assumptions incorporated into the design of new units may result in major equipment or material failures as well.

Our data are largely consistent with the findings reported by other researchers, although a larger proportion of the plants in our database reported design failures, undoubtedly because of the predominance of new technology plants in the database. Thirty of the 53 plants encountered what their owners termed "major problems" during startup. Equipment failures were cited in about as many cases as were design failures. But the combination of equipment and design failures was cited almost twice as often as either problem alone. Table 16 shows that among the 30 plants encountering major startup problems, 27 percent experienced only equipment breakdowns, 27 percent met with design failures, and another 47 percent experienced both. A few owners reported problems stemming from inadequate operator training, supervision, or operator errors, but these were minor problems that did not greatly affect the overall startup effort. Table 16 also shows the average startup time required for plants in each problem category. Plants that encountered major design problems experienced considerably longer startup times than other plants, especially if they were accompanied by equipment breakdowns as well. The longer startup times probably reflect how difficult such problems are to remedy.

In extreme cases, a major design change may prove necessary during startup. Such a change indicates the need for departure from the

[9]See, for example, Fulks, 1982; Malina, 1980.

Table 16

EFFECT OF STARTUP PROBLEMS ON STARTUP TIME

Problem	Number of Plants	Average Startup Time (Months)	Standard Deviation	Range
None	23	2.4	1.8	0 - 6
Equipment failure	8	4.5	4.5	1 - 15
Design failure	8	11.0	10.0	2 - 29
Equipment and design failure	14	17.4	9.0	3 - 30

process configuration or operating conditions assumed in the original design. They result generally from inadequate process understanding. Such design changes are far more likely to occur where technological advance is taking place, or where commercial information and experience are lacking. Major design modifications are usually associated with much longer startups. One-fifth of the plants in the database experienced major design changes during startup. This proved much more common for the pioneer plants. In fact, only two of these 12 plants were not first-of-a-kind units. These two fairly standard plants encountered major equipment failures that necessitated their entire redesign, but that did not greatly delay startup for these plants. For the other 10 plants with major design changes, startup time was substantial, averaging more than a year, as Table 17 shows. Moreover, major redesign was typically required for plants that encountered design failures in combination with major equipment breakdowns.

STARTUP TIME AND INNOVATION

Experience is the most frequently mentioned asset to managing a successful startup in the literature we surveyed. It is not simply experience with plant startups, but with the process being started up. The personnel must be experienced enough to assess whether the process is working and react quickly without totally relying on the myriad

Table 17

STARTUP TIME AND MAJOR DESIGN CHANGES

Major Design Change Required During Startup?	Average Startup Time (Months)		
	All Plants	Standard Plant	Pioneer Plant
No	6.0	2.6	9.9
Yes	14.8	2.0	15.9

of flowsheets and other documents that accompany the project. Fulks (1982) even suggests that an inexperienced organization will require 40–50 percent longer to start up a plant than an experienced one.

Table 18 shows the relationship between startup time and the firm's experience with the technology.[10] The most important distinction in Table 18 is between the startup time required for the pioneer plants and that required for the others, regardless of whether this was the first time the firm or any other had built a plant with that technology. Using a similar measure indicating whether the company had built the same type of unit before, the average startup time was less than three months; if not, startup averaged more than three times longer.

As we would expect, pioneer plants also suffer design failures more often, especially in combination with equipment breakdowns, than plants that use proven technology. Table 19 shows this distribution. Most of the cases that did not encounter major startup problems were standard units. Half the plants with equipment failures only were standard plants. And all but three of the 21 plants with design failures—with or without equipment problems—were first-of-a-kind facilities. The effect of experiencing these problems in a pioneer unit can result in much longer startup, as shown in Table 19. Pioneer plant startup time is much longer in every problem category. Standard plant startup exceeded five months in only the single case where both design and equipment problems also occurred with established technology. Even this plant was not an entirely standard unit, however, as it represented the largest plant of its type in the world when it was built.

[10]Data are insufficient to assess the effects of key personnel, such as the project manager and startup supervisor.

Table 18

TECHNOLOGY EXPERIENCE AND STARTUP TIME

Facility	Average Startup Time (Months)	Range	Number of Plants
First of a kind	12.1	0 - 30	30
First time built in the United States or Canada	2.6	2 - 4	6
First time built in the United States or Canada by this firm	2.2	1 - 6	9
None of the above	3.0	0 - 9	8

Innovation appears to be the single greatest factor associated with startup time. Whether or not a plant is a pioneer facility is clearly an important factor in explaining the length of startup, as we have seen. But certain aspects of innovation are particularly important as well. One of these is the degree of technological advance involved. This can be seen in Fig. 9, which shows the average length of startup according to the number of process steps that have not been demonstrated in commercial use before. Each category contains wide variation, and that variance grows somewhat with the number of new steps being introduced in the plant. Even so, the number of new steps closely parallels the average time required for startup. The average startup time is about five months with one new step, a year with two or three, and over a year and a half with four or more new steps.

A second important aspect on innovation influencing the length of plant startup concerns the basis on which the plant heat and material balances were initially established. To the extent that they were based upon commercial plant experience, the shorter the time required for startup, as Fig. 10 shows. Reliance on theory or development facilities is strongly associated with longer startup. Average startup time declines dramatically with an increase in the proportion of the balance equations based on commercial units. The range of startup time decreases proportionately as well.

Table 19

DISTRIBUTION OF STARTUP PROBLEMS AND TIME: PIONEER VS. STANDARD PLANTS

	Number of Plants		Average Startup Time	
Problem	Standard	Pioneer	Standard	Pioneer
None	15	8	2.1	2.4
Equipment failure	4	4	1.8	7.3
Design failure	2	5	2.5	10.8
Equipment and design failure	1	13	9.0	18.3

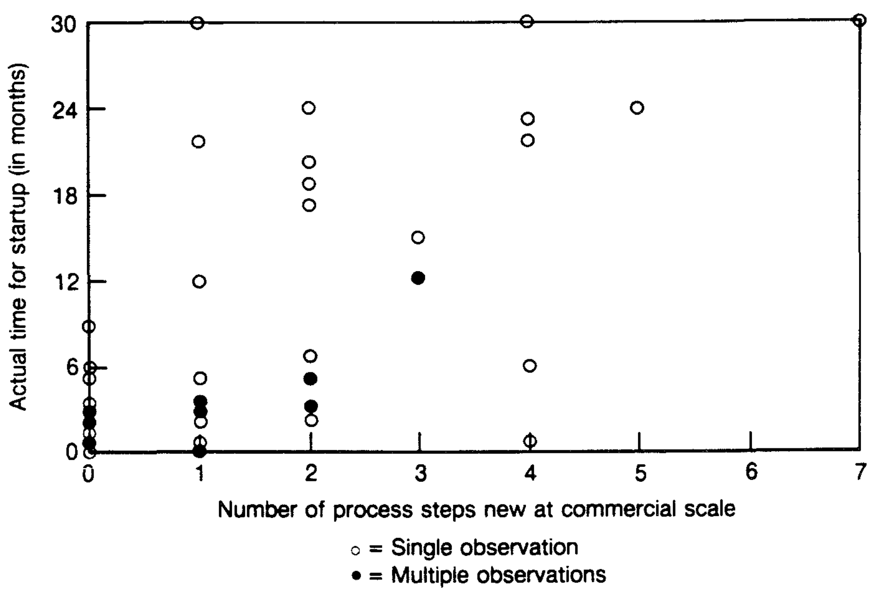

Fig. 9—Startup time and the number of new steps

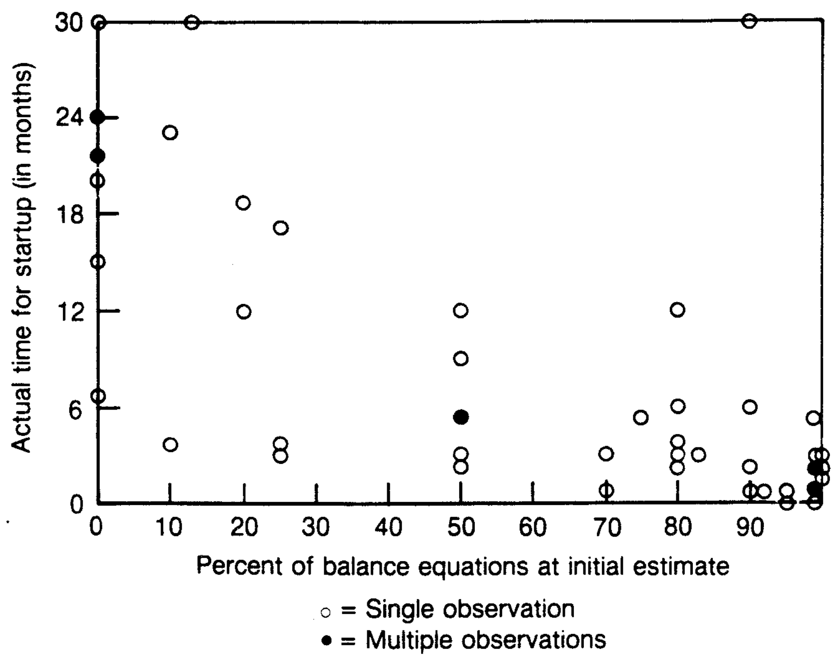

Fig. 10—Startup time and knowledge of H&M balances

The effects of innovation and experience are especially evident in the types of startup problems they are associated with. Table 20 shows the average number of commercially unproven steps and the proportion

Table 20

STARTUP PROBLEMS AND DEGREE OF INNOVATION AND EXPERIENCE

Problem	Average Number of New Steps	Average % of H&Ms Based on Previous Plants
None	0.6	80.6
Equipment failure	1.0	50.4
Design failure	1.8	50.0
Equipment and design failure	2.9	20.9

of the balance equations based on previous commercial units for each type of problem encountered during startup. Design problems, especially those accompanied by equipment failures, are strongly associated with the degrees of new technology and reliance on noncommercial experience in calculating the balance equations. Furthermore, major design changes during startup are associated with both measures of innovation. Plants requiring major design changes during startup had an average of twice as many new steps (2.5 rather than 1.1), and no less than one-half as much of the balance equations based on previous commercial units (29 percent rather than 66 percent).

