Understanding the Outcomes of Megaprojects

A Quantitative Analysis of Very Large Civilian Projects

Edward W. Merrow

40 Years
1948-1988

RAND

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With Lorraine McDonnell, R. Yılmaz Argüden

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PREFACE

This is the last report of the Process Industries Agenda of RAND's Private Sector Sponsors Program. The Agenda was supported by firms in the energy and chemical industries and was directed by Edward W. Merrow.

This project was motivated by the concern of many people in industry and government worldwide that very large projects—so-called megaprojects—have had problems that match their physical and financial size. This study is, to our knowledge, the first systematic analysis of a substantial number of megaprojects.

The report should be useful to decisionmakers involved in megaprojects and those responsible for the execution of such projects, including project planners and senior executives, especially in industries concerned with energy and other natural-resource development; government officials responsible for decisions on major public projects and for regulation and other forms of public control; megaproject cost estimators and schedulers in both industry and government; and individuals concerned with economic development, especially in the poorer nations of the world.

SUMMARY

Megaprojects—projects requiring huge physical and financial resources—have become relatively common in the past 15 years, as a result of demands for new remote mineral resources, needs for infrastructure in less-developed countries (LDCs), and the desire to exploit economies of scale. Despite the very great concerns of the actual and potential sponsors of such projects, no systematic empirical analyses have previously been made of the costs, problems, and operations of megaprojects. This report explores those issues by examining 52 civilian projects ranging in cost from $500 million to over $10 billion (in 1984 dollars).

Using primarily public sources, we have developed a database with which to address the following questions:

- Have megaprojects generally met their cost, schedule, and performance goals?
- Do megaprojects typically display poorer outcomes than smaller projects?
- What factors drive good and bad outcomes?
- What steps can be taken to minimize the cost, schedule, and performance risks associated with megaprojects?

Most of the projects in our database met their performance goals; many met their schedule goals; few met their cost goals. The average cost growth, measured from the beginning of detailed engineering (a fairly late point in project evolution), was 88 percent. The total cost overruns for 47 projects amounted to over $30 *billion*, in constant 1984 dollars. Only four of the projects examined actually came in on budget. In contrast, the average schedule slippage (measured from the beginning of detailed engineering to the end of construction) was only about 17 percent, and more than 30 percent of the projects were completed within the allotted time.

In terms of percentage cost growth or schedule slippage, megaprojects do not appear to have much worse outcomes than merely "very large" projects. For example, the percentage cost growth for projects that cost over $2 billion was not significantly different from that for projects costing between $500 million and $750 million. However, that is small comfort. The absolute value of cost overruns and schedule slippage increases with the size of projects, putting very large sums at risk in the case of megaprojects. And, in fact, we did find that very

large projects and megaprojects appear to have more cost growth than smaller projects. The average cost growth for projects in RAND's earlier pioneer plants database with capital costs under $500 million was only 31 percent, and similar cost growth is reported in other sets of smaller projects.

Cost growth and schedule slippage for projects in the megaprojects database are driven primarily by conflicts between the projects and host governments, i.e., institutional problems relating to environmental regulations and opposition, health and safety rules and regulations, and labor practices and procurement controls. The importance of such institutional factors clearly distinguishes megaprojects from their smaller cousins.

Technological innovation also plays a role in project outcomes. Doing something different—even slightly different—increases cost growth and schedule slippage and dramatically increases the probability of operational problems.

Projects in remote areas and LDCs generally cost more than other projects, but they do not manifest *more cost growth*, because estimators take into account the added costs associated with more difficult logistics. Unfortunately, but not surprisingly, projects in LDCs are also more likely to experience operational difficulties.

We recommend that the sponsors of megaprojects take the following steps to make their projects less risky:

- Significantly broaden the scope of the project definition phase to rigorously and systematically include cultural, linguistic, legal, and, above all, political factors. This means much more than performing the sort of "political risk assessments" that have become popular in the wake of the Iranian revolution. It means, for example, that research on local labor practices and rules should be at least as thorough as the soils and hydrology work done at the site.
- Train project managers to be geared at least as much to the project's institutional environment as to the internal project organization. Include experts on institutional issues in the projects, to provide broader support for project managers. For example, having the operating manager for the project work with the project's institutional environment in the early phases might provide some valuable project management support. (Of course, the project manager would have to remain in control of the project until the start of production.)
- Question whether the introduction of proposed new technology, construction techniques, or design approaches is absolutely

essential to the mission of the project. Sometimes innovation cannot be avoided in a megaproject, but it is prudent to investigate, following the sage dictum of always attempting to "make mistakes on a small scale and make money on a large scale."

ACKNOWLEDGMENTS

Many RAND staff members and people associated with the projects examined assisted in the research for this report. Bernard Aboba, Susan Anderson, Susan Bell, Loretta Merrow, Eleanor River, and Kathy Rosenblatt all contributed to assembling the database.

Reviews of an earlier draft by John Hackney, a prominent consultant to industry on capital projects, and James Stucker, a senior member of RAND's Systems Sciences Department, substantially strengthened the final report. The editorial work of Janet DeLand has resulted in a much clearer and more readable report.

We extend special thanks to the RAND library staff, who worked long, often frustrating hours to meet our demands for information on projects from all over the world. We hope that the result justifies their efforts.

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I. INTRODUCTION

The past 20 years have seen a virtual explosion in the number and variety of very large, so-called megaprojects—mammoth hydroelectric projects such as Tarbela in Pakistan, Itaipu in South America, and James Bay in Canada; pipeline projects such as the Trans Alaska Pipeline System (TAPS) and Argentina's Centro-Oeste Project; refinery and petrochemical complexes in Indonesia, Texas, and Saudi Arabia; mining and minerals-extraction projects such as Cerrejon in Colombia, the Statfjord Platform in the North Sea, Australia's Cooper Basin Project, and Papua New Guinea's huge copper and gold mining complexes; nuclear powerplants in many countries and synthetic-fuels plants in South Africa, Canada, and Colorado; and basic infrastructure projects such as shipping ports, airports, new cities, and universities.[1] Increases in the size of fixed capital projects[2] have been driven by the desire to exploit economies of scale, the needs of less-developed countries (LDCs) for basic infrastructure development, and the need to exploit increasingly remote and low-grade energy and other mineral resources. The desire of owners to go through complex and difficult approval processes once for a very large project rather than several times for smaller ones may also have increased the number of megaprojects.

As prices of energy plummeted and much of the world sank into a period of recession or slow economic growth in recent years, the number of new starts of megaprojects declined. This therefore appears to be a good time to systematically evaluate how well megaprojects have worked. The need for such an evaluation is summed up well by an Exxon engineer:

> To our despair, [megaprojects] often develop lives of their own and their lives sometimes defy control by us mere mortals.[3]

There is a common perception that megaprojects are not only difficult, but often unsuccessful. Whether megaprojects succeed or fail and the ways in which they do so are important, for a variety of reasons. A

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[1] A list of the projects included in this analysis is found in Appendix A to this report.

[2] A "fixed capital project" is any project *constructed at a site.* This definition excludes anything that is manufactured in one place and then purchased and used elsewhere, such as an airplane.

[3] D. G. Engesser, "Management of Large Projects," *Proceedings of the American Institute of Chemical Engineering Conference on Engineering and Construction Contracting,* September 20, 1982.

successful megaproject can spur economic growth in LDCs, while a failure can set development back for years. Such enormous sums of money ride on the success of megaprojects that company balance sheets and even government balance-of-payments accounts can be affected for years by the outcomes. Security in energy and other natural resources can be either enhanced or jeopardized by the success or failure of a megaproject.

The study reported here addresses the following questions:

- Have megaprojects generally met their cost, schedule, performance, and profit goals?
- Do megaprojects typically have more bad outcomes than smaller projects?
- Is "bigness" itself a problem, or are adjuncts of size, such as having equity partners, using new technology, or building in remote areas, the real culprits?
- What factors drive good and bad outcomes?
- What steps can be taken to minimize the cost, schedule, and performance risks associated with megaprojects?

This study was undertaken to assist in the decisionmaking involved in the development and execution of very large nonmilitary projects. It should be useful to:

- Project planners and senior executives in industries that are most likely to sponsor future megaprojects, especially in energy and other natural-resources development.
- Government officials charged with decisions on major public projects.
- Government officials charged with regulation and other forms of public control of projects.
- Project cost estimators and schedulers in both industry and government.
- Persons concerned with economic development, especially in the poorer nations of the world.

PROJECTS EXAMINED IN THIS STUDY

The database developed in this study consists of 52 projects with an average cost of about $2 billion (in 1984 dollars), which required, on average, more than four years from the beginning of detailed engineering to the end of construction. We define megaprojects simply as projects whose capital cost for completed construction (without any startup costs) exceeds $1 billion in constant 1984 dollars. Other definitions, such as number of total engineering or construction days, are possible, and may even be preferable. We use dollar cost because it is the only uniform measure of size that was universally available to us. Because we were interested in determining whether there is a noticeable difference in outcomes between large projects and very, very large projects, we focused on projects costing $500 million and over.

Megaprojects have a number of characteristic traits that are closely associated with many of the headaches that are presumed to accompany very large projects. Megaprojects tend to stretch available resources to the limit (and sometimes beyond)—resources such as labor, supplies of bulk materials such as concrete and pipe, managerial skills, and information systems. Megaprojects are often built in areas with inadequate basic infrastructure, i.e., transportation, communications, housing, and health and sanitation facilities. The climate may be hostile and the culture alien to those responsible for project management. Megaprojects often have a high profile within the sponsoring firms and agencies and in the politics of the host countries or political subdivisions. Megaprojects rarely go unnoticed by regulators. The success of these projects is so important to their sponsors that firms and even governments can collapse when they fail. Finally, megaprojects are usually long projects; thus there is ample time for things that affect project outcomes to change, and there is less likelihood of maintaining continuity in project management. Megaprojects, even when highly successful, are difficult projects.

ORGANIZATION OF THE REPORT

Section II describes the data-collection methods, the resulting database, and the statistical methodology used in the report. It discusses possible biases in the analysis that might result from extensive reliance on the open literature and some of the tests that we performed to check for such biases.

Section III presents a conceptual model of the causes of cost growth in megaprojects, and, by extension, schedule slippage. In particular, it discusses the ways in which megaprojects may be different from smaller projects of the same type.

In Section IV we address the issue of cost growth in megaprojects. The results of our quantitative analysis of cost growth are presented, and the qualitative factors that appear to influence cost growth among our cases are described.

Slippage in project schedules is examined in Section V. Nowhere is it more true than in megaprojects that "time is money." We present both a quantitative statistical analysis and a qualitative discussion of the factors associated with greater or lesser slippage in project schedules.

Section VI examines the factors associated with good and bad performance in megaprojects, in particular, the relationship between the use of new technology and poor project performance.

Finally, Section VII summarizes our conclusions about the factors that cause or influence the cost, schedule, and performance outcomes of megaprojects, especially those factors that can be manipulated through better management practices or investment strategies, and we compare our findings with the conventional wisdom in this area.

II. THE DATABASE AND METHODS OF ANALYSIS

To better understand the factors that shape the outcomes of large and very large capital projects, we developed a database of such projects. Past experience with similar analyses led us to conclude that we would need at least 35 projects for which all important data were available to perform robust statistical analyses. Using a variety of open data sources, we identified over 160 projects dating back to the mid-1960s that cost at least $500 million in constant 1984 dollars. Because most nuclear powerplants fit our cost criterion and because data were likely to be available, we included six of these projects in the database. Inclusion was based on the following criteria:

- The projects had to be *fixed capital projects,* i.e., facilities built at a site, as opposed to, for example, an aircraft development program. Otherwise, projects could be of any type—civil works development, minerals extraction, transportation, chemical processing, etc.
- The project's final cost had to be $500 million or more in constant 1984 dollars. While we would not normally call a $500 million project a megaproject, we were interested in understanding the differences, if any, between megaprojects and projects that are simply very large.
- To ensure that outcome information would be available, projects had to have been completed by mid-1985. We also included a few that were completed later.
- Geographic location was not restricted, but as a practical matter we excluded the Communist bloc, to avoid problems in obtaining information.
- Projects could be owned by government, industry, or a combination thereof.
- Finally, adequate information had to be available on cost growth, schedule, and key characteristics so that only minor augmentation would be needed from the project owners and contractors.

Fifty-two of the candidate projects met all of the criteria. This database is described below.

CHARACTERISTICS OF PROJECTS IN THE DATABASE

Figure 2.1 shows the distribution of the six types of projects contained in the database. In order of frequency, they are:

- Process and other manufacturing plants, including petrochemical complexes, steel mills, and pulp and paper mills.
- Petroleum refining complexes, including both greenfield and large expansion projects.
- Minerals extraction projects, including oil and natural-gas production facilities (both onshore and offshore), coal mining, metals mining and smelting, and synthetic-fuels mining and processing facilities.[1]
- Civil construction projects, including air and water ports, dams, and other infrastructure facilities, and transportation projects, all of which are energy pipeline projects.[2]
- Powerplants.

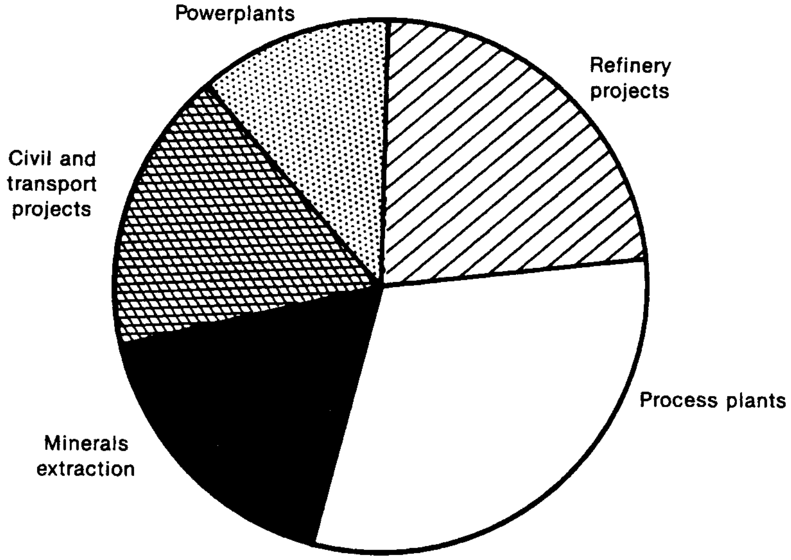

Fig. 2.1—Types of projects in the database

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[1] Synthetic-fuels facilities such as oil-sands and shale plants could be placed in the "process plants" category as well. Because these facilities are inextricably linked to mining, however, we have elected to include them as minerals extraction projects.

[2] We grouped these projects because they all involve enormous amounts of civil engineering.

Project Size

All 52 of the projects were major, complex undertakings. Even the smallest of them would not be considered routine by the owners or contractors involved. Project size is described below in terms of total cost, length of time to complete the project, and physical output.

Figure 2.2 shows the distribution of actual capital costs of the projects. The average project cost was just over $2.4 billion in constant mid-1984 dollars; the least expensive cost just under $500 million, and the most expensive cost nearly $14 billion. The least costly projects are all process plants, e.g., "world-scale" petrochemical complexes, a refinery expansion project, and a copper smelter. The most expensive projects are dams, such as Itaipu and Tarbela, and some of the synthetic-fuels facilities.

Figure 2.3 shows project length, as measured from the beginning of detailed engineering to the end of construction. The average project required 58 months to complete. As with dollar cost, however, there is enormous variation: The shortest project took just 32 months, while the longest required over a decade. As Fig. 2.3 indicates, the median project took more than four years, and over a third of the projects took more than five years. Four projects—two very large dams and two nuclear powerplants—required over nine years to complete. Because

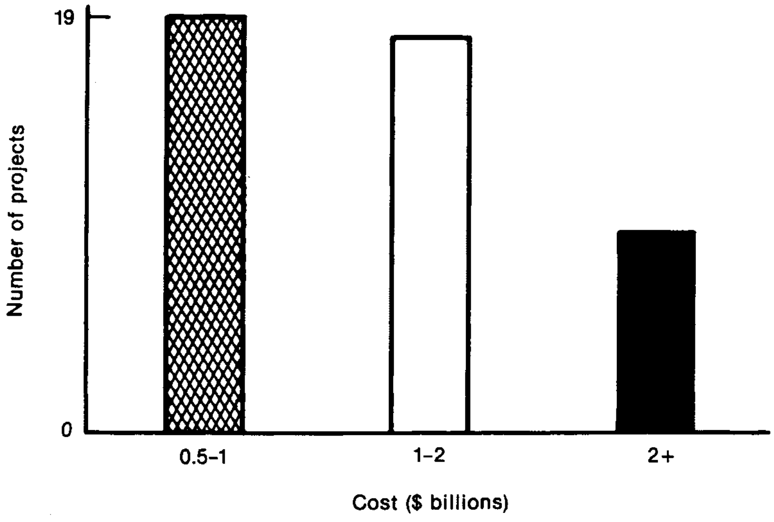

Fig. 2.2—Project cost

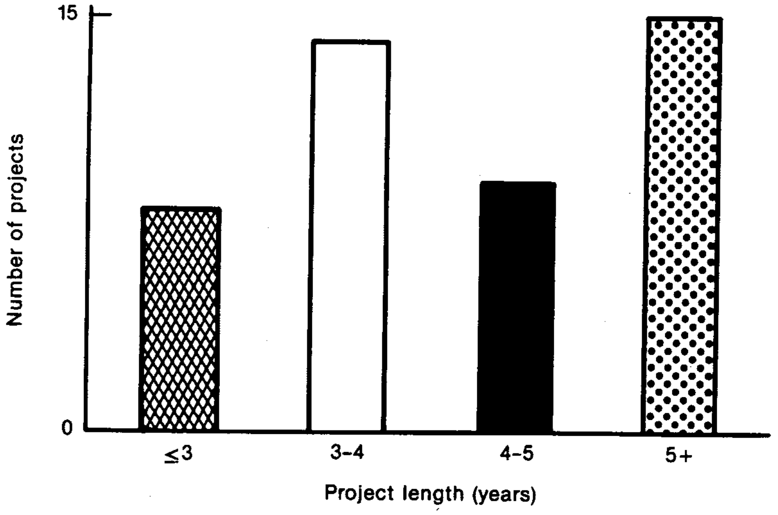

Fig. 2.3—Project length

many of these projects had lengthy planning and definition phases, and some had protracted startups, the average total project length is probably at least two years longer than the 58 months calculated.

Another measure of the prodigious size of these projects is their physical output. We measured capacity as the expected annual production from the project, in millions of pounds. We found that the average megaproject produces nearly 25 *billion* pounds per year. (The magnitude of this output can be appreciated by comparing it with the approximately 3 billion pounds of chemicals a large petrochemical complex produces per year.) However, the average is misleading in this case. As shown in Fig. 2.4, the capacity of most projects is less than 20 billion pounds per year equivalent—still an enormous amount.

In some cases, it was impossible to use a capacity measure; for example, the weight of production from an airport has no meaning. In 45 of the 52 projects, however, we were able to calculate output weight. Because the projects are so diverse, it was necessary to make a number of assumptions, and the resultant capacity measure is necessarily crude.[3] Nonetheless, capacity appears to work as a measure of size

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[3] For example, for electricity-producing projects we used the average weight of the equivalent amount of coal that would be required on an annual basis, assuming an annual capacity factor of 65 percent and a heat rate of 9,500 Btu per KWh to produce the number of megawatts on the nameplate.

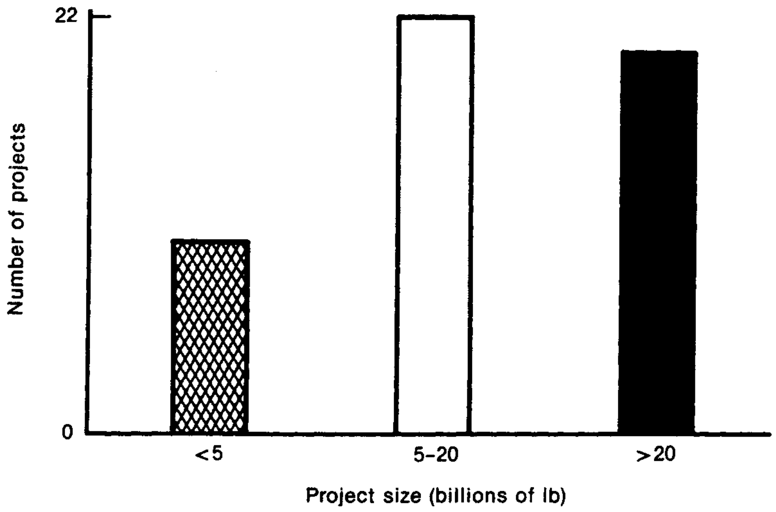

Fig. 2.4—Physical output of projects

because it does correlate well with other factors related to project size: actual and estimated cost, actual and estimated schedule, peak labor force on site, etc.

Project Location

Geography can affect project results in several ways. Some political jurisdictions have regulatory and other constraints that cause problems, and many LDCs lack the infrastructure necessary for the logistics of very large projects. Finally, labor availability and quality can vary enormously within countries as well as across international boundaries.

Because of the possible effects of geography on project results and the difficulty of project management, we wanted diversity in the database. The projects, therefore, are drawn from 16 countries. Figure 2.5 shows the geographic distribution of the projects. The United States is heavily represented—one-half of the projects have U.S. locations—because (1) megaprojects are overrepresented in the United States, and (2) data were more readily available for U.S. projects. We differentiated between the Gulf Coast and other U.S. locations because construction costs are generally considered low in the Gulf Coast area, where several very large energy-related facilities have been built in the past 15 years.

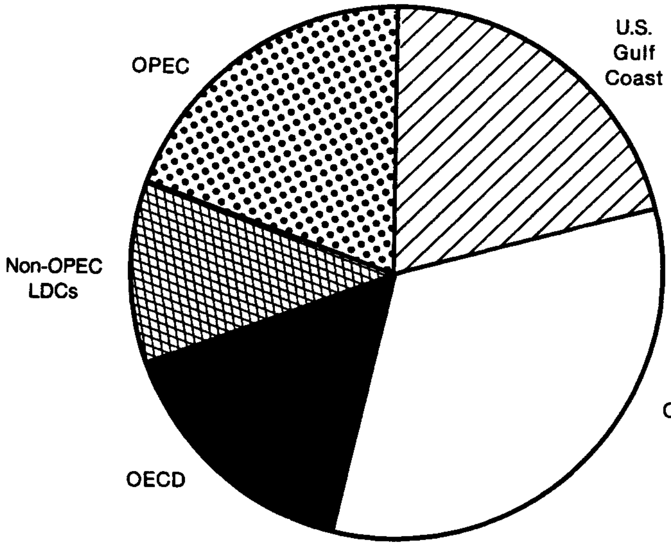

Fig. 2.5—Project location

For foreign-based projects, we distinguish between economically developed nations, such as members of the Organization for Economic Cooperation and Development (OECD), and LDCs. Among the LDCs, where one-third of the projects in the sample are located, we distinguished between members of the Organization of Petroleum Exporting Countries (OPEC) and others.

We also considered the effect of geographical remoteness. We defined a project site as "remote" if a labor camp was required for most construction workers. Generally, a labor camp is needed if the site is not within 100 miles of an urban area of sufficient size to provide for or accommodate the construction labor force. Remote sites obviously present several problems: Labor must be imported, transportation for heavy equipment may be a problem, local services must be provided, etc. Table 2.1 shows the distribution of remote and nonremote projects. For obvious reasons, all the minerals-extraction facilities and pipelines are located in remote areas—nonremote minerals extraction opportunities have long since disappeared in most parts of the world. Most of the other types of projects were located in nonremote areas, although remote sites are represented in each class.

Table 2.1

TYPES OF PROJECTS AND REMOTE SITES

Project Type	Remote	Nonremote
Minerals extraction	8	0
Nuclear plants	1	5
Civil projects	2	4
Refineries	3	9
Process plants	6	11
Pipelines	3	0
Totals	23	29

Project Ownership

Fourteen of the projects in the database, including major infrastructure projects and projects of nationally owned firms, are owned entirely by the public sector. In ten projects, one or more governments are equity partners, either directly or through a government-owned corporation. Thus, almost half of the projects have some form of direct government equity involvement.

International oil companies own most of the private-sector megaprojects. Thirty-three of the projects in the database have some oil-company investment, and oil companies are partners in most of the mining ventures, even nonenergy mining. Given the huge amounts of capital available to oil companies in the 1970s and the international character of those companies, such extensive involvement in very large projects is not unexpected.

It is also not surprising that more than half of the megaprojects are joint ventures.[4] We include as joint ventures projects owned by more than one company (such as the Red Deer Ethylene Project and the Cooper Basin Project), projects owned by more than one government (such as the Itaipu high dam), projects owned by combinations of governments and companies (such as the Yanbu refinery and the Ok

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[4] Joint ventures are much more common in the megaprojects database than in the RAND pioneer plants database, discussed in Edward W. Merrow, Kenneth E. Phillips, and Christopher W. Myers, *Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants*, The RAND Corporation, R-2569-DOE, September 1981. Only a few of the pioneer process plants are joint ventures, and those are among the very largest in the database. Most of the projects in the pioneer plants database are much more innovative than a random sample of process plants would be, and many of them entailed significant technical risk. None of the technically risky projects were joint ventures, which suggests that *technical risk* does not by itself induce firms to form joint ventures. The introduction of a significant technical innovation may even act as a barrier to forming a partnership, as the innovator may fear losing sole control over the new technology.

Tedi mine), and projects owned by two or more companies that have formed a corporate entity for the purpose of undertaking the project (such as the Syncrude Ltd. Project in Alberta).

Table 2.2 shows the attributes of megaprojects in the database that are associated with being a joint venture. Multiple partners help to spread the financial risk associated with megaprojects. Even if a project is not deemed particularly risky, any cost overruns or performance shortfalls can have huge financial consequences. It is not surprising that more expensive projects tend to be joint ventures.[5] Projects being built at new sites (so-called "greenfield" projects) that are removed from labor supplies also tend to be joint ventures, as do projects requiring extensive infrastructure development, e.g., minerals-extraction projects. Joint ventures may be formed to share special skills or resources or even because of joint ownership of a natural resource, such as the Itaipu dam.

Joint ventures may also be formed to meet a host-country requirement that the project involve a domestic (often government-owned) company. A partner from the host country can often provide better knowledge of local regulations and business practices and may be thought to provide some protection against unwanted interference by the host government. As discussed later in the analysis of cost growth and schedule slippage, having a government for a partner can create both problems and opportunities.

Table 2.2

CORRELATES OF JOINT VENTURES

Project Attribute	Correlation[a]
Total project cost (log)	+.44
Estimated project cost (log)	+.43
Greenfield project	+.34
Importation of labor was necessary	+.32
Temporary infrastructure construction necessary	+.42
Permanent infrastructure was constructed	+.34
Project involved minerals extraction	+.41

[a] All correlations significant at a probability of .05 or less.

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[5] The correlation shown in Table 2.2 is for the natural log of cost and estimated cost. Because cost and estimated cost range through several orders of magnitude, the logs provide a more linear and reliable method of calculating the correlation coefficient than the unscaled numbers.

METHODS OF ANALYSIS

Obviously, cost, schedule, and performance outcomes for a project are not strictly independent. Cost and schedule are closely linked by common causal factors, both directly and when delays force costs up. As discussed below, cost, schedule, and facility performance are also affected by technological innovation.

We examine each of these interrelated dimensions separately because in the projects for which data were available, both cost growth and schedule slippage are measured from the beginning of detailed engineering to the end of construction. Schedule slippage and cost growth associated with operational performance problems occur during startup, the length of which we were unable to measure. Scheduling decisions that might directly affect performance—e.g., a decision to begin detailed engineering prior to the completion of R&D—tend to occur prior to the beginning of detailed engineering. Because of these data limitations, we elected to examine each project outcome separately.

Statistical Methods

In addition to simple cross-tabulations, we use correlation, ordinary least-squares multiple regression, and logit regression to examine the database. Correlations are used in two ways: to show the simple relationships between variables and to show the relationships between potential explanatory variables and the residual variance from regression. The latter use shows that factors that might be thought to be associated with cost growth, schedule slippage, or facility performance shortfalls appear to be unrelated after the factors in the regression are considered.

Multiple regression is used because it is the best available parametric technique for associating sets of variables with particular project outcomes such as cost growth and performance. Regression also has some well-established diagnostic techniques that enable us to test the statistical quality of the models. The regression estimation technique was determined by the character of the dependent variables. Cost growth and schedule slippage are continuous measures, so least-squares was used. Our measure of facility performance, however, was binary: Did the facility experience performance problems or not? We therefore used logit regression, because least-squares may produce unreliable results with a binary dependent variable.

Sources of Data and Collection/Coding Procedures

Because budget constraints precluded visits to each owner or site to collect data, we relied primarily on publicly available information. We identified projects by reviewing energy, chemical engineering, civil engineering, and general engineering trade magazines and journals dating back to about 1970. We also reviewed the annual reports of more than 100 major engineering, energy, minerals, and chemical companies, searching for mention of large projects. We identified 167 projects, dating back to the mid-1960s, that appeared to have costs of at least $500 million in 1984 dollars, not including nuclear powerplants. Because most nuclear powerplants would fit our cost criterion and because data were likely to be available, we also selected a sample from that category.

After an initial list was prepared, on-line computer searches were conducted to locate articles, papers, and books on each of the projects identified. We collected the published material for each project and coded the results. (The coding worksheet we used is reproduced in Appendix B.) The accuracy of the coding procedures was checked with a blind test-retest procedure, which produced very high rates of agreement.

Possible Bias Introduced by Data Collection Methods

Collecting information primarily from secondary and journalistic sources has some potential pitfalls: (1) The distribution of outcomes may be skewed, and (2) information about the projects may be distorted.

The projects in the final database for which relatively more information was available in the public domain were projects about which someone, and usually a number of people, decided to write. Since projects with either very good or very bad results make better copy than those with unremarkable outcomes, it is possible that the cost growth and schedule slippage distributions may be somewhat skewed to the high and low ends. However, we are not particularly concerned about this possibility, for several reasons: First, only a little over half of the projects in the database have been subjected to such a filter; the others were either randomly drawn or were projects for which we had data from the sponsors prior to this study. Second, the projects did not have to perfectly mirror the universe of megaprojects to provide meaningful results about the relationships between project characteristics and results. The projects only had to be well distributed along the range from good outcomes to bad, and the database had to contain project characteristics associated with the outcomes.