STARTUP TIME AND MATERIALS HANDLING PROBLEMS

Longer startup time is also associated with difficulties encountered during process development and design. This relationship is especially pronounced for materials handling problems, as Table 21 shows. The more difficulty experienced with chemistry-related issues and materials handling problems, the more the time spent during startup. This is especially true for pioneer facilities that faced materials handling issues.

Table 21

STARTUP TIME AND DEVELOPMENT DIFFICULTIES

Average Level of Difficulty Encountered During Development[a]		Average Startup Time
	None	4.5
Chemistry-	1	7.4
Related	2	9.9
	3 +	11.0
	None	4.5
Materials	1	3.9
Handling	2	10.3
	3 +	14.3

[a]Values have been rounded to nearest whole number from average of scales ranging from zero: "No problem," to five: "Major problem."

Startup Time and Solid Feedstock Plants

One of the important factors found to be related to poor performance in the Pioneer Plants Study was whether a plant processed solid materials.[11] Solids processing facilities perform much worse than plants handling only liquids and gases. Further analysis has revealed that this problem is especially true for plants that use solid feedstocks, rather than processing solids only in an intermediate step.

Given the strong relationship between poor performance, unexpectedly high startup costs, and startup delays, it should not be surprising to learn that plants with solid feeds also suffer longer startups. These plants required an average of 12 months to start up, against an average of almost six months for plants using only liquid or gas feedstocks. Long startup phases were especially frequent for the first-of-a-kind solid feed plants. In fact, *none* of the 11 solid-feed pioneer plants used in this analysis met their startup schedules. Pioneer plants using unrefined solid feeds suffered the longest startups of all, as Table 22 shows. None of these facilities started up in less than a year.

STARTUP TIME AND PROJECT MANAGEMENT STRUCTURE

Earlier Rand research suggested the importance of using a particular management structure to facilitate communication and problem antici-

Table 22

PIONEER VS. STANDARD PLANT STARTUP TIME BY TYPE OF MATERIALS PROCESSED
(Months)

Materials Processed	All Plants	Standard Plants	Pioneer Plants
Liquid/gas feedstocks			
Liquid/gas processing only	7.8	3.4	10.8
Solids processing	2.6	1.8	4.0
Solid feedstocks			
Refined solid feedstocks	11.0	3.0	14.4
Raw solid feedstocks	14.3	2.2	21.6

[11]See Merrow, Phillips, and Myers, 1981, pp. 65–84.

pation for innovative projects.[12] These results are confirmed here using a somewhat larger database in Table 23, which shows the effect of using a representative management team on startup length. Much shorter startup times are associated with use of such a management style, especially for the pioneer projects. The 11 pioneer projects that failed to use such a team or dispersed project responsibility among different parts of the firm experienced startups more than twice as long. The probable explanation is not difficult to understand. Diverse input to project decisions is highly desirable. Especially in projects involving new technology, involvement of a team of representatives from the affected corporate departments is essential to minimize long, costly startups. Such teams are most effective when their members are recognized as having joint responsibility for the project's success. Using a team approach means bringing on board all the groups or divisions that will be involved in the project, and doing so early. These groups include R&D, process development, engineering, construction services, startup, and operations. It is especially important for R&D to remain through startup, and operations to be integrated in project management from the outset. They should be involved in the project throughout its life, not just when problems arise or when their division is about to take over the project. This can greatly reduce hand-off problems during and after startup.

Table 23

MANAGEMENT STRUCTURE AND STARTUP TIME
(Months)

Project Management Responsibility	Standard Plant	Pioneer Plant
Representative team approach used	1.8	7.5
Dispersed--team approach not used	2.8	17.0

[1]Myers and Devey, 1984, pp. 13–16, 25, 27, 29; also see Baker et al., 1983; Morris, 1983.

STARTUP TIME REGRESSION ANALYSIS RESULTS

Variables measuring different aspects and degrees of innovation together with plant feedstock and management team approach indicators were regressed on actual time of startup. Alternative regression models were evaluated using these factors in several combinations. Tables 24 and 25 show two models that proved best at explaining the variance in startup time with the smallest error term. Two variables were statistically significant ($p < .05$) in both models, the number of commercially unproven process steps and the portion of the balance equations based on previous commercial units. In addition, an indicator of feedstock type (raw solid feed versus all others) played a significant role in one model, shown in Table 24. This factor was not statistically significant in other results that used a subset containing the 35 plans for which management data were available. For pioneer plants, the use of a representative management team resulted in significantly shorter startups even after we controlled for the degree of innovation involved (new steps) and the firm's basis for initially establishing the plant's H&M balances. These results are shown in Table 25.

Table 24

STARTUP TIME REGRESSION ANALYSIS
WITH FEEDSTOCK

Variables in Model	Parameter Estimate	t-ratio
Intercept	9.827	5.3
Number of unproven process steps	2.486	4.9
Percent of H&M balances based on previous commercial plants	-0.108	5.2
If plant feedstock is unrefined solid	4.170	2.1
Coefficient of determination:	$R^2 = 0.69$	
Standard error of estimate:	$\pm$ 5.11	
Number of projects = 53		

Table 25

STARTUP TIME REGRESSION ANALYSIS WITH MANAGEMENT TEAM

Variables in Model	Parameter Estimate	t-ratio
Intercept	6.786	5.3
Number of unproven process steps	2.778	5.5
Percent of H&M balances based on previous commercial plants	-0.097	5.1
If representative team approach is used for pioneer project	-5.321	2.7
Coefficient of determination:	$R^2 = 0.70$	
Standard error of estimate:	$\pm$ 5.22	
Number of projects = 35		

These models suggest that, on average for plants in the database, we can expect about 10 or 11 weeks of startup time for each process step in the plant that has not been in commercial use before. In addition, the model predicts an extra month for each ten percentage points of the balance equations that are not based on previous commercial plants. If they are all based on such experience, startup is expected to require between ten and eleven fewer months. Finally, if the plant feedstock is an unrefined solid material, startup should take about four months longer than if the feedstock is some other material; alternatively, failure to use a representative team approach adds more than five extra months to the expected startup time. For an entirely standard plant with no new steps, for which most of the balances are based upon experience with commercial units, and that does not use an unrefined solid feed, the model predicts startup to be almost immediate. Together, these factors explain over two-thirds of the variance in startup time for the plants in the database. And each of the factors is easily known and measured early in a project's development. Even with advanced planning, startup may take longer than desired, but these results provide a method for managers to avoid being unduly surprised and disappointed.

APPLICATIONS OF STARTUP TIME MODEL

Again, it is instructive to illustrate these conclusions with an example. The characteristics of four hypothetical plants will be used to demonstrate the application of the model. A summary of these plants and their predicted startup times are presented in Figure 11. Plant A employs an established technology. There are no unproven process steps, 90 percent of the heat and material balance equations are based on previous commercial plants, and a liquid or gas feedstock is used. Startup time is virtually nonexistent for this type of plant. When a plant has a small amount of innovation (one new process step) and a good deal of commercial experience (75 percent of H&M balance equations are based on commercial experience), then the plant can expect to start up within three months.

Plants C and D are much more innovative than Plants A and B. These plants also illustrate the effects of differing management styles. Plant C, which has two new process steps, little commercial experience (25 percent of H&M balance equations based on commercial experience), and a representative management team, is likely to start up in 10 months. Plant D, which has the same technical characteristics as

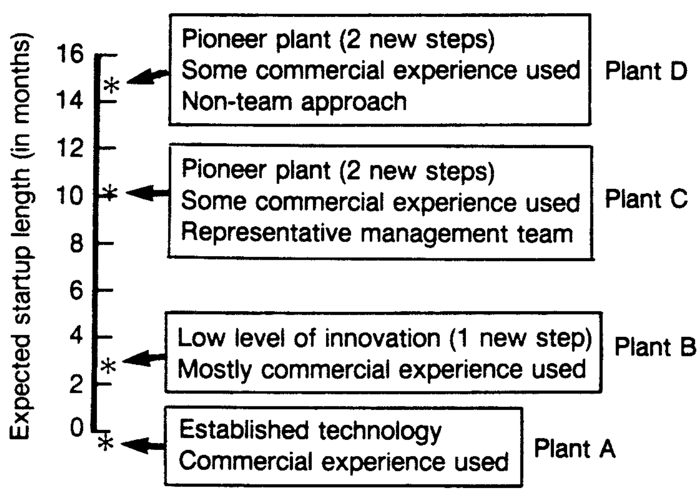

Fig. 11—Illustration of startup time model applications

Plant C, but a nonteam management approach, will take five months longer to start up for a total startup period of almost 15 months. These examples underscore the relative ease with which these models can be applied.