We were also concerned that the data obtained from the public record might be distorted or simply wrong. Distortions could have occurred for at least two reasons:

- Project sponsors are often the chief source of information about projects discussed in published articles. Sponsor personnel write the articles for professional journals, and their manuscripts are usually screened by their employers. There is a perfectly understandable tendency for project sponsors to accentuate the positive and minimize any difficulties.
- Journalistic accounts, especially of projects that have become politically controversial, may be unbalanced in precisely the opposite way. A journalist looking for a sensational story of ineptitude and corruption may choose not to discuss a project's important achievements.

Given the constraints of our data collection approach, there was no way that such problems could be completely eliminated. When coding the data for each project, however, we tried to balance the clearly negative and clearly positive accounts. In addition, in some cases we were able to clarify ambiguities by contacting project participants and by using other sources.

On the whole, we believe that the database accurately represents the projects it contains. Although some of the data are probably inaccurate because of the inherent limitations in our collection procedures, as long as the inaccuracies are random with respect to project results and characteristics, their only effect will be to limit our ability to perform accurate statistical analyses.

As shown in Sections IV through VI, we were able to account for most of the variation in cost growth, schedule slippage, and project performance using the characteristics in the database. Furthermore, the relationships between the predictor (independent) variables and these key project outcomes are reasonable and interpretable. This suggests very strongly that project information from public sources is in fact fairly accurate. The major weakness of the available data is insufficient detail to allow us to measure factors that we believe *should* be related to project outcomes. The most obvious example of this is our inability to measure the status of project definition at the time cost and schedule estimates were made. As discussed in Section III, this is a conceptually important variable.

Data Normalization

Prior to analyzing cost growth or schedule slippage of the projects in the database, we sought to minimize differences between projects caused solely by measurement problems. Our normalization procedures are described below.

To measure cost growth, we used estimated costs and final costs. Because cost growth is known to be related to the point in the project when costs are projected, we tried to use the estimate closest to the beginning of detailed engineering in all cases. We then removed the effects of inflation from the estimate, using the following procedure:

- Where necessary, currencies were converted to U.S. dollars, based on the exchange rates prevailing at the time.
- Unless we had information to the contrary, we assumed (in accordance with usual industry practice) that every cost estimate contained an escalation factor that inflated the entire estimated cost to the forecast midpoint of construction.
- We assumed that the escalation factor used was the rate of inflation in the appropriate cost index that occurred in four quarters prior to the time the estimate was made.
- We then inflated the entire cost estimate from its constant-dollar base year to 1984 dollars, using an appropriate cost index.[6]

This procedure removes the effects of inflation from the estimates and actual costs.[7]

The actual costs of projects were adjusted in a similar manner, except that expenditures were spread across the schedule, using an empirically derived cosine curve wherever the stream of expenditures was not provided in the documentation.[8] Costs expended in each year were then brought forward to 1984 dollars. Constant dollar costs for nuclear plants were obtained from earlier work by William Mooz.[9]

Schedule data were normalized by measuring the time from the onset of detailed engineering to the completion of construction. Gen-

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[6] For most projects we used the *Chemical Engineering Index.* This index very closely parallels the gross national product (GNP) price deflator and is a good overall index for process and refinery costs. For nuclear plant estimates, we used the Handy-Whitman index, and for civil projects, the *Engineering News-Record* (ENR) index.

[7] See Merrow, Phillips, and Myers, op. cit., 1981.

[8] The cosine curve was provided by John W. Hackney in a 1980 course entitled "Cost Engineering Economics."

[9] See William E. Mooz, *Cost Analysis of Light Water Reactor Power Plants,* The RAND Corporation, R-2304-DOE, June 1978, and *A Second Cost Analysis of Light Water Reactor Power Plants,* The RAND Corporation, R-2504-RC, December 1979.

erally, it is preferable to measure schedule to the completion of startup or "commissioning" of a project, but the available data on startup time were too sparse to permit that. The milestones chosen were available in the open literature for most projects and were subject to relatively little ambiguity. As with the cost estimates, we used the forecast of completion date made closest to the onset of detailed engineering as the basis for our schedule slippage estimates.

The Functional Form for Cost Growth and Schedule Slippage

Cost increases can be measured as the increase in dollars or the percentage increase in project costs. Analogously, schedule slippage can be measured in months or as a percentage of the planned schedule. In this analysis, we have used the ratio of the cost estimate to the actual cost of the project as our measure of cost growth and the ratio of planned to actual time as our measure of schedule slip. This, however, in effect controls for project size: A 10 percent increase in the cost of a $1 billion project will have the same weight as a 10 percent increase in the cost of a $10 million project, and a 1-month slip in a year-long project will have the same weight as a 6-month slip in a project planned for 5 years.

In the real world, however, given a distribution of possible cost growth results, one would be much more concerned about cost growth in a megaproject than in a smaller project. One may be indifferent between 1 percent cost growth in a megaproject and 1 percent in a small project, but this is probably not true for larger levels of cost growth because the consequences are so different. A 200 percent cost growth in what was estimated to be a $10 million project might eliminate the possibility of profit from the project, but it is not likely to be catastrophic to any but a very small firm. A 200 percent cost growth in what was to have been a $2 billion project, on the other hand, could swamp a company and even some governments. Thus, when considering megaprojects, one does not have the comfort of the law of large numbers.

Why, then, have we chosen to use the ratio measure? There are two basic reasons:

- We have no method for assigning the tradeoff between the perceived disadvantage of cost growth and schedule slippage and project size. If we assumed that there is no causal relationship between size and cost growth, we would hypothesize that project sponsors would be more concerned about and would take more extensive measures to prevent cost growth in megaprojects than in smaller projects.

- The ratio formulations provide normally distributed dependent variables that are easily interpreted and that eliminate the need to transform the variables, thereby decreasing the chances of obtaining misleading results.

Selecting the Base Estimate

More than one cost estimate is made for virtually all capital projects over the life of the project; at least three estimates are usually made, and frequently there are five or more.[10] For a variety of reasons, estimates made later in a project will be generally more accurate than those made earlier.[11] If we wish to compare the accuracy of estimates across projects, we must compare estimates made at about the same point in project development or the comparisons will be specious. Fortunately, large capital projects pass through typical stages on their way to completion: R&D (for projects that incorporate innovative technology), project definition and early engineering, detailed engineering, construction, and startup and operation. As our common reference point, we selected the cost estimate made closest to the commencement of detailed engineering.

This is usually the critical cost estimate for the "go/no-go" decision on a project, and it typically results in the authorization for expenditure (AFE). Because the early stages of a project, those prior to the onset of full engineering, account for a relatively small portion of the whole project cost (usually a few percent at most), the decision about whether to commit to the completion of a project can (and probably should) be postponed until those stages are complete. When detailed engineering begins, expenditures begin to mount rapidly. Detailed engineering alone accounts for more than 10 percent of total project cost, and site preparation work often begins concomitantly with detailed engineering or soon after.

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[10] For a discussion of different kinds of project estimates and the functions they perform, see Edward W. Merrow, Stephen W. Chapel, and Christopher Worthing, *A Review of Cost Estimation in New Technologies: Implications for Energy Process Plants*, The RAND Corporation, R-2481-DOE, July 1979.

[11] For a discussion of the reasons, see Merrow, Phillips, and Myers, op. cit., Secs. II, III, and IV.

In most cases, any changes in the scope of the projects in our database were made before the AFE.[12] This greatly reduces the need to make adjustments for changes in scope and is particularly important for this analysis because the kind of detailed information that would have permitted such adjustments to be made accurately were often not available.

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[12] Changes in scope are any *discretionary* changes in the size or configuration of a project. We do not include as scope changes modifications that are required to meet the original intent or goals of the project.

III. A CONCEPTUAL MODEL OF COST GROWTH IN MEGAPROJECTS

In this section, we present a conceptual framework for cost growth in megaprojects. We start with a general model of cost growth and then concentrate on how and why cost growth in megaprojects might differ from that in smaller projects.

As shown in Fig. 3.1, the causes of cost growth are not conceptually difficult to understand. There are only a few possibilities that can logically cause estimates and schedules to be wrong. In the simplest terms, deviations from cost or schedule occur because:

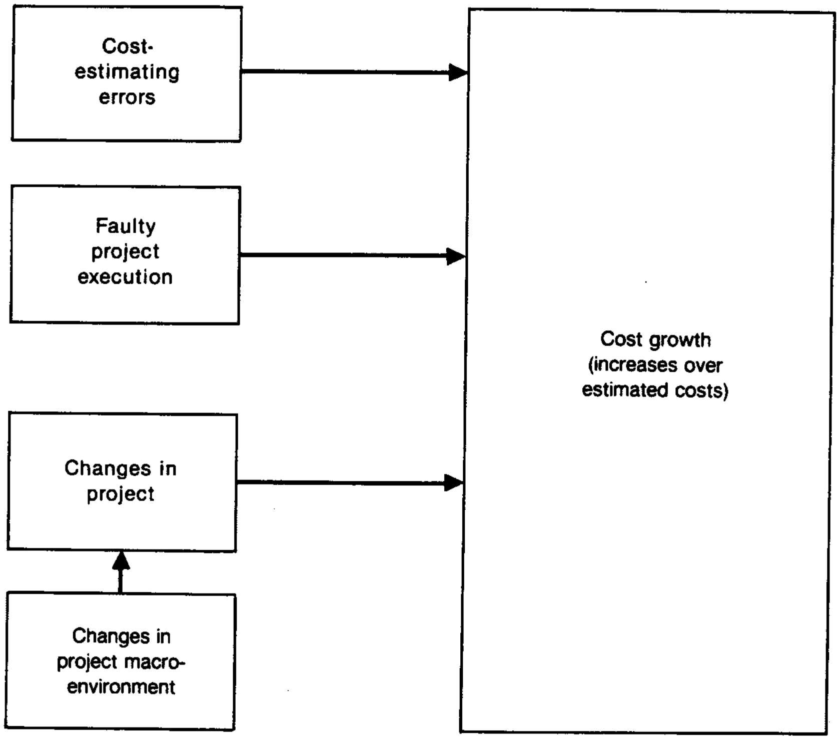

Fig. 3.1—A conceptual model of cost growth

- The estimates themselves were faulty.
- Project execution was faulty, causing costs to be higher (and schedules longer) than necessary.
- The project was changed—the thing estimated was not the thing actually built.
- The macroenvironment—the "state of the world"—assumed by the estimator was unrealistic, resulting in changes in the project or input costs.

The following discussion of these categories shows that, in practice, the causes of cost growth can be difficult to disentangle.

FAULTY COST ESTIMATES

The very word "estimate" connotes uncertainty. Estimates of cost can be either too high or too low, but for a variety of reasons, they are usually too low.[1]

Cost estimates tend to be optimistic primarily because it is difficult to estimate aspects that are not apparent when using the "bottom-up" cost and schedule estimating approach usually practiced in the engineering and construction industry. In the absence of specific information, such estimating methods usually fix at zero the costs and time requirements for things that are not readily apparent. Contingency allowances are not designed to adjust for the major sources of bias and therefore rarely do so.[2] Bottom-up cost estimation techniques usually work well only for standard (i.e., non-innovative) projects that are not

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[1] Cost estimates may be made too low to convince the person making the funding decision to proceed with a project he would otherwise reject as too costly. It would be naive to assume that cost estimates never involve deliberate deception. However, we do not believe that deliberate misrepresentation is the norm for the estimates examined in this report, for several reasons. First, deliberately underestimating costs is more common for very early cost estimates than later ones, because it is harder to hide costs as the dimensions and needs of a project become known. Deception in later stages probably requires at least the tacit cooperation of the project sponsor. In the projects we examined, there was little or no incentive on the part of owners/sponsors to go along with deception. Second, numerous suppliers provide engineering, construction, and cost estimating services for capital projects. Thus, lying to clients can lead to losses of future work. Third, if deliberately biased estimates were a major problem, we would not expect other factors to be able to account for much of the variation in cost growth. Finally, professional norms among cost estimators may help to overcome the temptation to make overly favorable assumptions. We will not consider this factor further, but it should be watched for, especially when assessing early estimates. See J. P. Large, *Bias in Initial Cost Estimates: How Low Estimates Can Increase the Cost of Acquiring Weapon Systems*, The RAND Corporation, R-1693-1-PA&E, February 1976.

[2] See J. J. Milanese, *Process Industry Contingency Estimation: A Study of the Ability to Account for Unforeseen Costs*, The RAND Corporation, N-2386-PSSP, January 1987.

perturbed by other problems, such as changing regulations. Even then, such techniques tend to underestimate cost and time in the early stages of project development.[3]

Poor project definition at the time an estimate is made is the most important source of faulty estimates. Projects evolve from general, often hazy ideas into highly specific plans that are ultimately transformed into physical reality. The closer the project is to completion, the easier it is to see and account for all aspects that contribute to cost and time. The better the definition of the project and the more detailed and all-inclusive the information available to the estimator, the better (i.e., less optimistic) the estimate will be.[4]

Project *complexity* also adds to the tendency to underestimate costs. Complexity adds to the estimator's task by increasing the number of areas that require definition; it also makes the interactions between different facets of a project more likely to go unnoticed and therefore unestimated.

Finally, before an estimate is completed, the estimator must make a set of *economic assumptions*, the most important of which concerns the amount of inflation to expect for the facility being estimated.[5] For long projects, which most megaprojects are, even small errors in the assumed inflation rate can make large changes in the number of dollars expended. As discussed below, we remove the effects of inflation in our analysis by adjusting the estimates and actual costs to a constant dollar basis.

In general, we would expect cost and schedule estimates for megaprojects to be slightly less accurate than analogous estimates for smaller projects, for several reasons: Megaprojects are more complex than their smaller cousins; they frequently involve the construction of significant amounts of infrastructure, while small projects rarely do; and they take more time, which makes escalation more likely to affect estimates.

Because most of our data come from publicly available sources, we do not have the detail necessary to measure the state of project definition for each of the cost estimates available to us. We therefore measure cost growth and schedule slippage from the same point in project

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[3] For a discussion of problems with the state of the art in cost and schedule engineering, see Merrow, Chapel, and Worthing, op. cit.

[4] Prior statistical analyses of cost growth have demonstrated beyond doubt the importance of project definition. See Merrow, Phillips, and Myers, op. cit.; and J. W. Hackney, *Control and Management of Capital Projects*, John Wiley and Sons, New York, 1965.