UNDERSTANDING STARTUP COSTS

Previous Research

Although a great deal has been written on cost estimating in general, few authors have addressed the problem of projecting startup costs. Published research can be categorized into three areas:

1. Development of empirical relationships between some measure of startup cost and a set of explanatory variables of those costs;
2. Specification of the component costs of startup activities; and
3. General discussion of problems experienced during startup and their relationship to startup cost.

Unfortunately, because many of the studies in the public literature are not well documented, it is impossible to apply these measures with any degree of confidence. More important, the analysis of *innovative* plants has received little attention in the literature. This shortfall is troubling because the factors that influence startup costs for innovative plants are likely to vary from those affecting more standard plants' startup costs.

Feldman's formula for projecting startup costs is often cited in the literature.[13] In developing a general formula, Feldman isolated five parameters: (1) direct fixed capital cost; (2) newness of the process and technology; (3) newness of the type of equipment; (4) quantity and quality of labor available; and (5) an interplant dependency factor. Feldman was attempting to measure startup cost as a percentage of the total fixed capital cost of the facility. To calculate costs, values are substituted in the equation based on the characteristics of the plant. The equation is as follows:

$$\text{Startup Cost} = A\,[0.10 + B + C + D + N(E)]$$

Where: A = Direct Fixed Capital Costs
B = Newness of Process and Technology
C = Newness of the Type of Equipment
D = Quantity and Quality of Labor Available
E = Interplant Dependency Factor
N = Number of Plants in Process Train

[13]Feldman, 1969.

The four explanatory variables (B,C,D,E) fluctuate as follows:

B = 0.05 if process is radically new,
0.02 if process is fairly new, or
− 0.02 if process is old.

C = 0.07 if equipment is radically new,
0.04 if equipment is very new,
0.02 if equipment is fairly new, or
− 0.03 if equipment is old.

D = 0.04 if labor is in very short supply,
0.02 if labor is in short supply, or
− 0.01 if there is surplus labor.

E = 0.04 if plant is very dependent on another plant,
0.02 if plant is moderately dependent, or
− 0.02 if plant is independent.

Although this technique has been extensively cited and a successful application has been reported, there are several limitations to the use of this formula.[14] First, Feldman notes that the equation applies only to large (1,000–1,400 ton/day) air-separation and ammonia plants. Second, Malina evaluated the Feldman formula and found that the use of the percentage of capital cost did not reliably predict project startup costs.[15]

Malina also derived a formula for predicting startup cost. He categorized projects into four types of plants (new, major modification, minor modification with extensive startup, and minor modification with minimal startup). Seven first-of-a-kind plants were analyzed and relationships between startup costs and two predictors—raw material costs and overhead costs—were developed. Plant complexity, experience with the process, performance guarantees in design and construction contracts, and newness of the technology were listed as important variables but were not included in Malina's analysis.

Malina's analysis suffers from two important drawbacks. First, his startup costs are estimated as a function of the estimated startup time. As we have seen, schedule slippage during startup is very common for innovative technologies and would consequently lead his estimates to be too low in many cases. Second, he encountered a great deal of variance when the factors for operating and overhead costs were applied individually. It is only through averaging these two estimates and

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[14]See, for example, Clark, DeForest, and Steckley, 1971, pp. 25–28.

[15]See Malina, 1980, pp. 167–168.

means for the seven plants that he arrives at his 100 percent prediction accuracy figure.

Derrick and Sutor have developed a more comprehensive method of estimating startup costs.[16] They have used a system that breaks down the costs of startup into subactivities, the costs of which are then estimated and summed to arrive at the estimate of the total startup cost. Derrick, at the time a supervisor of the Economic and Process Evaluation Division of Hooker Chemicals and Plastics Corporation, has utilized this method in estimates of Hooker plants. Derrick and Sutor break down startup costs into seven groups: (1) new fixed capital and maintenance costs over normal costs, (2) startup engineer salaries, (3) foreman and operator training, (4) yield loss and residue disposal, (5) utilities over normal consumed during startup, (6) engineering assistance during startup, and (7) other period costs exceeding normal (e.g., operating supplies, analytical costs, yard and equipment rentals).

The authors argue that this method is extremely accurate, but it assumes that a great deal is known about the plant's operating characteristics. With innovative plants, many of the input variables would require guesswork because data are limited on the specifics of plant operation. Additionally, the level of error increases two or three fold when estimates are merged.

Several authors have generally discussed the problems encountered during startup and their potential effect on costs.[17] Holroyd, for example, found that 10 percent of startup problems were related to design, 16 percent to construction, 61 percent to equipment, and 13 percent to human error. Gans as well as Fitzgerald and Finneran supported Holroyd's conclusion that equipment problems were the most important factor in predicting the success of plant startup. Although these variables are usually discussed in terms of performance during startup, they are also linked with startup costs given the strong relationship between performance and additional cost.

Several observations derive from the startup literature. First, most of the empirical analyses on startup costs were conducted in the late 1960s. No recent studies have attempted to statistically evaluate the factors explaining startup costs. In part, the dearth of published articles can be attributed to the tendency of private companies to consider their data and estimating techniques proprietary. Second, the studies are not well-documented. Applying the results of these studies to

[16]Derrick 1974, pp. 169–175; Derrick and Sutor, 1975.

[17]See for example Finneran, Sweeney, and Hutchinson, 1968; Fulks, 1982; Gans, 1976; Gans and Fitzgerald, 1966; Holroyd, 1967; Matley, 1969; and McCallister, 1971a and 1971b.

specific projects is not easy. Moreover, replicating and verifying the results of the research are extremely difficult. Third, although factors relating to the innovativeness of the process have been mentioned in the literature, few authors have measured the relationship between new technology and startup costs. As Rand discovered in previous work, unexpected startup costs can be a large contributor to overall cost growth in pioneer process plants.[18]

Analysis of Process Plant Startup Costs

Our analysis examines startup costs as the percentage of total project costs before startup. These costs are commonly viewed and expressed in this manner. The analysis uses our database of 51 process plants. Our assessment first characterizes startup costs for these facilities and then analyzes the factors that influence these costs. This analysis closely parallels the results presented above.

With innovative facilities and new technologies, startup costs as a percentage of total costs can vary considerably from plant to plant. Explaining this variance is one of the goals of our analysis. First, however, it is necessary to define the unit of analysis. The numerator, total startup costs, is total capitalized plus expensed costs incurred during the startup period, adjusted to mid-1980 dollars. Total capital cost, the denominator, is total project costs excluding costs for research and development and startup adjusted to mid-1980 dollars.

Figure 12 illustrates the distribution of startup costs as a percent of project costs through mechanical completion. Although the majority of plants (65 percent) have startup costs lower than 5 percent of total costs, many plants have startup costs over 10 percent. What project and plant characteristics influence or are related to high values of startup cost percent? As we did in analyzing startup time, here we examine technical problems encountered during startup, plant performance, measures of technological innovation and experience, research and development issues, and plant feedstock before presenting our model explaining startup costs.

Startup costs and time are strongly related. In fact, in six of the eight cases where the startup costs exceeded 10 percent, startup time was longer than one year. We therefore expect to find many similarities between the factors driving startup cost percent and those used to explain startup time.

[18]See Merrow, Phillips, and Myers, 1981.

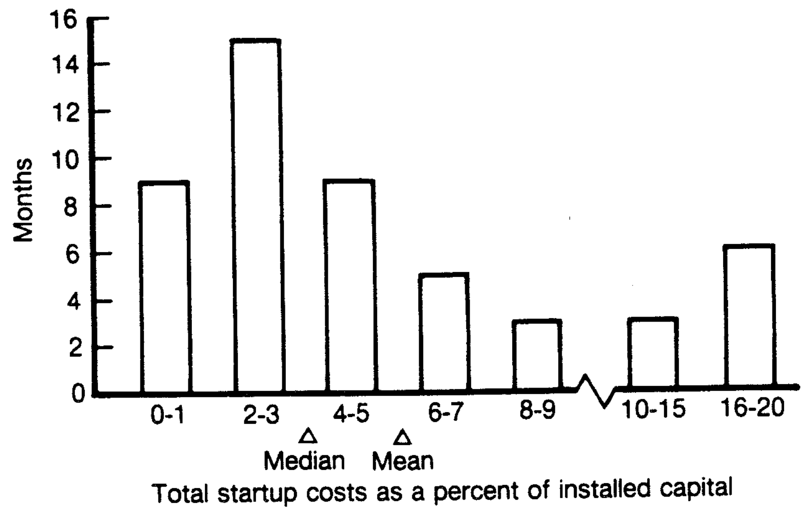

Fig. 12—Distribution of startup costs as percent of capital costs

Effect of Startup Problems on Startup Costs

We reviewed above the types of problems encountered during startup and their effects on the length of the startup phase. Table 26 demonstrates a similar relationship between these types of problems and startup costs. Design failures, especially in conjunction with equipment breakdowns, are associated with significantly higher proportionate startup costs. Such high average percentages reflect how costly design problems are to overcome.