[5] In one sense, making correct inflation assumptions is much less important than it seems. Inflation *per se* does not increase the real costs of a project or change its fundamental economic value, provided the products' prices keep pace with the costs of the facility.

development, i.e., the onset of detailed engineering. By selecting a similar point in the evolution of all of the projects, we should be able to dampen the variability in cost growth and schedule slippage due to differences in project definition.[6]

FAULTY EXECUTION

Project execution consists of the detailed engineering, procurement, cost/schedule/quality control, construction, and commissioning of a project. Without doubt, more has been written about the "how to's" of project execution than all other aspects of project management combined. We concede that serious blunders in the execution of a project can lead to significantly higher costs than necessary. However, to our knowledge, no systematic analysis of capital projects has ever been made which concluded that blunders by project managers in executing projects are even an *important* source of cost growth or schedule slippage, much less a dominant one. In fact, systematic empirical analyses have consistently suggested that other aspects of project management, such as careful technology selection, conservative project phasing, and thorough project definition, are more important to cost growth, schedule, and performance outcomes.[7]

In some cases, it is possible to point to particular items that are usually subsumed under project execution management as major sources of increased cost. A good example is poor labor productivity. While inept day-to-day labor supervision might lead to poor labor productivity, we strongly suspect that other factors are the underlying causes—factors such as remote sites, failure to plan for adequate manpower training programs, poor understanding of local labor practices,

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[6] The effect of project definition is not eliminated, however, for two reasons. First, we could not always pinpoint which of two proximate estimates was closest to the onset of detailed engineering. This is a measurement error problem. Second, while project definition is correlated with, and to some extent causally related to, different stages in the evolution of projects, the correspondence is not perfect. By the time detailed engineering begins, most projects are fairly well defined. Some, however, are still quite poorly defined. For example, the TAPS was very poorly defined when work started in the field. This undoubtedly contributed to a poorer cost estimate than would have normally been available at that point in project development. Because we cannot fully account for project definition and detail in our analysis of megaprojects, we must expect less precision in the resulting models of cost growth and schedule slippage than would have been possible with more complete data.

[7] See Merrow, Phillips, and Myers, op. cit.; C. W. Myers and R. F. Shangraw, *Understanding Process Plant Schedule Slippage and Startup Costs*, The RAND Corporation, R-3215-PSSP, June 1986; Edward W. Merrow, *A Quantitative Assessment of R&D Requirements for Solids Processing Technology*, R-3216-DOE/PSSP, July 1986; C. W. Myers and M. Devey, *How Management Practices Can Affect Project Outcomes: An Exploration of the PPS Database*, The RAND Corporation, N-2196-SFC, August 1984.

changing or unclear labor regulations, and the like. These factors must be dealt with in the original decision to undertake a project and in early planning. By the time project execution begins, it is usually too late to prevent damage to a project's cost and schedule.

CHANGES IN PROJECTS AND REAL COSTS THAT CAUSE COST GROWTH

The project estimated early in project development is often not the project actually built. Scope changes, technological innovation, and such extraneous factors as unusually bad weather can lead to either changes in the configuration of a project or increases in the cost of its execution. We discuss these below.

Changes in Project Scope

We define *scope change* as any *discretionary* change in the size or configuration of a project. Scope changes include both additions to and subtractions from a project, as well as discretionary changes in the elements that make up the project. Scope changes that reduce the size or number of elements in a project can cause early cost estimates to be too high, other things being equal. Conversely, increases in size or the addition of elements will cause prior cost estimates to be too low.

Most changes in scope result from changing market conditions or a better understanding of the need for the project. The longer a project takes to get to field construction, the more room there is for scope changes to be made, and the more likely they are. However, decreases and increases in scope are both sometimes used by ingenious (or desperate) project managers to mask what would otherwise be cost overruns. By eliminating items or reducing size, managers can sometimes stay within budget without unduly reducing the benefits of the project. Increasing the scope of a project can, by exploiting economies of scale, keep the product unit cost the same as it would have been without any cost overrun. Adding elements to a project can sometimes be used to confuse the issue of whether the project as originally planned was overrunning its budget.

In our analyses, we were unable to adjust estimates or schedules to account for changes in scope because the data necessary for such adjustments were unavailable. When we encountered cases where significant changes in scope occurred after the estimate and schedule had been made, our only course was to delete the cases from the database.

However, we found few such cases because of the relatively late point from which we measured cost and schedule changes.

Technological Innovation

We defined *innovation* simply and broadly as the inclusion of anything novel or commercially untried in the design, materials, or construction of a project. We also included things done in the same manner as before but at a larger-than-ever scale. Innovation is closely related to cost growth in virtually all studies that have considered such relationships.[8]

The relationships between innovation and cost growth and schedule slippage are sometimes obscured by difficulty in identifying innovation. Technological innovation is usually defined as involving "high technology," on the cutting edge of the translation of science into practice. Yet modest and subtle changes from current practice, even *retrogressions* in the state of the art, can cause problems that lead to cost growth and schedule slippage.[9]

Doing something in a different way reduces the amount of information available to the cost and schedule estimator. The effect of innovation on cost and schedule estimates is thus similar to that of poor project definition. It is important to note, however, that innovation may well lead to cost growth and schedule slippage even when it results in cheaper products than had heretofore been available. Innovative technologies frequently reduce cost, but not as much as the early, highly optimistic estimates had suggested.

Other Factors That Can Increase Costs and Schedule

A variety of other factors can also affect cost and schedule. Unusually bad weather, strikes, labor shortages, equipment shortages, and failed deliveries of equipment can all increase the costs of a project, sometimes significantly. However, the duration of megaprojects probably reduces the effects of such factors. Short projects are more

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[8] See, for example, A. J. Alexander and J. R. Nelson, *Measuring Technology Change: Aircraft Turbine Engines*, The RAND Corporation, R-1017-PR, June 1972; E. C. Capen, "The Difficulty of Assessing Uncertainty," *Journal of Petroleum Technology*, August 1976; M. M. Hufschmidt and J. Gerin, "Systematic Error in Cost Estimates for Public Investment Projects," in J. Margolis (ed.), *The Analysis of Public Output*, Columbia University Press, New York, 1970; Merrow, Chapel, and Worthing, op. cit.; Merrow, Phillips, and Myers, op. cit.; and R. Perry, et al., *Systems Acquisition Strategies*, The RAND Corporation, R-733-PR/ARPA, June 1971.

[9] For example, a major source of difficulty for the first commercial nuclear powerplant was that low-pressure steam turbines were no longer available and it was necessary to relearn the art of their manufacture!

likely to be seriously affected by, say, bad weather, than projects that spend several years in the field. In addition, longer schedules may allow for more flexibility to overcome the effects of failed equipment deliveries and the like.

Longer schedules can achieve such beneficial effects only if estimators and schedulers are realistic about the prospects of bad weather, strikes, and so forth. Optimistic assumptions about the weather for the duration of a project's field construction are more likely to hold for a project that spends six months in the field than for one that spends three years in the field.

The "other factors" category illustrates how hard it can be to categorize the causes of cost growth and schedule slippage. For example, failure to account for the effects of extreme cold in arctic regions is categorized as cost growth due to bad estimating, not bad weather. On the other hand, an out-of-season storm that sinks a ship carrying major equipment is categorized as just plain bad luck.[10] Strikes and shortages may be the result of poor management practices that alienate labor and fail to provide proper training and procurement, rather than the result of truly independent cost growth factors.

CHANGES IN THE MACROENVIRONMENT OF A PROJECT

Every project is executed in the context of a particular political, economic, and cultural environment. The legal system, labor practices, attitudes toward worker health and safety, environmental concerns and constraints, and basic economic facts such as the relative prices of key inputs and products are manifestations of the "macroenvironment" of capital projects. The salient elements of the macroenvironment can vary from project to project, geographically (especially from country to country), and in time.

A project's macroenvironment can affect cost growth and schedule in two ways: (1) by being unknown to some degree to the project planners, estimators, and managers, and (2) by changing. In the case of a project with *competent decisionmakers*, poor knowledge of the macroenvironment is usually a greater problem when the project is overseas relative to its owners and primary contractors; for projects that are "at home," change in the macroenvironment is the more likely cause of cost growth and schedule slippage.

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[10] This example is not hypothetical; a ship carrying equipment to the Union Carbide petrochemical complex at Ponce, Puerto Rico, did sink. Significantly, good project management enabled most of the cost and schedule effects to be mitigated.

We hypothesize that misapprehension of cost and schedule effects of the macroenvironment is a major cause of problems in all projects, but in megaprojects in particular.[11] Unlike other aspects of project planning and definition, understanding the macroenvironment has never been fully routinized as a part of project planning, because in familiar surroundings, many aspects of the macroenvironment go completely unnoticed. For example, cultural and linguistic antagonisms between members of the construction work force are usually not relevant for projects built in the United States but may be a serious problem for the same projects built overseas. Similarly, one may assume that there is no need to establish training programs for projects on the Gulf Coast, but there are times when changes in the macroenvironment of such programs are essential to project success (see Section IV).

We believe that megaprojects are more likely to have problems stemming from the macroenvironment because:

- They are more likely to involve owners and contractors whose primary base of operations is outside the cultural and linguistic area of the project.
- They are much more likely than small projects to create their own change in the environment, i.e., megaprojects are often so large and so important in their institutional setting that they create their own uncertainty in the macroenvironment.[12] Unlike their smaller cousins, megaprojects can often spark regulations, political opposition and support, and even the need for new technology. When this occurs, the risks and uncertainties attendant to the project undergo a fundamental and qualitative change. It is no longer possible to manage by following good initial planning, with straightforward execution of the plan, dealing with only minor contingencies along the way. Rather, project management must involve continuous planning and constant adjustment.

THE SPECIAL BURDENS OF MEGAPROJECTS

The conventional wisdom is that megaprojects suffer more cost growth than more modestly sized projects. Table 3.1 lists the factors

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[11] This echoes a conclusion of Ivars Avots, who found that changes in the environment were particularly important for large projects. ("Cost-Relevance Analysis for Overrun Control," *Project Management*, Vol. 1, No. 3, August 1983.)

[12] F. E. Emery and E. L. Trist, "The Causal Texture of Organizational Environments," *Human Relations*, Vol. 18, 1965, pp. 21–32.

associated with cost growth and suggests whether megaprojects are likely to be better, worse, or no different than smaller projects.

We would expect megaprojects to be worse on all but two of the factors listed in the table: the status of *project definition* at any particular stage of the project, and the effects of bad weather. In terms of project definition, megaprojects might be better defined because:

- Cost growth entails such extraordinary absolute dollar risks in megaprojects that owners are probably more cautious about making final funding decisions. They may therefore require more project planning, site definition, and preliminary engineering before authorizing expenditures.
- Many megaprojects are, because of their great financial needs, joint ventures. Joint ventures require a higher level of project definition than single-owner projects, in order to assign risks appropriately.

Table 3.1

ARE MEGAPROJECTS MORE DIFFICULT?

Factor Contributing to Cost/Schedule Growth	Relative Difficulty of Megaprojects	Comments
Cost estimating		
Project definition	Unknown	See text
Complexity	More difficult	
Detail	More difficult	
Economic assumptions	More difficult	Longer schedules
Project execution	More difficult	Remote sites, strange surroundings, difficult logistics
Project changes		
Scope change	More difficult	Longer schedules
Technological innovation	More difficult	Innovation is forced
Other factors		
Bad weather	Unknown	
Labor problems	More difficult	Megaprojects can create shortages
Equipment shortages	More difficult	
The macroenvironment		
Political problems	More difficult	Megaprojects are high profile
Regulatory problems	More difficult	
Cultural/linguistic problems	More difficult	Owners/workers more likely to be expatriates

On the negative side, megaprojects are much harder to define because they are generally much more complex than smaller projects. Furthermore, they often have innovative characteristics—if only their huge physical size—that militate against adequate project definition until detailed engineering is well under way.

The longer project schedules for megaprojects might provide more opportunities to adjust for external factors such as bad weather. On the other hand, longer schedules make it more likely that such external factors will be encountered. In every other respect, megaprojects are unambiguously more likely than smaller projects to be subject to forces that encourage cost growth and schedule slippage. In particular, we emphasize the special, perhaps peculiar, role the macroenvironment can play in shaping the outcomes of megaprojects.

IV. COST GROWTH IN MEGAPROJECTS

In this section, we explore the extent of the actual cost growth in the projects in our database. We also examine statistically the factors and project characteristics associated with accurate or inaccurate cost estimates and present a model that estimates total cost directly as a function of project characteristics.

We start by defining cost growth and its components—estimated and actual costs—and then compare the cost growth in the megaprojects with cost growth in other types of projects. We consider the factors that are (and are not) associated with cost growth in megaprojects. We then describe a statistical model of cost growth in megaprojects and its implications. Finally, we discuss the capital cost model.

DEFINING ACTUAL COST, ESTIMATED COST, AND COST GROWTH

In this study, *actual cost* refers to the capital costs of a facility in U.S. dollars, adjusted to a constant 1984 dollar value. Included are engineering and procurement costs, construction costs, and indirect costs. Actual costs do not include the costs associated with any research and development that may have preceded or accompanied the project, or costs of commissioning and startup, whether or not they were capitalized. The *estimated cost* is the estimate of actual cost made closest to the beginning of detailed engineering.

The typical stages of a project are shown in Fig. 4.1. Unless there is an applied R&D program to ready the technology for commercialization, projects start with a phase called *project definition.* This phase brings a project from the purely hypothetical stage, through the first examination of feasibility, to the point at which all major elements *should* have been identified, a detailed schedule prepared, and a cost estimate prepared. This estimate—the type 2, or AFE, estimate—is the one generally used by project sponsors in deciding whether to go ahead on the project or stop it. For projects that appear to be particularly risky, the final go-ahead may be delayed until the middle or even the end of detailed engineering. We measured cost growth starting at the type 2 estimate and continuing until the completion of construction.

The point at which cost growth is measured is very important. Estimates made earlier, e.g., during R&D or prior to the end of project definition, tend to be subject to much greater cost growth. Later

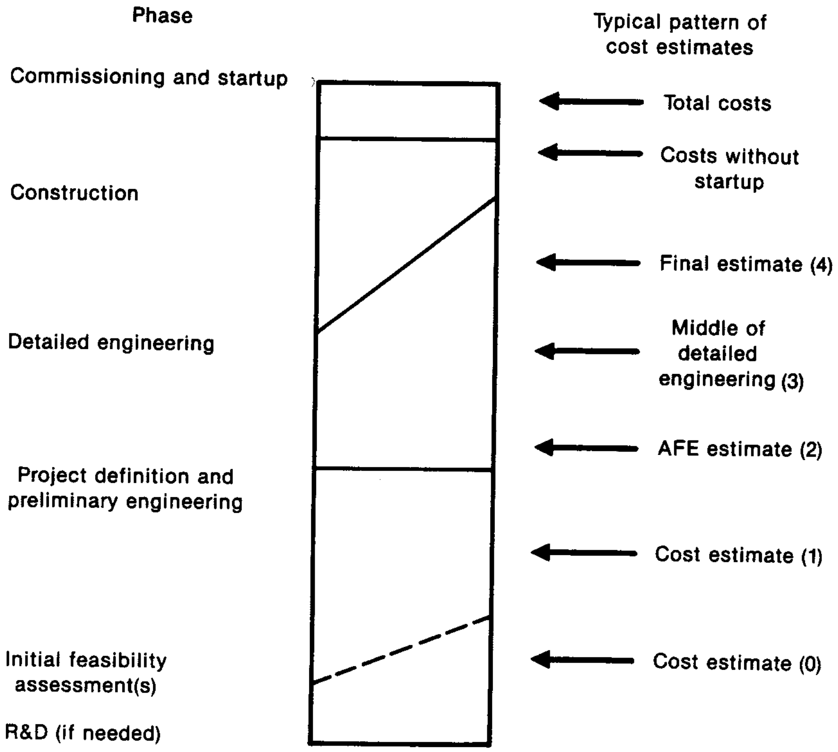

Fig. 4.1—Typical project phases

estimates, made when more information is available, are usually subject to a bit less. Well-done project definition results in far more accurate cost estimates.

COST GROWTH IN MEGAPROJECTS

We use the ratio of actual to estimated costs to assess the cost growth found in the megaprojects database. Table 4.1 shows the means, standard deviations, and ranges of cost growth for the entire database and for different types of projects contained in it. Refineries experienced about the same degree of cost growth as other process

Table 4.1

COST GROWTH IN THE MEGAPROJECTS DATABASE

Facility Type	Mean	Std. Dev.	Minimum	Maximum	N
Refineries	1.63	0.52	0.99	2.54	12
Process plants	1.67	0.68	0.98	3.22	16
Minerals extraction	1.99	0.86	1.27	3.71	7
Civil/transport	2.14	1.26	0.97	4.53	6
Nuclear plants	2.57	0.67	1.63	3.41	6
All projects	1.88	0.80	0.97	4.53	47

plants; on average, their costs increased about 65 percent over the estimate.

Minerals-extraction facilities (oil production platforms, minerals development, etc.), civil works and transportation projects such as dams, new cities, and pipelines, and nuclear powerplants generally experienced worse results. Their AFE estimates were, on average, less than half of the final cost, in constant dollars. Unlike facilities in the other three categories, none of the minerals-extraction projects or nuclear powerplants were well estimated; in the best of them, cost grew by over a quarter, while in the worst, it nearly quadrupled. However, some of the refineries and process plants experienced more cost growth than the average minerals-extraction or nuclear plant projects. In fact, the worst of the process plants in terms of cost growth ranks with the worst of the extraction and nuclear projects. The largest cost growth was incurred by the TAPS.

In Fig. 4.2, we compare the cost growth among megaprojects with that examined in several other analyses. The average growth (88 percent) is about the same as that in major U.S. weapons systems developed in the 1950s, when such systems embodied a great deal of technological advance. It is substantially higher than the growth in any other group of projects shown.

Does Size Alone Matter?

Is it the sheer size of megaprojects that makes them especially problematic? We will address this question by looking for direct correlations between measures of size and problems of cost growth, schedule slippage, or performance.

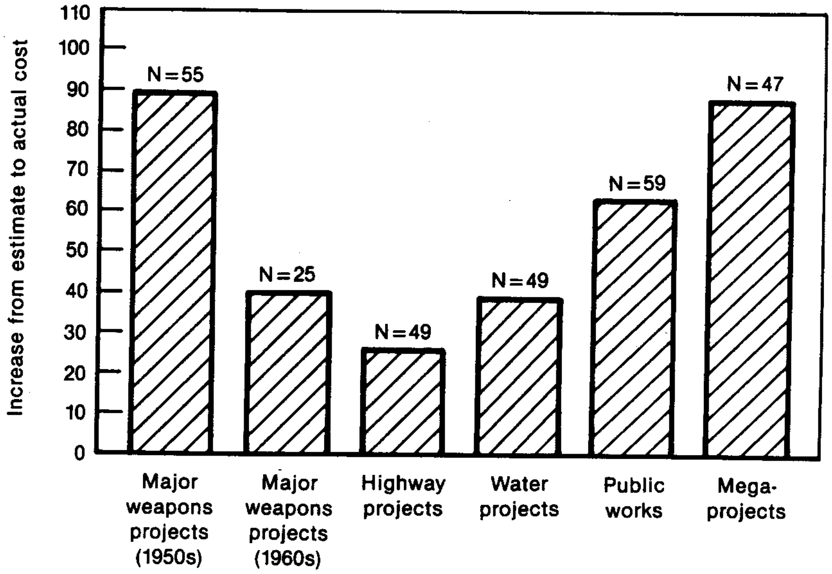

Fig. 4.2—Comparative cost growth of different types of projects
(SOURCE: Merrow, Chapel, and Worthing, op. cit., p. 73.)

The database contains two measures of size: the total cost of the project, i.e., its financial "size," and the capacity of the project, a measure of physical size. As discussed in Section II, our capacity measure is necessarily somewhat crude, but it does provide a reasonable measure of the output for those projects for which output is an appropriate concern.

Table 4.2 shows the correlations among the (natural) log of total cost, the (natural) log of capacity and cost growth, schedule slippage, and whether or not projects experienced operational problems after completion, a measure of performance.[1] None of the relationships between size and project outcomes is statistically significant at the .05 level. Therefore, no simple relationship between large size and problematic outcomes can be demonstrated.

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[1] The logs of cost and capacity are used because both measures range through several orders of magnitude and the logs produce more linear relationships.

Table 4.2

THE RELATIONSHIPS BETWEEN SIZE AND OUTCOMES

Item	ℓn Cost	ℓn Capacity
Cost growth	+.27	−.12
Schedule slippage	−.17	−.06
Operational problems	+.28	−.13

The Correlates of Cost Growth

Although cost growth is apparently not related to project size, it is related to four other kinds of factors:

- Problems between the project and the government(s), as manifested by regulatory disputes.
- Innovation in the project.
- Project ownership.
- The types of infrastructure the project involved.

Cost Growth and Regulation. By far the most important predictor of cost growth and schedule slippage in megaprojects is the extent to which the project encountered regulatory constraints in the following areas:

- The protection of the natural environment from the effects of the project.
- The protection of the public health and safety from the effects of the project.
- Controls on the use of labor or procurement.
- Other governmental standards or regulations.

Table 4.3 shows the relationship between the presence of such regulatory standards and cost growth and schedule slippage.

In and of themselves, regulations should not cause either cost growth or schedule slippage. These things occurred in our database projects because the effects of regulations on cost and schedule were not factored into cost and schedule estimates. In particular, regulatory cost effects associated with environmental problems and health and safety issues were not accounted for. Problems associated with constraints on labor and procurement were also not accounted for in the schedule estimates.

To help examine the relationships between regulatory problems and project outcomes, we developed a simple scale, which we call the

Table 4.3

HOW REGULATIONS AFFECT OUTCOMES

Item	Cost Growth	Schedule Slippage
Environmental regulations	0.44[a]	0.36
Health and safety	0.47	0.57
Labor or procurement controls	0.30	0.51
Summed scale of above items	0.70	0.64

[a] All correlations significant at a probability of .05 or less.

"regulatory problems scale." It consists of the sum of the problems found in Table 4.3. Thus, it ranges from 0 (no regulatory problems with environment, worker health and safety, and labor or procurement controls) to 3 (problems in all three areas).[2]

The extent of regulatory problems is not associated with geography or many other project characteristics:

- The correlations between the regulatory problems scale and project siting in remote areas, difficult climates, LDCs, etc., are not significant.
- With the exception of items directly related to regulatory concerns, such as water and sewage facilities, there is no relationship between the provision of permanent project infrastructure and regulatory problems.
- Regulatory problems are about equally common for joint ventures and single-owner projects.
- Regulatory problems are not associated with the degree of innovation in projects.

There are, however, a few project characteristics that might serve as indicators of potential regulatory problems:

- The need to import labor and construct temporary housing is associated with more control on labor. When labor is imported to the site, there is often the potential for a great deal of friction, either with the local population or with the host government.
- There is a very strong relationship between large numbers of subcontractors and regulatory problems. The number of sub-

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[2] Other formulations of the scale were tested and found to be no better than the simple additive scale.

contractors *per se* is not really important, but organizationally complex projects more often run afoul of government regulations. This may be a problem of coordination and control in highly complex situations.
- If a project has a large public ownership, the chances of encountering regulatory problems decline somewhat.
- There is a strong relationship between nuclear powerplant projects and health and safety regulations.

Innovation and Cost Growth. Virtually any form of technological innovation in a project is likely to result in cost growth. Even when technological innovation leads to lower costs than would have resulted without it, the degree of improvement is routinely overestimated by the designers. In the megaprojects database, there are three (admittedly crude) measures of innovation:

- Whether or not the project embodied any first-of-a-kind technology (about 30 percent of the projects did).
- Whether the project employed any new materials or methods of construction (about 15 percent of the projects did).
- Whether the project was the largest project of its kind when constructed (about half of the projects were).

None of these measures has a significant simple (two-variable) relationship with cost growth. However, when the effects of regulatory problems on cost growth are controlled, a positive relationship between the first two measures and cost growth is found. No relationship was discovered between being the largest to date and cost growth.[3] As discussed later (in Section VI), however, we did find a relationship between being the largest ever and operational performance difficulties.

Project Ownership and Cost Growth. We divided ownership into three categories: entirely private-sector owned, entirely public-sector owned, and mixed private and public investment. The associations between ownership and cost growth are shown in Table 4.4. Projects in which the public sector is either the owner or an equity partner experience substantially more cost growth than private-sector projects.[4] At least in the simple relationships, there appears to be no

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[3] The lack of relationship between being the largest and cost growth was not surprising; analyses of cost growth in process plants also failed to reveal any relationship (see Merrow, Phillips, and Myers, op. cit., Sec. IV).

[4] From these data alone, we cannot tell whether public-sector projects are simply estimated lower (and therefore experience more cost growth), or whether the effect of public ownership is to increase costs. Our examination of actual costs later in this section, however, indicates that the latter is the case.

Table 4.4

OWNERSHIP AND COST GROWTH

Ownership	No. of Projects	Cost Growth
Public	13	1.9
Mixed	9	2.4
Private	25	1.7

cost growth advantage to having government as a part-owner rather than the sole sponsor of a project. In fact, the mixed cases are, on average, the worst.

Given the importance of regulatory factors, one might suspect that public projects would be subject to closer regulatory scrutiny than private projects. In fact, the opposite tends to be true. Complete public ownership is associated with significantly fewer regulatory problems than private ownership. There is no significant difference between mixed and private ownership.

Infrastructure and Cost Growth. Many megaprojects involve much more than a discrete single project. Because they are often in remote areas and because their requirements are so large, megaprojects often require extensive infrastructure development. The database contains information on whether or not various kinds of infrastructure were associated with project construction. We divided the infrastructure items into two groups: project-related facilities and major permanent facilities (see Table 4.5). In general, we would expect that added infrastructure items would be associated with greater cost growth—more infrastructure means a more complex project, more items to estimate, and more effort required to reach a given level of project definition. In the case of major permanent facilities, that is exactly the result we find. Airports, waterworks, and permanent housing (which usually means that a town was constructed at the site) in particular are associated with more cost growth.

However, project-related infrastructure—building a road into the site and the construction of a camp—is associated with *less* cost growth. The reason for this apparent paradox is quite simple: The need for temporary housing and road-building, which is usually identified by cost estimators, signals to project planners that more definition is needed to provide a basis for cost estimation. We suspect that cost contingency allowances are generally higher for projects in remote sites, and this too helps improve—i.e., to increase—the cost estimates.

Table 4.5

TYPES OF INFRASTRUCTURE

Project Infrastructure	Permanent Infrastructure
Roads	Railroads
Construction-crew housing	Ports
	Permanent housing
	Airports/heliports
	Hospitals

This is confirmed by the fact that the need for project-related infrastructure is associated with higher-than-expected estimates.[5] Higher estimates result in less cost growth. As will be shown in Section V, the same factors are at work for reducing schedule slippage.

A MODEL OF COST GROWTH IN MEGAPROJECTS

When the four types of factors discussed above are incorporated into a regression equation, the following model results:

$$\begin{aligned}\text{Cost growth} = 1.04 &+ .78 \times \text{number of regulatory problems faced}\\ &+ .56 \text{ if a publicly owned project}\\ &+ .59 \text{ if new materials/construction methods used}\\ &+ .42 \text{ if first-of-a-kind technology used}\\ &+ .29 \times \text{number of permanent infrastructure items}\\ &- .54 \times \text{number of temporary infrastructure items}\end{aligned}$$

The full regression results are shown in Table 4.6. Data for cost growth were available for 47 projects. The regression model accounts for about 80 percent of the variation in cost growth (as provided by the R-square), and the standard error of the estimate (SEE) is less than ±.39. One can obtain a sense of how well the model accounts for cost

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[5] When we regress the estimated (constant dollar) cost against the capacity and ownership of the project, we find a strong positive correlation between the residuals and the project-infrastructure items. No significant relationship is found with the permanent infrastructure items.

Table 4.6

DETAILS OF COST GROWTH MODEL

Variable	Mean	Std. Dev.	Minimum	Maximum
Cost growth	1.88	0.80	0.97	4.53
Regulatory scale	0.77	0.91	0	3
First of a kind	0.34	0.48	0	1
New materials/tech.	0.15	0.36	0	1
Public sector project	0.28	0.45	0	1
Temp. infrastructure	0.60	0.88	0	2
Perm. infrastructure	0.62	0.87	0	3

Number of obs. = 47
F (6, 40) = 25.81
Prob. > F = 0.0001
R-square = 0.80
Root MSE = 0.39

Variable	Coefficient	Std. Error	t	Prob > |t|
Constant	1.04			
Regulatory scale	+0.78	0.07	10.89	0.000
First of a kind	+0.42	0.13	3.14	0.003
New materials/tech.	+0.59	0.17	3.41	0.002
Public sector project	+0.56	0.15	3.81	0.001
Temp. infrastructure	−0.54	0.09	−6.18	0.000
Perm. infrastructure	+0.29	0.08	3.81	0.001

growth by comparing the SEE with the standard deviation of cost growth (.80).[6]

PREDICTIVE USE OF THE COST GROWTH MODEL

If the regression model is used as a predictive equation to help anticipate the amount of cost growth in large projects and megaprojects, the following procedure should be used. First, the base cost estimate for the application must be made at the beginning of detailed engineering. It should be prepared using conventional bottom-up cost estimating techniques. Second, although one of the input values—regulatory problems—cannot be known with certainty *ex ante*, the prospects for regulatory problems can still be realistically assessed and reasonable

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[6] The largest correlation of independent variables is .51, well below the point at which one has to seriously consider multicollinearity (i.e., about .90).

inputs can be developed. Alternatively, the coefficient of the regulatory problems scale (.78) could be used to examine the sensitivity of the estimate to regulatory problems. Third, the standard error of the prediction should be calculated, since it provides a range within which one can be confident of the actual results occurring. The standard error of prediction is a function of the particular set of inputs being used. Therefore, using the standard error is far better than providing a single number, because it realistically presents the accuracy of the forecast cost growth. This is especially important for this model, because the standard error of the model remains fairly large.

The following caveats should be noted. This model has not been validated by using new data to test the predictive accuracy of the equation. However, the results of a "jackknifing" experiment with it were very encouraging. When randomly split in half and reestimated, all variables remained significant except the use of new materials or techniques of construction. New materials were not significant because only two of the seven projects that used new materials or techniques of construction fell into that draw.

The model provides some important insights into what goes wrong with projects. First, the dramatic effect of the political process on cost growth cannot be ignored. Problems with government regulation are responsible for more cost growth than any other factor. This does not suggest that government regulations are necessarily wasteful or inefficient; some are, some are not. Rather it suggests that unless the regulatory environment is very well understood, the costs for a megaproject will not be well understood.

This result is not a statistical by-product of having six nuclear powerplants in the database. Although nuclear powerplants generally experience severe regulatory problems, the relationship between regulation and cost growth and schedule slippage for nuclear plants does *not* appear to be special in any way. The presence of the same type of regulatory problem has about the same effect for a process plant, a dam, a refinery, or a nuclear powerplant. The only special feature of the nuclear plants is that they are much more likely to have regulatory problems than other types of facilities. Table 4.7 illustrates this point. The absence of regulatory problems essentially levels the amount of cost growth across projects.[7] Nuclear plants, which as a group experience the worst cost growth, look about average when the effects of regulatory problems are removed. Refineries, which actually experience

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[7] If the nuclear powerplants are removed from the sample and the cost-growth regression is rerun, the results remain the same; all of the variables remain significant, and no other variables become significant. The R-square declines modestly.