In those extreme cases where a major design change was required, startup costs were also proportionately much greater, as Table 27 shows. Major design modifications are associated with much longer and more costly startups, especially for pioneer facilities, which are also more likely to need major design modifications during startup. In fact, of the 11 plants requiring such changes, only one is not a first-of-a-kind unit, although it was the first time the firm had built such a plant. In the other ten cases, startup costs as a percent of actual costs are more than double those of the 19 pioneer plants that did not experience startup design changes.

Table 26

EFFECT OF STARTUP PROBLEMS ON STARTUP COSTS
(Percent)

Problem	Average	Standard Deviation	Range
None	2.4	2.1	0 - 7
Equipment failure	1.6	2.0	0 - 4
Design failure	5.7	2.7	2 - 10
Equipment and design failure	14.8	6.2	2 - 20

Table 27

EFFECT OF MAJOR DESIGN CHANGES ON AVERAGE STARTUP COSTS
(Percent)

Major Design Changes Required?	First of a Kind?		
	No	Yes	Total
No	1.4	6.1	3.5
Yes	3.6	13.7	12.8

Early Plant Performance and Startup Costs

Proportionately high startup costs are strongly associated with poor plant performance. That is, substantial expenditures (relative to costs through construction) were incurred trying to bring the plants to operating capacity. Table 28 shows the average level of design capacity achieved during each three-month period following the first startup effort, according to the percent of additional costs incurred during startup. Performance for all plants improved substantially over the

Table 28

PLANT PERFORMANCE AND AVERAGE PERCENT OF DESIGN CAPACITY ACHIEVED AFTER STARTUP

Startup Cost Percent	Months 1-3	Months 4-6	Months 7-9	Months 10-12
0 - 0.5	62	64	70	85
0.6 - 1.9	65	79	87	85
2.0 - 4.9	50	67	76	83
5.0 - 9.9	30	48	57	68
10.0 - 20.0	13	22	34	44

course of the first year of operation, with most plants reaching 80 percent or more before year's end. Plants where startup costs were 2 percent or less were operating at an average of 60 to 70 percent within a short time. Poorer performing plants had to spend proportionately greater amounts, however. The plants that failed to reach even 50 percent of capacity by year's end spent more than 10 percent additional capital during this phase.

STARTUP COSTS AND TECHNOLOGICAL INNOVATION AND EXPERIENCE

Projects involving new or unproven technology typically encounter more difficult, lengthy, and, as a result, more costly startups. The literature emphasizes that technically advanced units usually spend a higher proportion of project costs during startup.[19] This conclusion is also readily drawn from our data. Table 29 shows that first-of-a-kind plants spend a far higher proportion of costs during startup than other less technically innovative kinds of plants. The range of percentages for the nonpioneer plants is narrowly constrained to 4 percent or less, in fact, and for the pioneer plants it reaches 20 points.

[19]See for example, Feldman, 1969; Malina, 1980.

Table 29

TECHNOLOGY EXPERIENCE AND STARTUP COST PERCENT

Facility	Average Startup Cost	Range	Number of Plants
First of a Kind	8.8	0 - 20	29
First time built in United States or Canada	0.8	0 - 4	7
First time built in United States or Canada by this firm	1.7	0 - 5	8
None of the above	1.8	0 - 3	8

Table 30 shows a similar effect for the firm's experience with similar units. If the owner had built plants of the same type that were technically similar, startup cost percent was small, less than 2 percent. Lacking such experience, firms encountered startup cost percent several times greater.

Table 30

FIRM EXPERIENCE AND STARTUP COST PERCENT

Firm Has Built Technically Similar Plants	Average	Range	N
Yes	1.8	0 - 7	15
No	7.1	0 - 20	36

This relationship also holds for more continuous innovation measures. Figure 13 shows that the average startup cost percentage increases dramatically as a function of the number of commercially unproven process steps in the plant. The startup costs for the seven plants with four or more new steps averaged just over 16 percent of capital, while they averaged less than 1.5 percent for the 19 plants that had no new steps. Similarly, Fig. 14 illustrates the importance of basing the plant's heat and mass balances on experience with commercial units. Startup costs averaged over 10 percent for the 16 plants with 25 percent or less of the balance equations known from commercial units, or at least double the average cost percentage for all the other plants.

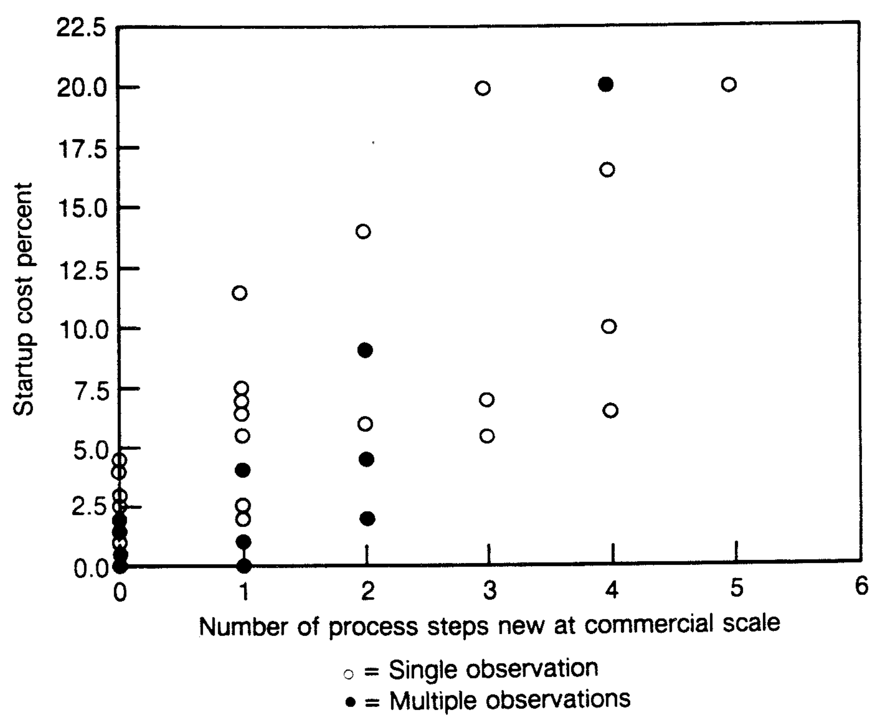

Fig. 13—Startup cost percent and the number of new steps

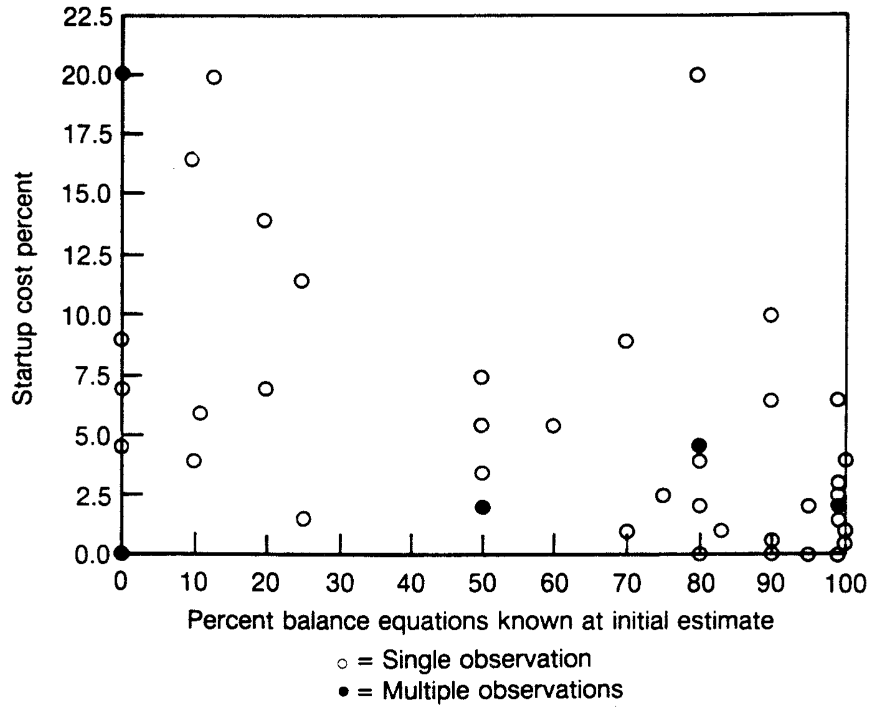

Fig. 14—Startup cost percent and knowledge of H&M balances

STARTUP COSTS AND MATERIALS HANDLING PROBLEMS

Difficulties encountered during process development and design are also excellent indicators of problems associated with high startup costs. The greater the degree of difficulty with key problem issues, the larger the share of project costs spent during startup. As Table 31 shows, this relationship is pronounced for both the extent of materials handling and chemistry related difficulties.