Table 4.7

REGULATORY PROBLEMS AND FACILITY TYPES

Facility Type	Average Score on Regulatory Problems Scale	Average Cost Growth if Est. Effects of Regulatory Problems Are Eliminated
Refineries	0.25	1.44
Process plants	0.53	1.26
Resource extraction	1.00	1.21
Civil/transport	1.00	1.36
Nuclear plants	1.67	1.27
All projects	1.88	1.28

the lowest level of cost growth of any type of project, show the most cost growth when the effects of regulation are removed.

Four examples, two displaying no cost growth and two suffering severe cost growth; should make the model more intuitively obvious. As shown in Table 4.8, the Itaipu hydroelectric project and the Union Carbide Ponce petrochemical complex, despite being highly complex projects, had no cost growth after the beginning of detailed engineering. Itaipu is a joint venture of Brazil and Paraguay on the Parana River and is the world's largest hydroelectric project, with an eventual installed capacity of 12,600 Mw and a capital cost near $10 billion. Itaipu demonstrates that government-owned projects do not necessarily experience cost growth. The project involved a modest amount of new technology to handle special power-conditioning needs, and labor camps were necessary to help handle a peak labor force of 37,000.

While unusually good weather and a lack of geological surprises played some role in the project's success, the key ingredients were very

Table 4.8

EXAMPLES OF COST GROWTH IN MEGAPROJECTS

Project	Regulatory Problems	Public Ownership	New Materials, Techniques	Pioneer Technology	Labor Camp	Infrastructure	Cost Growth Ratio
Itaipu	0	Yes	No	Yes	Yes	No	0.97
Ponce	0	No	No	No	No	No	0.98
Ok Tedi	2	Part	No	No	Yes	Yes	1.88
Trunkline LNG	2	No	No	No	No	No	2.97

careful definition of the project in the early stages and virtually complete harmony between the national partners during the course of the project. In fact, these two attributes are probably causally related: The need to define the roles and responsibilities of the two partners made a high level of project definition essential very early in the project. The fact that one of the partners, Paraguay, had very limited financial means probably also reinforced the need to define all aspects of the project carefully. The lack of disputes between the host governments and the project is without doubt the key attribute in the project's staying within budget. The fact that the host governments are the owners undoubtedly contributed to a smoother regulatory situation.

Ponce is a world-class petrochemical complex built by the Union Carbide Corporation in Ponce, Puerto Rico. Like Itaipu, this project experienced no conflict with the host government. The potential for labor conflict and cultural antagonism was clearly present, but the owner and the prime contractor were aware of the danger and mounted a strong effort to surmount it. Key personnel were given intensive Spanish lessons. Training programs were established to use local labor for craft as well as general construction jobs, and local people were given all but a few plant jobs after the completion of startup. The contractor's labor relations were described as "nothing short of fantastic."

In contrast to Itaipu and Ponce, the cost of Papua New Guinea's Ok Tedi project increased significantly from its estimate. This project was built by a consortium of foreign-owned firms and contractors, and a minority interest was held by the government. Several factors contributed to the high cost growth. First, Ok Tedi is extremely remote and required extensive infrastructure to build and operate. In addition, a severe drought necessitated changing the means of transport to the site from river barges to C-130 cargo planes, at a substantial increase in cost.

Regulatory problems also contributed to cost growth. The government was concerned about possible environmental effects and was under political pressure to "be tough" with the project. In part, this was the political aftershock of a previous foreign mining venture in the country that had been branded a "giveaway" by the political opposition.

Finally, Ok Tedi appears to be a project in which meeting schedules was the top priority. Therefore, heroic measures were taken to stay on time, even at some increase in cost.

The Trunkline Gas Company LNG project, which consisted of marine and receiving facilities for imported liquefied natural gas

(LNG), nearly tripled in capital cost (in constant dollars). The project was a regulatory nightmare. Indeed, regulatory hurdles were the only negative factor for this project, but those hurdles were numerous, and they were high. A total of 130 federal, state, and local permits were required for the project. Changing construction regulations, largely aimed at LNG safety issues, were the single most important contributor to cost escalation.

SIGNIFICANT NONCORRELATES OF THE MODEL RESIDUALS

After formulating a basic regression model for cost growth, we can explore hypotheses about other factors by examining the relationship between those factors and the remaining variation in cost growth. The "residuals" are calculated by subtracting the cost growth predicted by the model from that which actually occurred for each observation.

In particular, we are interested in whether certain factors associated with project organization have a detectable residual effect on cost growth. Table 4.9 shows the relationships among a number of such factors and the residuals of the cost growth model. The table reveals no statistical relationship between cost growth and any of the factors listed. We do not even find a relationship between labor shortages or stoppages and cost growth. As discussed in the next section, it appears

Table 4.9

CORRELATIONS OF COST GROWTH MODEL RESIDUALS AND PROJECT ORGANIZATION

Variable	Correlation	Statistically Significant?
Labor-related factors		
Peak labor force on-site	+0.05	No
Labor imported to site	–0.04	No
Labor shortage	–0.01	No
Labor stoppage	+0.07	No
Management-related factors		
Number of subcontractors used	–0.03	No
Equipment shortages	–0.15	No
Number of turnovers in project management	–0.15	No
Modular or phased construction used	–0.09	No
Owner experienced with type of project	+0.15	No

that although such things affect schedules, project managers can usually prevent the delays from causing constant-dollar cost growth.[8]

In other management areas as well, we found no relationship with cost growth. This does not mean that poor project management will not cause cost growth. But it does suggest that the management of *project execution* is usually a second-order problem, in comparison with basic management strategy in the planning and development of the project. We return to this issue in Section VII.[9]

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[8] The distinction between real and nominal dollars is important here. In an inflationary period, any delay is likely to result in nominal dollar increases in cost, whereas real costs (excluding the time-value of money) may not necessarily increase.

[9] Unfortunately, we had no way of directly assessing the "quality" of project management.

V. SCHEDULE SLIPPAGE IN MEGAPROJECTS

Meeting schedules is important for virtually all projects and absolutely essential for some. We begin this section by discussing how we measured schedule slippage. We then examine the conceptual similarities and differences between cost growth and schedule slippage, discussing the important correlates of schedule slippage. The section concludes with a statistical model of schedule slippage.

MEASURING SCHEDULE SLIPPAGE

We define schedule slippage as the ratio of the actual time between the beginning of detailed engineering and the completion of construction to the estimated time. The measure is completely analogous to the cost growth measure, using the same project milestones for the beginning and the end of the measurement period.

We could have measured schedule slippage in terms of the number of months by which actual time exceeded (or underran) estimated time, but as in the case of cost growth, we believe that the ratio formulation provides a better normalization of the data. We tacitly assume that a six-month slip in a planned year-long project is more important than a six-month slip in a planned four-year project. While this is reasonable from one perspective—project participants could well have anticipated that much slippage in the second case, but not in the first—it is not an entirely defensible assumption. In fact, a six-month slip in the second project, which was probably a much more costly project, almost certainly implies greater absolute economic loss than a six-month slip in the first project.

Acceptable statistical models can be produced using either method of measuring schedule slippage. Because of the very large variability in project schedules in this analysis, the ratio formulation was preferred.[1] Also, because it is completely analogous to the measurement of cost growth, this formulation facilitates comparisons.

Table 5.1 presents the means, standard deviations, and ranges of schedule slippage for each type of project in the database. The degree of schedule slippage is modest for most types of facilities and only about 17 percent for all projects together. That means that the average

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[1] For an example of the alternative formulation using months of slippage as the measure, see Myers and Shangraw, op. cit.

Table 5.1

SCHEDULE SLIPPAGE IN THE MEGAPROJECTS DATABASE

Facility Type	Mean	Std. Dev.	Minimum	Maximum	N
Refineries	1.08	0.16	0.91	1.50	12
Process plants	1.16	0.18	0.82	1.45	14
Civil/transport	1.25	0.29	0.93	1.63	6
Minerals extraction	1.12	0.28	0.97	1.80	8
Nuclear plants	1.39	0.20	1.19	1.60	6
All projects	1.17	0.23	0.82	1.80	46

project's schedule slipped about eight months beyond the four years planned at the beginning of detailed engineering. Although the two factors are related, schedules do not slip commensurately with cost growth: The average schedule slipped by 17 percent, whereas the average cost estimate "slipped" by 88 percent.

As was the case for cost growth, refinery projects had the best record of schedule slippage, averaging only 8 percent. At the other extreme, nuclear plants had the greatest average slippage as well as the greatest average cost growth. The only really surprising finding in terms of cost growth is that the average cost growth of minerals-extraction projects was considerably above the average of all types of projects. Their average schedule slippage, however, was the second best of all project types (12 percent), despite the fact that one of the minerals-extraction projects suffered an 80 percent schedule slippage—the worst of the 46 projects for which slippage could be calculated. We discuss the reasons for this apparent anomaly later in this section.

CONCEPTUAL SIMILARITIES AND DIFFERENCES BETWEEN COST GROWTH AND SCHEDULE SLIPPAGE

The basic factors driving costs to increase will usually also increase project length and vice versa. The correlation coefficient between cost growth and schedule slippage among plants in the megaprojects database is a statistically significant +0.53.

It is tempting to include project schedule or schedule slippage as an independent variable for predicting cost growth, and this has in fact been done in some prior studies.[2] But while schedule slippage may to

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[2] See, for example, Robert Summers, *Cost Estimates as Predictors of Actual Weapons Costs: A Study of Major Hardware Articles*, The RAND Corporation, RM-3061-PR, March 1965; Merrow, Chapel, and Worthing, op. cit., Sec. II.

some extent be an independent source of cost growth, it suffers three important drawbacks in a cost growth model:

- Some of the possible independent effect of schedule slippage on cost growth should be normalized by adjusting for inflation and scope changes.[3]
- The actual schedule is never known until a project is complete; therefore, any model using a schedule-derived variable will be useful for heuristic purposes only.
- To a large extent, cost growth and schedule slippage are *both* caused by other factors that affect both parameters simultaneously and in similar ways. Thus, it is conceptually incorrect to include schedule slippage in a cost growth model.

For exactly the same reasons, it is inappropriate to include cost growth in a model of schedule slippage.

Our primary hypothesis regarding schedule slippage is that it results from technological innovation, regulatory factors, and the quality of schedule estimates.[4] As in the case of cost growth, we would expect technological innovation to cause schedule problems because of uncertainty and the possibility of unpleasant surprises. The resolution of these problems requires both time and money.

The relationship between regulatory factors and schedule slippage is well known for many types of projects. Table 5.2 shows the relationship between schedule slippage and regulatory issues and also includes the same relationship for cost growth. Not only are all ten of the correlations significant, they display a remarkably similar pattern for the two outcomes.

Table 5.3 compares the simple (uncontrolled) relationships between cost growth and schedule slippage and a few key project characteristics.

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[3] The relationship between scope change and schedule slippage can be very important if the external environment is subject to a great deal of change. For example, in weapons systems development, long schedules almost insure that the threat will change, which will require changes in the nature of the system being developed. Schedule slippage simply exacerbates that problem. The same is often true for long civilian projects. The more time between conception and completion, the more likely fundamental changes are to occur in the market for the project's product. These, in turn, will cause changes in scope or deliberate slowdowns or speedups in the project's schedule. Nuclear powerplants have frequently been subject to slowdowns because the demand for electricity has failed to keep pace (see W. A. Radlauer, D. S. Bauman, and S. W. Chapel, "The Impact of Project Management on Nuclear Construction Lead Times," *Power Engineering*, Vol. 89, March 1985). Conversely, the TAPS was speeded up because oil prices rose more than fourfold while the project was in progress.

[4] In general, less is known conceptually and empirically about the phenomenon of schedule slippage than about cost growth. For this reason, we have less to say about the potential sources of schedule slippage that do not also affect cost growth.

Table 5.2

THE RELATIONSHIPS AMONG COST GROWTH AND SCHEDULE SLIPPAGE AND REGULATORY PROBLEMS

Type of Regulatory Problem	Cost Growth (N = 47)	Schedule Slippage (N = 46)
Environmental	0.44[a]	0.36
Health and safety	0.47	0.57
Labor regulations	0.30	0.51
Other	0.40	0.34
Regulatory problems scale	0.70	0.64

[a] All correlations significant at a probability of .05 or less. Any differences between data in this table and those in earlier sections result from slightly different numbers of observations.

Again, as with cost growth, we find no relationship between capacity and schedule slippage. Similarly, there is no apparent relationship between schedule slippage and the other measure of size, actual cost. This suggests that schedules for megaprojects do not tend to slip any more than those for projects that are simply large. There is no simple relationship between schedule slippage and project performance. The only significant relationships in Table 5.3 are between cost growth and schedule slippage and project length.

Table 5.3

CORRELATES OF COST GROWTH AND SCHEDULE SLIPPAGE

Item	Cost Growth	Schedule Slippage
Capacity (natural log)	+0.12	−0.02
Actual cost (natural log)	+0.27	−0.17
Whether project operated well	−0.06	−0.07
Length of schedule	+0.35[a]	+0.51[a]

[a] Significant at a probability of .05 or less.

A MODEL OF SCHEDULE SLIPPAGE IN MEGAPROJECTS

When we combine the various factors associated with schedule slippage by means of multiple regression, we obtain the following model:

Schedule slippage = + .98

+ .15 × number of regulatory problems faced

+ .23 if first-of-a-kind technology is used

− .14 if new materials/construction methods used

− .14 if project is a minerals-extraction project

+ .16 if labor shortages occurred during construction

The model can be interpreted literally as follows: Starting at completing the project within 98 percent of the planned schedule, one should add 15 percent for each of the three types of regulatory problems that might be encountered—environmental, health and safety, and controls on labor or procurement. Being beset by all three types would increase a project's schedule by about 45 percent. If the project uses technology that has not been used commercially before, add 23 percent to the estimated schedule. If the project employs new techniques or materials of construction, the expected schedule slippage should be *reduced* by about 14 percent of the original schedule. Minerals resources projects are, as suggested earlier in this section, a little better on average in meeting their schedules. Finally, if labor shortages occur, they result in an average slippage of 16 percent.

The full details of the schedule slippage model are shown in Table 5.4. As indicated by the coefficient of determination (R-square), the model accounts for over 83 percent of the variation in schedule slippage, and the overall equation is statistically significant, as indicated by the probability on the F-statistic. All of the individual coefficients are well below a 5 percent probability of being indistinguishable from zero, the cutoff we have adopted for all regression results.

The root-mean-squared error (the standard error of the estimate) is ±10 percent. This compares with a standard deviation of schedule slippage of 0.23.

Table 5.4

DETAILS OF SCHEDULE SLIPPAGE MODEL

Number of obs. = 38
F (5, 32) = 31.51
Prob > F = 0.0001
R-square = 0.83
Root MSE = 0.10

Variable	Coeff.	Std. Error	t	Prob.	Mean	Range
Schedule slippage (actual/planned					1.15	0.82–1.80
Regulatory problems	.15	0.02	6.6	0.001	0.74	0–3
First of a kind	.23	0.04	6.0	0.001	0.29	0–1
New materials/tech.	−.14	0.05	3.1	0.004	0.16	0–1
Minerals extraction	−.14	0.05	2.8	0.008	0.16	0–1
Labor shortages	.16	0.03	3.6	0.001	0.29	0–1
Constant	.98					

PREDICTIVE USE OF THE MODEL

The following procedure should be followed in using this model to help anticipate schedule slippage. First, the schedule for the project should be prepared using conventional scheduling techniques. Second, although two of the input values (regulatory problems and labor shortages) cannot be known with certainty *ex ante*, the prospects for regulatory problems and labor shortages can still be realistically assessed and reasonable inputs can be developed. Alternatively, the coefficients can be used to examine the sensitivity of the schedule to regulatory and labor shortage problems. Third, the standard error of the prediction should be calculated, since it provides a range within which one can be confident of the actual results occurring. The standard error of prediction is a function of the particular set of inputs being used and is thus far better than a single number, because it realistically presents the accuracy of the forecast schedule slippage.

We must emphasize that this model has not been validated by using new data to test the predictive accuracy of the equation. However, the results of a "jackknifing" experiment were very encouraging about the model's reliability. When the sample was randomly split and the model reestimated, all independent variables remained statistically significant.

IMPLICATIONS OF THE SCHEDULE SLIPPAGE MODEL

As in the case of the cost growth model, regulatory problems play an important role in the schedule slippage model. Regulatory problems are the largest contributor to schedule slippage and they create larger swings in expected cost growth than any other factor. In extreme cases, regulatory problems add about 45 percent to the estimated project schedule.

As noted above, the use of first-of-a-kind technology creates more opportunity for surprises, and those surprises are almost always unpleasant. It is interesting to note, however, that the use of new materials and methods of construction is associated with less slippage in schedules, but more cost growth. We believe that this occurs because the new materials and techniques are devised to reduce construction schedules and work toward that end. For example, the Great Canadian Oil Sands plant in Canada used new techniques that enabled the owners to continue construction during the coldest parts of the winter, thereby permitting them to meet their construction schedules. New materials and construction techniques, however, are associated with greater cost growth, so the tradeoffs between cost and schedule must be considered when making decisions about new materials or construction techniques.

Minerals-extraction projects, including oil platforms and mining projects, are being completed with less schedule slippage than one would expect, given their other characteristics. In cases such as Mobil's Statfjord A platform, the Ok Tedi gold and copper complex, the Cerrejon coal mining venture in Colombia, ARCO's Prudhoe Bay facility, the Canadian tar sands complexes, and the Union Oil shale facility, it is clear that meeting schedules was given top priority for the simple reason that getting the facilities into production on time can result in enormous gains. In several cases, "weather windows" were also a factor in making schedules overwhelmingly important. As several of these projects make painfully clear, however, meeting the construction schedule (or at least slipping less than would have ordinarily been expected) does not necessarily insure that the project will start up on time.

It is not at all surprising that labor shortages are associated with schedule slippage. A lack of labor necessarily slows progress. However, labor shortages are not associated with cost growth or higher actual cost (in constant dollars). This indicates to us that project managers are accommodating to the delays caused by labor shortages by getting other work done and perhaps by improving the definition of the project and employing less overtime. Labor productivity may also be enhanced by longer schedules, resulting in less cost growth.

SIGNIFICANT CORRELATES AND NONCORRELATES OF THE MODEL RESIDUALS

After we have accounted for the factors in the equation, we can test whether other variables might be significant by correlating the "residuals" of the model with those variables.[5] These correlations allow us to test some of the conventional wisdom about what is associated with schedule slippage. Table 5.5 shows the correlations of the residuals from the schedule slippage model and a number of project site descriptors.

The conventional wisdom holds that remote sites, difficult climates, and the need to import labor are all sources of unexpected problems. As in the case of cost growth, however, our data do not lend support to this hypothesis. Table 5.5 shows that after we control for the effects of variables in the slippage model, there is no statistical relationship between any measure of remoteness and schedule slippage. This is not to suggest that remoteness does not create problems, but rather that remoteness does not create *unexpected* problems.

The conventional wisdom also holds that building in LDCs is associated with disappointing project results. Again, the data do not lend

Table 5.5

CORRELATES OF SCHEDULE SLIPPAGE MODEL RESIDUALS AND PROJECT SITE

(Number of observations N = 38 unless otherwise noted)

Variable	Correlation	Statistically Significant?
Whether or not the project is at a remote site	−0.01	No
Whether or not the climate permitted year-round construction (N = 36)	−0.05	No
Whether or not labor was imported to the site (N = 35)	+0.02	No
Project location		
U.S. Gulf Coast	−0.07	No
Other U.S.	0.04	No
Other developed countries	−0.02	No
OPEC countries	−0.13	No
Non-OPEC LDCs	0.17	No

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[5] The residual value is merely the actual schedule less the schedule slippage predicted by the model.

support to this hypothesis.[6] There is no apparent relationship between schedule slippage (or cost growth or performance shortfalls) and locale.

This does not necessarily suggest that building locale is irrelevant to schedule slippage. In particular, some countries impose a variety of problematic regulatory constraints on projects. That factor would be picked up by the regulatory problems scale in the model. Table 5.6 shows the correlations between various regulatory problems and project locations. The table suggests that regulatory problems may result in some slight locational effects on schedule slippage. However, only 2 of the 25 coefficients in Table 5.6 are statistically significant at .05, although a number of others, mostly in the same rows, approach significance. U.S. locations, except for the Gulf Coast,[7] appear to be more beset with regulatory problems than other locations in the world, and projects in OPEC nations appear less likely to encounter such problems. Locating a project in poor countries of the Third World *per se* is unrelated to any regulatory problem that we were able to measure.

To explore the possibility of a relationship between project ownership and organization and schedule slippage, we examined the correlations of the schedule slippage model residuals and several descriptors of organization. Several of the results, shown in Table 5.7, are surprising:

- Although more than one-quarter of the projects experienced one or more labor stoppages, we find no relationship with longer schedules. This may result from the crudeness of our measure;

Table 5.6

REGULATORY PROBLEMS AND PROJECT LOCATION

Area	Constraints on Labor and Procurement	Environmental Regulations	Health and Safety	Other Regulatory Problems	Regulatory Problems Scale
U.S. Gulf Coast	−0.12	−0.28	0.04	−0.15	−0.19
Other U.S.	0.09	0.27	0.29	0.18	0.37[a]
Other developed countries	0.21	0.25	−0.10	0.11	0.13
OPEC countries	−0.11	−0.26	−0.30	−0.12	−0.34[a]
LDCs	−0.07	0.04	0.01	−0.04	0.00

[a] Significant at a probability of .05 or less.

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[6] Construction of projects in LDCs *is* more expensive than construction of projects with similar characteristics elsewhere, but that is not a surprise to those involved.

[7] In accord with the conventional wisdom, the U.S. Gulf Coast probably presents fewer regulatory problems than other parts of the country.

Table 5.7

CORRELATES OF SCHEDULE SLIPPAGE MODEL RESIDUALS AND PROJECT ORGANIZATION

(Number of observations N = 38 unless otherwise noted)

Variable	Correlation	Statistically Significant?
Number of workers on site at the peak (N = 26)	+0.11	No
Whether or not there were labor stoppages (N = 35)	+0.03	No
Number of turnovers of project management	−0.02	No
Whether or not the project used phased or modular construction (N = 34)	+0.20	No
Number of subcontractors (N = 27)	+0.28	No
Whether or not the project was a joint venture	−0.16	No
Whether or not the project was publicly owned	+0.20	No
Whether or not government holds an equity share	+0.15	No

we were unable to measure the length and severity of the work stoppages.

- Turnovers in project management did not appear to cause undue problems for the projects. This finding is important because, given the length of megaprojects, turnover among key project management personnel is often inevitable and has been of concern to the industries that build large projects.
- Modular or phased construction, sometimes touted as a solution to megaproject problems, seems not to be much help in terms of schedule slippage. If such construction had a substantial effect, we would see a significant *negative* correlation. Instead, the correlation we find is positive, but not statistically different from zero.
- Finally, any ill effect of joint ventures, public ownership, or government equity partnership in megaprojects' schedule slippage is not apparent here.

The last point deserves some attention because it runs counter to the cost-growth finding. Table 5.8 adds schedule slippage to Table 4.4, showing the relationship between ownership and project outcomes.

In contrast to the finding for cost growth, however, schedule slippage for public-sector projects is much lower than average. The average publicly owned project slipped *only 5 percent* over its scheduled time. Cost and schedule, of course, can trade off, especially in the form

Table 5.8

OWNERSHIP, COST GROWTH, AND SCHEDULE SLIPPAGE

(Numbers of projects shown in parentheses)

Ownership	Cost Growth	Schedule Slippage
Public	1.9 (13)	1.05 (13)
Mixed	2.4 (9)	1.22 (7)
Private	1.7 (25)	1.22 (26)

of a fast-track schedule leading to increased costs. It appears that governments are willing to pay more to have their projects arrive on time. This tradeoff appears to be generally less appealing to private-sector investors, although it is clearly present in some cases.

VI. THE PERFORMANCE OF MEGAPROJECTS

The performance of projects in the database was measured in terms of whether or not they always produced as they were intended to, following the completion of startup. In comparison to a continuous scale, such as production as a percent of nameplate, this is a rather severe test. Nonetheless, 27 projects for which performance information was available passed it. Significantly, as shown in Table 6.1, satisfactory operation is an important predictor of whether a project will produce profits at the expected rate. Although good performance does not *assure* profitability (eight projects with good performance failed to produce profits), it is almost a requisite.[1] Only two projects that experienced operational problems managed to be profitable. In one case, the project earned its return on investment only because the owner was a regulated utility. The other case, the Tarbela Dam in Pakistan, experienced some operational difficulties at the beginning, but was sufficiently cost-effective that the problems did not dominate the outcome.[2]

Table 6.1

LINKAGE BETWEEN PERFORMANCE AND PROFITABILITY

(Data on profitability were available for only 36 projects)

		Was Project Profitable?		
		No	Yes	Total
Was Performance Up to Expectations?	No	15	2	17
	Yes	11	8	19
	Total	26	10	36

NOTE: Chi-square = 4.1170 Prob. > chi^2 = .042

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[1] The chi-square statistic indicates that the probability of finding this pattern randomly is less than .05.

[2] Most of the projects that operated well yet failed to show profits were caught in a downturn in the markets for their products. This was especially true of recent energy-related megaprojects and some metals mining and processing projects that were caught in the worldwide overcapacity in primary metals.

PERFORMANCE AND TECHNOLOGICAL INNOVATION

Unlike cost growth and schedule slippage, which are often the result of regulatory problems and other project-management and strategy-related factors, performance depends primarily on the smooth functioning of project technology.[3] Established, commercially proven technologies should not and usually do not result in performance problems. The use of first-of-a-kind technologies or novel systems often does result in moderate to severe performance degradation, at least for some period after startup.[4]

Table 6.2 shows the relationship between operational performance and the three measures of innovation included in the megaprojects database. The data in Table 6.2 support the widely understood notion that innovative technology can result in performance shortfalls, as well as the contention that, for megaprojects at least, *any* novel aspect can cause performance difficulties. Projects that were the largest of their type built to that time were much less likely to perform well than others. In addition, all eight of the projects that adopted new construction materials or methods experienced performance problems.[5]

Table 6.2

RELATIONSHIP BETWEEN PERFORMANCE PROBLEMS AND INNOVATION

	Always Performed Well?	
Type of Innovation	Yes	No
First-of-a-kind technology	5	12
New materials or methods of construction	0	8
Largest project of its type ever	7	16

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[3] We, of course, examined the possibility of a relationship between facility performance and other project attributes. Although some attributes, such as remote sites, were found to be correlated with facility performance, the correlations are not important after the effects of innovation are controlled for.

[4] The relationship between innovative technology and performance difficulties is well established. See, for example, Merrow, Phillips, and Myers, op. cit., Sec. V; and Merrow, op. cit.

[5] These two findings may be unique to megaprojects. In pioneer and conventional process plants, no relationship has been found between being the largest of its type or using new materials or methods construction and poor performance (see Merrow, Phillips, and Myers, op. cit., Sec. V).

A MODEL OF PROJECT PERFORMANCE

Using the three measures of innovation discussed above, we constructed a simple additive scale that ranges from 0 (none of the innovative features present) to 3 (all three present). Although all three of the items are individually related to our performance measure in a statistically significant manner, the scale enables us to effectively combine them. As shown in Table 6.3, the chances of successful performance decline as the innovation scale increases. All 18 of the projects that had no innovative features always operated as intended. Those with one innovative feature were unpredictable, but 14 of the 17 projects with two or more innovative features experienced operational problems.

We can use the innovation scale to model the results of Table 6.3 using logit regression. Because the dependent variable—whether a project has always operated as intended—is binary, we used logit regression instead of the ordinary-least-squares approach employed elsewhere in this study. Logit regression calculates the probability that a project with a given set of characteristics will be in one group or the other. A good model will correctly classify most of the observations.

Table 6.4 provides the details of the logit regression. The model is clearly significant, as indicated by the chi-square value. The coefficient of the innovation scale is statistically significant at a probability of less than .0001.

As shown in Table 6.5, the model correctly classified 38 of the 46 projects. Of the 8 projects that were misclassified by the logit regression, 5 were false positives and three were false negatives.

These findings do not necessarily mean that technological innovation in megaprojects is always a bad idea. In many megaprojects, innovation simply cannot be avoided. For example, the very fact of being a

Table 6.3

RESULTS USING INNOVATION SCALE

	Number of Innovative Features (score on innovation scale)				
Problem Status	0	1	2	3	Total
Experienced problems	0	5	12	2	19
Always operated well	18	6	3	0	27
Total	18	11	15	2	46

NOTE: $chi^2(3)$ = 23.9031, Prob. > chi^2 = .0001.

Table 6.4

A LOGIT MODEL OF MEGAPROJECT PERFORMANCE

Logit estimates	Number of obs.	=	46
	$chi^2(1)$	=	27.78
Log likelihood = −17.29	Prob. > chi^2	=	0.0001

Variable	Coefficient	Std. Error	t	Prob > |t|	Mean
Opgood					0.59
Innovation	−2.37	0.63	−3.77	0.001	1
Construction	2.98	0.86	3.46	0.001	1

Table 6.5

ACTUAL VS. PREDICTED PERFORMANCE

		Actual Performance	
Model Prediction of Performance	Good	24	5
	Not good	3	14

megaproject often means the project is larger than anything of its type. The results do suggest, however, that any opportunity to try a new technology on a more modest commercial scale should be taken. The synthetic-fuels facilities provide useful examples. Among six synfuels megaprojects—SASOL II, SASOL III, Great Plains coal gasification, Union Oil shale, Great Canadian oil sands (Suncor), and Syncrude—the first three were preceded by the long-term operation of a small commercial plant, the SASOL I coal liquefaction facility. All three performed very well almost from the beginning. The Union Oil shale and Suncor tar sands were first-of-a-kind projects. They experienced extremely long, difficult, and expensive startups. Syncrude was the second tar sands facility, but a conscious decision was made to introduce technology in it that had not been tried. The result was a startup period of more than four years before the plant could sustain something close to design capacity for any length of time.

VII. CONCLUSIONS

In this section, we discuss the implications of our analysis, highlighting those findings that are unexpected or new. First, we address the question of whether large size is in and of itself the main *cause* of problems. We then discuss the most important element driving cost and schedule outcomes: the way in which a project interacts with government. We then discuss the role of new technology and other factors and conclude with some suggestions about where the examination of megaprojects should go from here.