Startup Costs and Type of Materials Processed

Solids handling plants not only have greater trouble reaching design performance operating capacity, but take longer simply to start up and

Table 31

STARTUP COST PERCENT AND DEVELOPMENT DIFFICULTIES

Average Level of Difficulty Encountered During Development[a]		Average Startup Cost Percent
	None	3.7
Chemistry-Related	1	3.9
	2	4.7
	3 +	9.5
	None	2.0
Materials Handling	1	3.3
	2	7.2
	3 +	10.8

[a]Values have been rounded to nearest whole number from average of scales ranging from zero: "No problem," to five: "Major problem."

require a higher proportion of capital to do so. This last relationship is shown in Table 32, which gives the average startup cost percent according to the type of materials processed in the plant. Facilities that involve unrefined solid feedstocks suffer more costly startups in particular. Raw solid feed pioneer plants spend an average of twice as high a percentage on startup than other pioneer units, as Table 33 shows.

STARTUP COSTS REGRESSION ANALYSIS RESULTS

Table 34 presents the results of a regression analysis that identified the factors most useful in explaining startup costs as a percentage of costs spent through mechanical completion. These factors capture the level of technological innovation involved in the plant; the extent to which materials handling issues involving feedstock characteristics, abrasion, solid, liquid, or gas handling, and waste handling posed development difficulties; whether the plant handles a feedstock that has not been processed or refined; and whether the firm had experience in building similar types of units.

Table 32

STARTUP COST PERCENT AND TYPE OF MATERIALS PROCESSED

Materials	Average Startup Cost	Range
Liquid/gas feedstocks		
Liquid/gas processing only	5.2	0 to 16
Solids processing	3.8	0 to 9
Solid feedstocks		
Processed solid feedstocks	4.8	0 to 12
Raw solid feedstocks	10.1	0 to 20

Table 33

PIONEER VS. STANDARD PLANT STARTUP COSTS BY TYPE OF MATERIALS PROCESSED

Materials	Standard Plant	Pioneer Plant
Liquid/gas feedstocks		
Liquid/gas processing only	1.6	7.8
Solids processing	1.5	6.5
Solid feedstocks		
Processed solids	0.4	7.0
Raw solid	1.2	15.4

Table 34

STARTUP COSTS REGRESSION ANALYSIS MODEL

Variables in Model	Parameter Estimate	t-ratio
Intercept	-0.062	0.7
Number of unproven process steps	2.613	8.8
Average level of development difficulty with materials-handling issues	1.036	2.8
If plant feedstock is unrefined solid	2.903	3.3
Coefficient of determination:	$R^2 = 0.73$	
Standard error of estimate:	$\pm$ 3.26	
Number of projects = 51		

The model suggests that, on average for the plants in the database, we can expect startup costs as a percent of the capital spent through construction to increase by about 2.6 percentage points for each process step or block in the plant that incorporates commercially unproven technology. In addition, the model indicates that if materials handling issues posed major problems during development, up to five additional percentage points of startup costs will be needed. If the plant handles a solid feed that has not been refined, expected startup cost percent increases an additional 2.9 percentage points. The standard error of prediction for the 51 plants in this analysis is $\pm$ 3.3 percentage points. Together these four factors explain over 70 percent of the total variance in the percent of costs spent during startup.

These results are largely consistent with the limited body of quantitative research on startup costs described earlier. Technologically advanced facilities spend proportionately higher amounts during startup than units using established technologies. Other research has not previously identified solid feedstocks as especially problematic, however, except for earlier Rand research on plant performance.

APPLICATIONS OF STARTUP COST MODEL

To reinforce the implications of this model, the startup costs of several hypothetical plants will be predicted. This application is illustrated in Figure 15. We have shown that startup cost as a percent of total plant cost is influenced by the number of unproven process steps, the average level of development difficulty with material handling issues, and whether the plant has an unrefined solid feed. Plant A represents a facility that will have very low startup costs. It has a low level of innovation (one new process step), no materials handling problems, and a liquid or gas feed. This plant will probably expend around 3 percent of the total plant costs on startup. Plant B is similar to Plant A except it has a moderate materials handling problem, causing startup costs to average approximately 5.5 percent of total costs. Startup costs jump considerably when we consider a plant similiar to hypothetical Plant C. This plant has two unproven process steps, moderate problems with materials handling issues, and a raw solid feedstock. As a result, approximately 11 percent of the total plant costs will be spent on the startup of this plant. These results suggest that with the knowledge of several plant parameters, one can gain a good understanding of the resources that must be committed to plant startup.

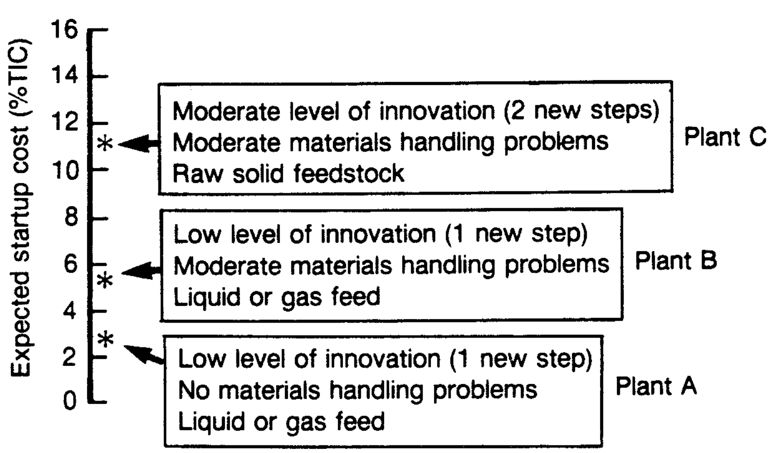

Fig. 15—Illustration of startup cost model applications

IV. CONCLUSIONS

This report quantifies the key factors driving construction and startup schedules as well as the costs of startup. Although the focus is on pioneer plants, the results should prove useful in understanding schedule slippage for more standard units as well.

The tools developed can be used as additional methods for evaluating planned construction and startup schedules. These methods employ project and technology characteristics that are identifiable at any stage in a project's development once the schedule plan is established—even during project definition, before major financial commitments have been made. They reflect characteristics of the level of technological innovation embodied in a project, its management approach, and whether the plant uses unrefined solid materials as feedstock.

The analyses described in this report indicate that each of these problems is explained by a limited set of project characteristics. Specifically, the major factors influencing these outcomes are:

- *Construction schedule slippage* is strongly associated with poor project definition at the start of detailed engineering, planned long concurrency between detailed engineering and construction for pioneer plants, and the use of unrefined solid feedstocks.
- *Total startup time* can be explained by the number of commercially unproven process steps, the portion of the plant heat and material balances based on previous commercial units, and whether the plant processes an unrefined solid feedstock. In addition, placing responsibility for the project in a team composed of representatives from each of the corporate divisions, rather than dispersing project responsibility across these divisions, appears to result in better communication and shorter startups.
- *Startup costs as a percentage of total costs* are closely related to the number of new process steps, the extent of difficulty with materials handling issues (such as feed characterization, abrasion, solids handling, and waste handling) encountered during process development, and whether the plant processes an unrefined solid feedstock.

These results hold several important implications for project planners, estimators, and evaluators as well as for corporate and project managers. First, management can make a substantial and quantifiable difference. Several factors critically affecting project schedules reflect strategic choices about how individual projects should be managed. Circumstances may encourage project (and corporate) managers to push a project into the field as rapidly as possible, even without the benefit of better project definition. Such strategies are not without substantial costs, however, at least in terms of the accuracy of schedule and cost plans. The management decision to invest in more thorough project definition before proceeding to detailed engineering usually results in more accurate estimates of construction time and project costs. The more that is known about the process design and specific site conditions at the time an estimate is prepared—whether for costs or construction schedule—the more accurate the estimate is likely to be. This is true for all projects.

A second aspect of management effects concerns the decision on when to begin construction relative to expected progress of detailed engineering. First-of-a-kind projects tend to overlap these phases more often than other projects. And in most cases, they pay a substantial penalty for doing so in terms of the accuracy of the construction schedule. Pushing a project—especially a pioneer plant—into the field early can prove more costly and take longer than expected. Fast-tracking by substantially overlapping engineering and construction often leads later to construction delays while engineering catches up. Planned concurrency of eight months or more between these phases typically adds more than a half year to the actual schedule for first-of-a-kind facilities.

A third aspect of project management is how it is structured. Integrating the diverse (and sometime conflicting) perspectives of corporate R&D, engineering, and operations (or manufacturing) by making such a team responsible for its successful execution is associated with considerably shorter and smoother pioneer plant startups. Problems may be anticipated earlier and resolved more easily as a result, instead of plaguing the plant operators during startup.

Another implication of this analysis concerns innovation. The use of commercially unproven technology is a major factor explaining all three outcomes. It is often not until startup that serious design problems are recognized; corrections then are usually costly and time consuming. Technological innovation can be particularly troublesome when coupled with either a lack of experience by the firm with building similar plants, or an inability to rely on previous commercial units in establishing the plant's basic heat and material balances. It is not just the use of new technology that is important, but also the degree of technical advance attempted. Thus, plants involving only one or two new process steps typically experience shorter and less costly startups than those involving three or more new steps.

Unrefined solid feedstock materials pose severe difficulties that result in longer than expected construction and startup and higher startup cost percentages. These plants also tend to be more innovative (in our sample at least) and suffer more problems with materials handling issues during development. In particular, raw solid feed plants tend to rely much less on commercial experience in calculating the H&M balances for the plant during design.

Finally, the analysis presented here and the resulting statistical models can be used as aids to help improve project planning. For projects similar to those in the database, these models can be applied to estimates of project construction and startup length and cost as checks on their probable accuracy. Such evaluations, moreover, can be performed with a minimal amount of data, all easily measurable at an early stage in the project's development.

Appendix

THE PROCESS PLANT DATABASE

Thirty-eight firms in the oil, chemicals, and minerals processing industries supplied detailed proprietary information concerning the cost, schedule, and performance of 56 commercial-scale projects, their technical characteristics, and the types of difficulties encountered. All of the projects were carried out by the private sector without government subsidy and resulted in commercial processing plants. Partial data for 44 of the projects come from the Pioneer Plants Study (PPS) database completed in 1981, augmented by subsequent information concerning schedule and startup.[1] Data for an additional dozen projects, many involving established technologies and solids processing, were obtained as part of on-going research on solids plant performance and technology cost improvement.

The project developments contained in the database were obtained from companies using broad sampling guidelines. Firms were asked to supply data on plants that were:

- Constructed in the United States or Canada within the past 15 years.
- Greenfield,[2] collocated, or add-on units, but not revamps of an existing plant.
- Plants for which reliable and fairly complete data were available.[3]

Over the past three years, we have also encouraged firms to provide plants that handle solid materials and plants that use more established technologies. The individual firms selected one or more of their major projects and provided information collected through a 60-page worksheet.

The owners of the plants in the database are broadly representative of the process industries: 22 of the projects are owned by chemical

[1]See Merrow, Phillips, and Myers, 1981, Sec. III, for additional description of the Pioneer Plants Study database.

[2]Refers to a completely new, stand alone facility.

[3]Because of the manner in which most firms capture and retain information from projects, obtaining relatively complete data proved to be a difficult task. This problem has been systematically examined in Myers and Argüden, 1984.

companies, 19 by petroleum companies, eight by mineral processing companies, and seven more by firms with their main line of business outside the process industries. Most are medium to large firms relative to others in their industry.

Nondisclosure agreements between The Rand Corporation and each firm protect all data characterizing the individual projects as well as their sponsors and personnel. We describe the database to give the user of the report as much insight as possible into the nature of the projects from which we draw conclusions without compromising the secrecy agreements under which the data were obtained. This insight is intended to help the reader and potential user assess when and how the results can be applied.

We start this section by providing a set of general, descriptive characteristics of the projects in the database. We then discuss the degree to which the plants incorporate innovative technology—an important consideration for any analysis of schedule and startup problems in particular. We conclude with a discussion of how these characteristics are related, followed by a summary of several attributes of project management that were measured.

GENERAL PROJECT CHARACTERISTICS

All plants in the database were constructed in the United States or Canada between the mid-1960s and 1983. About one-quarter are refinery or refinery byproduct units, another quarter produce olefins, and a smaller share involve inorganic material. Other characteristics that should help the reader gauge the projects include plant capacity, complexity, capital cost, and the length of the projects.

Plant Capacity

Measured in terms of design output, the plants range from just under 1 million pounds per year to just over 100 billion pounds. As shown in Table A.1, about three-quarters of the plants in the database are large by process industry standards—over 100 million pounds per year in output. The average plant produces almost 4 billion pounds per year if operating at design production rate. This mean value is heavily weighted toward a few extremely large plants, however; half the plants produce less than 425 million pounds per year, and only 11 percent are rated at more than 5 billion pounds per year. The six largest capacity plants are petroleum processing facilities.

Table A.1

SIZE OF PLANTS IN THE DATABASE

Plant Design Capacity (in millions of pounds per year)	Number of Plants	Percent
< 1 - 20	6	10.7
21 - 50	6	10.7
51 - 200	6	10.7
201 - 400	9	16.1
401 - 1000	9	16.1
1001 - 3000	7	12.5
3001 - 5000	7	12.5
above 5000	6	10.7

Plant Complexity

As defined here, plant complexity measures the number of physical and chemical steps in the process from the point that raw materials enter as feedstocks until product emerges. We measure plant complexity by counting the number of functional subsystems, or blocks, in a plant.[4] Not included in the count of a plant's complexity are technically proven cleanup steps off the main process train or parallel identical steps as in a multiple train plant. Complexity and capacity are not correlated in this database. Some highly complex plants have fairly small throughputs, and some simple units have large output rates. Some highly complex units, such as major refining facilities, have large output rates. This is not true of all petroleum processing units in the database, however. Table A.2 shows the distribution of plant complexity for plants in the database. The average plant has about five major subsystems on the main process train. Almost a third of the sample has seven or more and may be considered complex plants.

[4]The principal alternative method of measuring complexity is to use the number of pieces of major equipment. In the past we collected data for complexity in both ways. Our analysis indicated, however, that the step counts were at least as good for statistical purposes as the major equipment counts and a good deal easier to obtain. Therefore, in assembling the database we have obtained only process step counts. The process step counts are typically obtained from what are called "block" process diagrams.

Table A.2

PLANT COMPLEXITY

Plant Complexity Count (number of major subsystems or process blocks)	Number of Plants	Percent
1 - 3	11	19.6
4	11	19.6
5	9	16.1
6	7	12.5
7	6	10.7
8	5	8.9
9 - 11	7	12.5

Plant Costs

Table A.3 shows the distribution of capital costs. Measured in mid-1980 dollars, the plants in the database range in capital cost from just under $1 million to over $1 billion, excluding both R&D costs and all startup costs, both of which can be major cost elements.[5] The average plant cost about $140 million, with more than half costing over $50 million, and almost one-fifth costing over $200 million. Startup costs ranged from essentially none to over $100 million (mid-1980). Although the average plant required over $9 million for startup (about 4 to 5 percent of the capital costs), half the plants spent less than $2 million. Because startup costs are the object of the analysis reported in Sec. III, we describe them in more detail there.

Project Length

Table A.4 describes the average elapsed time for the projects by phase. The projects are fairly long, totaling well over four years from the beginning of project definition until the end of startup. Project definition was not conducted as a formal exercise for some projects, while other projects wrestled with it for several years before the initiation of detailed engineering. Detailed engineering lasted an average of

[5]Expenditures for R&D and startup are not accounted for uniformly across the process industry. R&D costs often are not charged to a particular project's budget, for example. Or they may be aggregated over a long-term development effort. They may not be applicable because the technology was not developed by the firm building the plant. Startup costs are subject to different accounting difficulties, discussed in Sec. III.

Table A.3

PLANT CAPITAL COSTS

Capital Cost Through Mechanical Completion (in millions of mid-1980 $)	Number of Plants	Percent
< 1 - 10	7	12.5
11 - 20	9	16.1
21 - 50	9	16.1
51 - 75	11	19.6
76 - 100	3	5.4
101 - 200	7	12.5
201 - 400	4	7.1
above 400		10.7

Table A.4

PROJECT LENGTH BY PROJECT PHASE
(Months)

Project Phase	Mean	Median	Range
Project definition	15.1	12.0	0 - 54
Engineering	19.8	18.5	4 - 57
Construction	21.8	22.0	5 - 51
Startup	8.0	4.0	0 - 30

about 20 months, and construction about 22 months, although they varied from quite short efforts to more than four years. As shown by the range as well as by the difference between the arithmetic average (the mean) and the median, the time required for plant startup is severely skewed. More than half the plants started up in four months or less, but almost a third required a year or more to reach steady-state operations. Three plants never started successfully. (We have ended the startup period measure after two and a half years of effort for these three plants, to prevent the analysis from being slanted toward plants where startup efforts had essentially ended, even after extraordinarily difficult and lengthy startup periods.)

TYPES OF MATERIALS PROCESSED

As shown in Table A.5, 20 of the 56 plants in the database use solid feedstocks; the remainder either do not involve solids at all, or convert liquids and gases into solids during processing. Of the 20 processes using solid feedstocks, eight use "raw solid feeds"—a solid that has undergone no chemical processing before being introduced into the plant.

MEASURES OF NEW TECHNOLOGY

The projects in the database vary enormously in the extent to which they introduced new and advanced technology. Some are fairly standard plants using well-established technologies.[6] Others are the first commercial results of long and arduous R&D phases and introduce major new processes. Some are major advances in the technical state of the art. This variability is useful because it permits us to look for differences as a function of the project's technical advance. Good measures of the extent to which new technology is present enable us to

Table A.5

FEEDSTOCKS OF PROCESSES

Materials	Percent	Number
Liquid/gas feedstocks		
Liquid/gas processing only	39.3	22
Liquid/gas and solids	25.0	14
Solid feedstocks		
Processed or refined	21.4	12
Raw or unrefined	14.3	8

[6]Process plants are almost never truly standardized; even plants that by our definitions incorporate no new technology almost always introduce some new technical "wrinkles." In addition, site and scale differences work against repetition of designs.

control for the degree of innovation in the project as we examine other factors associated with project schedule slippage and startup problems. Other things being equal, we would always expect a more technically ambitious project to have more problems—especially during startup.

Pioneer Plants

Probably the most straightforward measure of technological innovation is whether the plant is a first of a kind, or pioneer, facility. This means that the plant used technology that had not been demonstrated in commercial use. Thirty-three of the 56 projects were first of a kind plants. If the technology had no commercial history, we generally would expect more difficulties to be encountered. Problems stemming from the use of pioneering technology may manifest themselves throughout a project's development as the process design evolves. Lack of commercial experience leads to greater uncertainty about process operating conditions, equipment sizing, materials, etc. These problems are most likely to show up—and with great influence on a project's profitability—during plant startup. Equipment or design failures can lead to costly downtime, while attempts are made to adjust, replace, or redesign.

Because one of our major interests concerned the effects of technological innovation on project cost, schedule, and performance, we have sought to measure new technology in various ways. Most of these deal with the extent and basis of a firm's experience with the technology. A facility may not be the first of its kind in the industry, but it may be the first one constructed in the United States or Canada, or it may be the first one of its kind built in the United States or Canada by that company. Or it may instead be one of a series of such plants built by the firm in the United States or Canada. Table A.6 shows the distribution of the plants by these characteristics. Note that a first of a kind plant by definition is also one built for the first time in the United States or Canada by any firm. In addition, a firm may not have direct experience with the exact technology, but it may instead have experience with technically similar processes. Fifteen companies reported having built one or more previous plants of a similar type.

Commercially Unproven Process Steps

Another measure of technological innovation in a plant is the number of new steps in the process. A step here is defined the same way as when counting complexity—a functional subsystem in which a change is made to the material being processed. A step is new if it is

Table A.6

COMMERCIAL HISTORY AND FIRM EXPERIENCE WITH TECHNOLOGY

Facility	Percent	Number of Plants
First of a kind	60.7	33
First time built in United States or Canada	10.7	6
First time built in United States or Canada by this firm	16.1	9
None of the above	14.3	8

commercially unproven—if the chemistry or hardware have not been used before in the same service in a commercial plant. Scale of previous use per se is not an issue. If a step has been used at a smaller scale in a commercial facility—one that is intended to make a product for sale rather than to produce information for facility design—then it is not new. We therefore distinguish between scale-up from a commercial facility and innovation as separate problematic dimensions.

Table A.7 shows the distribution of new steps in the database. Twenty of the 56 plants have no new major subsystems on the main process train. The remaining plants have between one and five new steps, with an average between one and two. The number of new steps needs to be put in context. The introduction of a new process step is the exception rather than the rule for process plants (although the opposite is true in our database). In many cases a substantial development effort involving millions of dollars is necessary to introduce new technology. Introducing a new process step can be an expensive undertaking and must be undertaken carefully.

There can be many reasons for introducing a new step, all of which are in one way or another aimed at making money:

Table A.7

DISTRIBUTION OF NEW STEPS

Number of Commercially New Process Steps	Percent of Plants	Number of Plants
None	35.7	20
One	25.0	14
Two or three	26.8	15
Four or more	12.5	7

- To cut capital costs, for example, by combining what was previously two or more steps into one or by reducing the severity of process conditions.
- To improve yields (the amount of product from a given quantity of feedstock).
- To improve product quality.
- To introduce a new product.

Generally, the introduction of one new step is undertaken within the context of improving an existing process. As the number of new steps introduced increases, it becomes more likely that a substantially new process or product is being introduced.

The absence of any new step does not necessarily indicate that no aspect of the plant is innovative. The plant may introduce new minor equipment such as pumps or valves or may integrate existing steps in new ways. Of the 20 plants in the database that have no new steps, five have some innovative minor equipment and four have one or more first-time integrations of commercially proven steps. Of the remaining eight, three were the largest unit of its type constructed to that point. In fact, half of the 20 plants that have no new steps were the largest units of their type then in existence. Therefore, of the 56 plants in the database, only seven were in any true sense attempted "replicates" of earlier plants.

Basis for H&M Balance Equations

The degree of technical uncertainty involved in designing, constructing, and starting up a plant depends on more than just whether the process had been commercially proven in a previous plant. Technical uncertainty also depends on the basis or source of the process information used in designing the plant. The extent to which the plant's heat and material balance equations are based upon experience with operating commercial plants rather than estimated from theory is an important measure of this information. The heat and materials (mass) balances are the basic equations that govern flows in the plant. They are necessary for estimating the size of all equipment. These equations model all of the energy and material flows in and out of every step in the plant. When the equations are not available from operating experience with the technology, they can be estimated on the basis of other information about the chemistry involved in each process step. If this information is not very good, however, the calculated balances will not be matched in practice. Operating experience is often not available, especially for innovative plants; in such cases, the equations may be calculated from any of several sources, including:

- Operating data from analogous commercial units.
- Data from a full-scale pilot or demonstration facility.
- Data from a scaled-down development version of the process.
- Laboratory data.
- Computer simulation models.
- Theoretical information (such as equilibrium data, heat and mass transfer correlations, published kinetics data or design correlations).

We expect that errors in the balance equations would be more likely when actual data from identical commercial units are not used. We have found the proportion of heat and material balances that are based on commercial units to be strongly related to early plant performance and not entirely dependent on the degree of innovation involved.[7] Table A.8 shows the distribution of the percentage of the balance equations based on previous commercial units at the time of the initial capital cost estimate for each of the 56 plants.

Firm knowledge of the balance equations in part reflects the level of new technology being introduced into a plant. Table A.9 shows the average percent of the heat and mass balances based on previous commercial units according to the number of new process steps in the

[7] See Merrow, Phillips, and Myers, 1981, Sec. V.

Table A.8

DISTRIBUTION OF PERCENT OF BALANCE EQUATIONS BASED ON PREVIOUS UNITS

Percent of Heat and Material Balances Based on Prior Commercial Plants	Percent of Plants	Number of Plants
0	17.9	10
1 - 25	16.1	9
26 - 50	14.3	8
51 - 80	17.9	10
81 - 95	14.3	8
96 - 100	19.6	11

plants. Knowledge of the balance equations is not strictly a function of the number of commercially unproven blocks in the plant, however. Each category of new steps contains almost the entire range of balance equations based on previous units. Even some plants introducing no new steps relied entirely on noncommercial experience or theory in estimating the balances.

Reliance on previous commercial units for calculating the balance equations also depends on a firm's experience with the type of plant being built and with the technology itself. Table A.10 shows the relationship of the balance equation variable and the extent to which the plant itself is a first-of-a-kind facility. The more a facility resembles a pioneer plant, the less the firm tends to rely on commercial experience in calculating the balance equations. If it is a pioneer plant, it makes a substantial difference if there is no facility like it in the United States or Canada, and to a lesser extent if the firm involved had no such unit before. In each category, however, considerable range in knowledge is evident. In the four cases of pioneer plants where the companies reported having built plants of a related type, their experience apparently resulted in better understanding of the H&M balances at an early stage. These four plants knew an average of 84 percent of the balances from previous commercial units, despite having between one and four new steps each.

Table A.9

RELATIONSHIP OF NEW STEPS TO KNOWLEDGE OF BALANCE EQUATIONS

Number of New Steps	Average Percent of Balance Equations Based on Commercial Units	Range
None	77.3	0 - 100
One	59.8	0 - 100
Two or three	35.7	0 - 80
Four or more	30.3	0 - 100

DESIGN AND DEVELOPMENT DIFFICULTIES

As part of the data collection effort, we obtained information about the level of technical difficulty encountered during R&D and early process design and development stages. Engineers familiar with the development effort assessed the extent of difficulty involved in work in each of ten areas. Four deal with process chemistry problems, while the other six concern materials handling issues:[8]

Chemistry-related Issues:

- Problems with the existence or creation of IMPURITIES in intermediate process streams.
- Problems with the control of TEMPERATURE in the process.
- Problems with the control of PRESSURE in the process.
- Problems with CORROSION of equipment.

[8]For full definitions and discussions of these see Merrow, Phillips, and Myers, 1981; and Horvath, 1983.

Table A.10

RELATIONSHIP OF INNOVATION TO KNOWLEDGE OF BALANCE EQUATIONS

Facility	Average Percent of Balance Equations Based on Commercial Units	Range
First of a kind	41.0	0 - 100
First time built in United States or Canada	67.2	0 - 100
First time built in United States or Canada by this firm	70.1	0 - 100
None of the above	93.0	50 - 100

Materials Handling Issues

- Uncertainties in FEEDSTOCK characteristics.
- Problems with ABRASION of equipment.
- Problems with SOLIDS HANDLING such as flow, plugging, etc.
- Problems with LIQUIDS HANDLING.
- Problems with GAS HANDLING.
- Problems with WASTE HANDLING including disposal.

These issues were measured using a scale of zero to five, with zero indicating no problem at all and five indicating a major problem that had to be overcome. Judging the seriousness of an issue encountered during development was necessarily subjective. Our interest was in identifying those issues that might be associated with particular problems during later project stages. Encountering a problem during process development does not guarantee its successful resolution, of course, or even that all major process problems were recognized and dealt with. These measures are very useful ways to identify key problem areas in certain types of plants, however, and are valuable, reliable predictors of problems later.[9] The most difficult issues concerned problems with waste handling, corrosion, impurities, feedstock characteristics, and solids handling. Table A.11 lists the average values for each of the issues, along with the average value of the composite score when the items are averaged together to create a Chemistry-related Issues index and a Materials Handling Issues index.

The level of difficulty encountered during process development corresponds in part to the levels of innovation and experience involved in the plant. In Table A.12, the chemistry problems have been combined and averaged; the materials handling issues have been averaged together in a similar fashion. The extent of problems with the chemistry issues is almost four times greater for pioneer plants than for standard ones, while the handling problems are about 2.5 times greater.

Table A.11

DESIGN AND DEVELOPMENT DIFFICULTIES

Problem Area	Item Average	Index Average	Index Range
Chemistry-related issues		1.4	0 - 5.0
Impurities	1.61		
Temperature	1.29		
Pressure	1.13		
Corrosion	1.68		
Materials-Handling issues		1.5	0 - 4.2
Feedstock	1.59		
Abrasion	1.11		
Solids Handling	1.55		
Liquids Handling	1.32		
Gas Handling	1.30		
Waste Handling	1.82		

[9]The IMPURITIES variable helps explain project cost growth, for example, and the WASTE variable helps explain early plant performance. These models are described in Merrow, Phillips, and Myers, 1981.

Table A.12

AVERAGE LEVEL OF DIFFICULTY ENCOUNTERED DURING DEVELOPMENT[a]

Facility	Chemistry-Related Problems	Materials Handling Problems
First of a kind	1.89	1.82
First time built in United States or Canada	1.25	1.08
First time built in United States or Canada by this firm	0.67	0.98
None of the above	0.47	0.73

[a]Index is given in Table A.11.

Process development difficulties with materials handling are closely related to the knowledge of the heat and material balance equations from previous units, while chemistry-related problems are not, indicating the difficulties involved in relying on other commercial units to calculate the H&M equations when introducing new processes involving materials handling.

INNOVATION AND SOLIDS PROCESSING

The data collection and earlier analysis identified solids processing facilities and technological innovation as two key factors affecting early plant performance.[10] We now describe how these two important characteristics are related to each other in this database. Because we wish to assess the potentially separate effects of innovation and the type of material being processed in the plant, our sample includes standard units, some of which handle solid materials, as well as fairly

[10]See Merrow, Phillips, and Myers, 1981, Sec. VI.

innovative facilities, some of which handle only liquids or gases. All combinations are represented, as Table A.13 illustrates.

Among these plants, there is a slight tendency for the solid feedstock plants to incorporate new technology to a greater extent than the plants using liquid or gas feeds. This is evidenced further in Table A.14, which shows the average number of steps incorporating new technology according to whether the plant handles solid feedstock. The pioneer solid feedstock and liquid/gas-only plants are quite innovative, with an average two and a half commercially unproven process steps. The pioneer plants that handle solid materials but not as feedstocks are somewhat less innovative, with an average between one and two steps. Yet many of the most innovative plants in the database, as measured by the introduction of unproven process steps or the proportion of capital those steps involve, are liquid and gas plants.

Technical innovation and the types of materials processed by a plant interact strongly to affect the knowledge of the heat and material balances. Pioneer plants that process solid materials show significantly lower values on the balance equation variable, as seen in Table A.15. It is very difficult for firms to calculate the balances on the basis of previous units when introducing new technology to a process that

Table A.13

INNOVATION AND TYPE OF MATERIALS PROCESSED

Materials	First-of-a-kind Plant? No	First-of-a-kind Plant? Yes	Total
Liquid/gas feedstocks			
Liquid/gas processing only	8	14	22
Solids processing	9	5	14
Total	17	19	36
Solid feedstocks			
Processed solid	3	9	12
Raw solid	3	5	8
Total	6	14	20

Table A.14

AVERAGE NUMBER OF NEW STEPS AND TYPE OF MATERIALS PROCESSED

	First-of-a-kind Plant?	
Materials	No	Yes
Liquid/gas feedstocks		
Liquid/gas processing only	0.3	2.4
Solids processing	0.1	1.6
Solid feedstocks		
Processed solid	0.0	2.1
Raw solid	0.0	3.2

handles solid feeds. Of the ten plants where none of the balance equations was available from commercial experience, all but one handle solid feedstocks. In fact, 12 of the 18 plants with one-quarter or less of the balances based on actual commercial plants employed solid feeds. The range is much more constrained for solid feed pioneer plants as well. None has a value higher than 50 percent. Nonpioneer plants that process refined solid feeds appear somewhat anomalous in that their average value on the balance equation measure is only 35 percent. They appear much more like innovative solids plants than the plants that use established technology. In a way they are. Although they incorporate no commercially unproven technology, they cannot be called entirely standard plants either. All three involve technologies that had never been demonstrated before in commercial use in the United States or Canada, and two also represent the largest facilities of their type at the time they were built. In addition, plants that handle solid materials as feedstocks experience much greater process development difficulties than other types of plants, especially for pioneer solid feed facilities. They are not much different in the extent to which they encounter chemistry-related problems.

Table A.15

AVERAGE PERCENT OF BALANCE EQUATIONS BASED ON UNITS BY TYPE OF MATERIALS PROCESSED

Materials	First-of-a-kind Plant? No	Yes
Liquid/gas feedstocks		
Liquid/gas processing only	77.5	60.5
Solids processing	84.2	65.0
Solid feedstocks		
Processed solid feedstocks	35.0	14.6
Raw solid feedstocks	98.3	10.0

PROJECT MANAGEMENT

It is often argued that the single most important factor determining a project's success or failure is its management. Good management selects "do-able" projects in the first place and abandons losers before they become costly disasters. We have not attempted to test this broad notion, nor could we with the data available. We have measured two factors that reflect how the project management was structured: whether it is vested in a strong manager with broad decisionmaking authority, as opposed to a committee approach; and whether responsibility for project design and execution was vested in a management team composed of representatives of the affected corporate divisions, including R&D, engineering, and, especially, operations. The distribution of these two factors is shown in Table A.16. These characteristics represent conceptually and empirically distinct approaches to project management.

Strong project management authority with a representative team approach is the dominant combination of management styles for the projects in the database, as seen in Table A.17, although each combination is well-represented. Other things being equal, we would expect problems to be uncovered and resolved earlier during project definition and design when all corporate functions are brought together from the

Table A.16

PROJECT MANAGEMENT STRUCTURE CHARACTERISTICS

Project Management Structure	Percent of Projects	Number of Projects
Authority		
Strong	68	28
Committee style	32	13
Responsibility		
Representative team approach	60	24
Dispersed responsibility/no team approach	40	16

Table A.17

PATTERNS OF MANAGEMENT STRUCTURE
(Number of projects)

Project Management Authority	Representative Team Approach	Dispersed/Team Approach Not Used
Strong single manager	18	8
Committee style	5	8

beginning of the project and made jointly responsible for its successful execution and startup. This contrasts with an approach where the project is handed off to each division in sequence. Under the dispersed responsibility approach, each functional area is responsible for only a part of the project. For example, R&D ends its involvement once detailed design begins; the operating (or manufacturing) division becomes involved primarily only when construction is completed.

Other project characteristics reflect corporate or project management decisions about the relative timing of project phases, the degree of project definition before the start of detailed engineering, and the type of contract used for construction.[11] Table A.18 shows the average values and their associated ranges for these management planning variables.

Project definition is measured as the combined degree of site definition and process engineering accomplished by the approximate start of detailed engineering. The index ranges from a high of 8, indicating all definition and design is conceptual, to 2, indicating that the degree of definition of all site characteristics and process design information used is definitive and based upon completed work. The most interesting aspect of this measure is its wide variation, despite being measured at approximately the same point in each project's development. In fact, the level of project definition accomplished by the start of detailed engineering varies from full definition to almost none. This variation is almost as great as the variation in project definition across all the estimates in the database, ranging from conceptual R&D estimates to definitive early construction estimates. Table A.18 also shows the degree to which construction was scheduled to overlap with engineering design. Excessive concurrency can delay the construction schedule if engineering design falls behind its schedule. Even when engineering remains on schedule, long scheduling overlaps may reflect pressure to get into the field prematurely. Construction may slip as a result. Of course, these pressures may reflect legitimate requirements to complete the project as quickly as possible. Planned concurrency reflects a deliberate management choice, in any event.

Table A.18

AVERAGES AND RANGES OF MANAGEMENT PLANNING CHARACTERISTICS

Characteristic	Average	Range
Level of project definition at start of detailed engineering (2 = full/8 = no definition)	3.9	2 to 6.8
Months of planned engineering and construction concurrency	8.2	(-4) to 24

[11]The effects of these and other management characteristics on cost growth, schedule slippage, startup, and early plant performance are described in Myers and Devey, 1984.

Finally, Table A.19 shows the type of contract used during project construction. Nearly two-thirds of all the projects (and 70 percent of the pioneer projects) used cost-plus contracts.

Table A.19

TYPE OF CONSTRUCTION CONTRACT USED

Contract	Percent of Plants	Number of Plants
Fixed price	21	12
Cost-plus	64	36
Other (time/materials; in-house)	14	8

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