IS BIG NECESSARILY BAD?

Very large projects—those costing well over $1 billion—are no more likely to experience problems than projects that are merely large, i.e., in the $500 million range. On the other hand, megaprojects are no *less* likely to experience serious problems, and that, we believe, is the major concern of past and potential sponsors. The larger the project, the more important is the accuracy of early estimates. The absolute amount of money involved is so large that cost overruns can disrupt the planning of companies and governments for other projects.

The demand for more accurate cost estimates has not been met, but not because of a lack of effort. The concern about cost and schedule overruns in megaprojects that has been widely cited in the literature is a reflection of the effort that has gone into improved planning and estimating for megaprojects. Nevertheless, we believe that greater attention to the factors discussed in this report, especially those highlighted below, could result in better cost, schedule, and performance forecasts for future megaprojects.

The data on cost growth, schedule slippage, and performance shortfalls of megaprojects are certainly sobering, but the most chilling statistic is that only about one in three of these projects is meeting its profit goals.[1] Cost growth, schedule slippage, and especially performance problems play a role in this, but they are not the whole story. Megaprojects take so long to develop from concept to reality that the need or opportunity for profits that originally spawned them may have passed by the time they are ready to begin producing.

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[1] Of the 36 projects in our database for which profits are relevant, only 10 are currently generating profits at the level originally expected.

MEGAPROJECTS AND THE STATE

The most important correlate of cost growth and schedule slippage is the relationship between a megaproject and the governments within whose jurisdictions it is built. In our statistical models, the relationship between project and state is captured largely by the regulatory problems scale. Difficult relationships are characterized by problems with environmental regulations, health and safety rules, and government restrictions on labor and procurement practices that conflict with the desires of the project managers.

As would be expected, large projects and megaprojects are more likely to have regulatory conflicts with the state than smaller projects. But the threshold for encountering serious difficulty with regulatory problems occurs long before the $1 billion mark. Indeed, while we can distinguish between the level of regulatory conflicts of projects in our database and those in the pioneer plants database, which fall in the $100 million range, we cannot distinguish between projects whose costs run from about $500 million to many billions of dollars.

Because the necessary data were unavailable, our statistical analysis does not enable us to distinguish whether the added cost and time associated with regulatory problems springs from the stringency of the regulations and the arbitrariness of the state or from the incompetence and unwillingness of some projects to recognize and abide by regulations. There appear to be examples of both kinds. Although certain areas of the world offer more accommodating regulations than others, there is enormous variation in the degree to which regulatory problems occurred in different projects within the same political jurisdiction.

Owners and contractors who are considering projects could save a good deal of time and money by following a few obvious rules of thumb with respect to government:

- Exploring the regulations of the host government[2] with respect to all aspects of a project is an *absolutely essential part of project definition.* In some cases, project sponsors were simply ignorant of existing regulations, and the projects paid dearly for that ignorance. Ignorance of the laws is no excuse, even when one cannot speak, read, or write the language in which they are written.
- Laws and regulations must be seen as legitimate by project managers, even when they are privately considered distasteful or wasteful.

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[2] The term "host government" applies equally to federal, state, and local governments both in the United States and abroad. The effects of regulatory problems do not appear to be a function of locale, although their frequency is.

- The host government makes the rules; the host government can change the rules.
- The project being considered may cause the regulatory rules to change either by generating information or by generating problems and opposition that politicians will seek to resolve or benefit from.
- Politicians consider getting elected and staying in office more important than the success of a project. It would be unreasonable to expect otherwise.
- Bureaucrats are bureaucrats the world around; one should not expect those in other countries to be any more reasonable, understanding, flexible, or responsive than those at home.

Because the relationships between a project and its political environment are so important to project success, greater demands are placed on the skills of project managers. Effective megaproject managers must deal extensively and effectively with host government officials, and often with a number of joint-venture partners, in addition to handling all of the within-project chores and headaches. Unlike the manager of a small domestic project, the megaproject manager requires staff to assist with external relations, government regulations, and the like. Just as the design supervisor should be an expert in design, those charged with assisting the project manager in dealing with the host government should be experts in the politics and regulations of the host jurisdiction.

This need should be distinguished from the "political risk assessments" that became very popular in the wake of the Iranian revolution.[3] Assessments of political risk tend to concentrate on issues such as political instability and the danger of expropriation. While such assessments may be useful in deciding whether or not to undertake a project, they are not a substitute for political savvy in project execution, nor do they substitute for the development of solid knowledge of local requirements during project definition.

THE USE OF NEW TECHNOLOGY

The incorporation of new technology in a megaproject almost ensures that the project will make more mistakes than money. The use of new technology is the only factor that is associated with bad results

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[3] Louis Kraar, "The Multinationals Get Smarter About Political Risks," *Fortune*, March 24, 1980, pp. 86–100.

in all three dimensions: cost growth, schedule slippage, and performance shortfalls.

Given the relationship between the use of new technology and difficulties in projects, why did 44 percent of the projects in the database opt for novel technology or techniques and materials of construction?

- In some cases, the nature of the project required novelty and relatively large scale at the same time. Prototype projects such as the Great Canadian Oil Sands or Union Oil shale ventures were the first commercial plants of their type, and to have any reasonable hope of financial success they had to be large enough to take advantage of the economies of scale associated with a single train of the process.
- In other cases, new technology or techniques were used because what was thought of as "new" was too narrowly defined. Doing *anything* that has not been done commercially increases the risk of problems in a megaproject. Because the results of problems in a megaproject are so devastating, it is very difficult to justify taking the sorts of chances that would be routine on a small project.
- In a few cases, those responsible for the design of projects were so sure of their own brilliance that they felt they could handle the use of new technology although others had failed. They invariably had serious problems and acquired humility the hard way.

None of the above discussion should be interpreted as being "anti-innovation." Rather, megaprojects are simply inappropriate vehicles for experimentation. If project economics cannot withstand appreciable cost growth, schedule slippage, and performance shortfalls, thoroughly proven technology should be used throughout or the project should be abandoned. If the project economics do not look favorable with conventional technology, new technology is very unlikely to provide the answer, although it may enable project champions to delude themselves, their sponsors, and lenders in the short run.

COST GROWTH VS. SCHEDULE SLIPPAGE VS. PERFORMANCE SHORTFALLS

There was a great deal of cost growth among the projects in our database. When one considers that the estimates were made *after* the project definition and preliminary engineering were complete,[4] an average 88 percent cost growth is quite remarkable. It is all the more remarkable in view of the amount of money involved. The average cost overrun was about $650 million. The total overrun amount exceeded $30 *billion* for 47 projects. Furthermore, this does not include the overruns incurred after the completion of construction. Those overruns could add another 5 percent or more to average cost growth.[5]

Compared with such cost growth, the amount of schedule slippage seems very tame indeed: The average project's schedule slipped only 17 percent between the beginning of detailed engineering and the end of construction. This amounts to about 8 months more than planned. *Between staying within cost and maintaining schedule, the owners of megaprojects appear to prefer to avoid schedule slippage.* This appears to be true for all owners, but especially for public owners of megaprojects. Extraordinary efforts were made in a number of projects to maintain the schedule. However, in no case did we find evidence that stringent schedules were relaxed to reduce cost growth. The desire to complete projects on time was especially prevalent for minerals-extraction projects, such as oil platforms and mining projects. For example, the Ok Tedi project encountered several obstacles that would normally have led to substantial schedule slippage. Rather than permit that, additional contractors were added, and "heroic" measures were taken. The five synthetic-fuels plants in the database—the Great Canadian and Syncrude oil sands projects, the SASOL II coal liquefaction project, the Great Plains coal gasification project, and the Union Oil shale project—have only two features in common: They were all massive, complex, risky undertakings, and they all completed construction on or ahead of schedule. This is quite reasonable in light of the capital-intensive nature of such projects.

There may be a relationship between longer engineering and construction schedules and better project performance. Our performance data are too crude to verify such a relationship, but it is worthy of further investigation if only because project performance is the most important outcome. We strongly suspect that the key link between schedule and performance is the point at which detailed engineering is begun. If detailed engineering is performed before all the conceptual aspects of the design and all matters requiring R&D have been completed, poor performance results. A project that does not perform as

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[4] Or *should* have been complete.

[5] This assumes that the percentage of unanticipated costs of startup about equals that for smaller projects (see Merrow, Phillips, and Myers, op. cit.; and Myers and Shangraw, op. cit.).

planned produces no profits. There are no benefits for economic development; there are no lessons learned. As one wit put it, "Even white elephants have uses; a *dead* white elephant, however, is of no use to anyone."

THE EFFECTS OF PROJECT LOCATION

We explored two attributes of project location in this analysis: remoteness and area of the world. Remoteness of projects from population centers is clearly related to cost growth. The best single indicator of *remoteness* in our database is whether or not a labor camp was required for the construction of the project. The presence of a labor camp means that labor could not be drawn from the surrounding area and that there was insufficient local housing to accommodate the influx of workers. Rather than leading to worse outcomes, which would have been a reasonable expectation, the need for a labor camp is clearly associated with *less cost growth.* This finding reflects the association—direct and indirect—between labor camps and somewhat more realistic cost estimates. However, remote sites are also sometimes associated with very undesirable outcomes. The requirement to build major permanent infrastructure is associated with greater cost growth.

The area of the world in which a project was built had little effect on outcomes. Although projects in LDCs tended to be a little more costly, other things being equal, *they did not exhibit more cost growth or schedule slippage than other projects.* Higher cost is to be expected when much of the labor and materials and virtually all of the engineering have to be imported. However, we found no relationship between LDC projects and performance shortfalls. A megaproject constructed in the United States, outside of the Gulf Coast, appears to encounter as much cost growth and schedule slippage as one constructed anywhere else in the world.[6] On the other hand, two factors that are more likely to come into play in an LDC are associated with cost growth: the need for permanent project infrastructure and public ownership. These factors have the same effect on project outcomes in any region, however. The absence of any major differences in the factors that drive good and bad outcomes between projects in the United States and

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[6] As noted earlier, U.S. projects outside the Gulf Coast were subject to more regulatory constraints than in any other area. By contrast, the Gulf Coast projects had about half the number of regulatory problems as the average project. LDC projects were about average in terms of regulatory difficulties, and OPEC projects faced the fewest such problems.

projects in the rest of the world suggests that many of the lessons from U.S. projects may be transferable to projects elsewhere.

NEXT STEPS

Cost, schedule, and performance outcomes are remarkably predictable, even with the relatively crude data with which we were working. More than three-quarters of the variation in outcomes can be explained by the factors examined. But this analysis was only a first step toward isolating and understanding the causes of problems in megaprojects.

Much more analysis is needed to identify the circumstances that lead to regulatory problems and other conflicts between projects and host governments. This in turn must result in basic changes in project planning and management to avoid or at least mitigate the effects of such problems. Because this kind of analysis falls outside the traditional realm of engineering concerns, industry will have to turn to nontraditional sources of expertise.

Appendix A

PROJECTS EXAMINED

Project Name	Location	Type
Arkansas 2	Russellville, Arkansas	Nuclear powerplant
Badak LNG Plant	Indonesia	LNG plant
Balikpapan	Kalimantan, Indonesia	Oil refinery
Bougainville Copper Mine	Papau, New Guinea	Copper mine
Carter Creek Plant	Carter Creek, Wyoming	Gas processing plant
Chalmette	Chalmette, Louisiana	Refinery complex
Cilicap Refinery	Central Java	Refinery
Cooper Basin Liquids Project	NE South Australia	Hydrocarbon development
Copper smelter	Western U.S.A.	Copper smelter
Dallas/Ft. Worth Airport	Dallas/Ft. Worth, Texas	Airport
Dumai	Central Sumatra	Oil refinery
Exxon Baytown Refinery	Baytown, Texas	Residual oil
Farley	Columbia, Alabama	Nuclear powerplant
Garyville Refinery	Garyville, Louisiana	Oil refinery
Gas Pipeline	Neuquen Basin, Argentina	Pipeline
Great Canadian Oil Sands	Fort MacMurray, Alberta	Tar sands plant
Great Plains	Beulah, North Dakota	Coal gasification
Hadera Power Station	Hadera, Israel	Coal-fired power
Helms High Sierra	Fresno, California	Storage facility
Itaipu	Brazil/Paraguay	Hydroelectric project
Jari Plantation	Brazil	Pulp mill
Las Truchas	Michoacan, Mexico	Steel complex
Loop	Louisiana	Offshore oil port
Mobil Joliet Refinery	Joliet, Illinois	Oil refinery
North Ana I	Mineral, Virginia	Nuclear powerplant
Ok Tedi Project	Papua New Guinea	Gold/copper mine
Pascagoula Residium	Pascagoula, Mississippi	Heavy-oil refinery
Pembroke FCC	Wales	Fluid cat cracker
Ponce Project	Ponce, Puerto Rico	Petrochemical plant
Prudhoe East Facility	Alaska	Oil processing plant
Rancho Seco	Clay, California	Nuclear powerplant
Red Deer Ethylene Plant	Red Deer, Alberta	Ethylene plant
Riyadh Campus/King Saud University	Saudi Arabia	University
Saber Refining Co.	Corpus Christi, Texas	Alkylation Unit
SASOL II	Union of South Africa	Coal liquefaction
Saudi Petrochemicals	Jubail, Saudi Arabia	Petrochemical complex
Statfjord A	North Sea	Offshore platform
Surry I	Gravel Neck, Virginia	Nuclear powerplant

Syncrude Ltd., Oil Sands	Mildred Lake, Alberta	Tar sands plant
Tarbela Dam	Pakistan	Hydroelectric dam
Tennessee Eastman	Texas	Coal gasification
Texaco CPI Plant Expansion	Convent, Louisiana	Oil refinery
Trans Alaska Pipeline System	Alaska	Oil pipeline
Trojan	Prescott, Oregon	Nuclear powerplant
Trailblazer Pipeline	Beatrice, Nebraska	Transportation project
Trunkline LNG	Lake Charles, Louisiana	LNG refinery
Union Oil Shale	Parachute Creek, Colorado	Oil shale plant
World Scale Olefins	Texas Gulf Coast	Petrochemical plant
World Scale Olefins II	Gulf Coast	Petrochemical plant
World Scale Olefins III	Texas Gulf Coast	Petrochemical plant
Yanbu Petrochemical Complex	Yanbu, Saudi Arabia	Petrochemical complex
Yanbu Refinery	Yanbu, Saudi Arabia	Refinery

Appendix B

MEGAPROJECTS WORKSHEET

Code: ________

1. Project Name ____

2. Location ____
city state/province country

3. Type of Project

Oil Refinery	1
Off-shore Oil Platform	2
Nuclear Power Plant	3
Hydro Electric Dam Plant	4
Synthetic Fuels Plant	5
Mining/Smelting Operation	6
Chemical Processing Plant	7
Infrastructure Development only (e.g., new city, highway)	10
Transportation Project (e.g., pipeline, railroad)	11
Other (please specify)	8

4. Plant output capacity (in appropriate units).

5. Did construction of this project involve:

Building a facility at a new site	1
Expansion or modification at an existing site	2

6. Project Participants

A. Owner/operator(s) % of ownership

_________________________ ____________________

B. Prime Contractor(s)

ANSWER ONLY IF PROJECT IS A JOINT VENTURE. SKIP TO QUESTION 8 FOR SINGLE-OWNER PROJECTS

7A. Number of firms involved in joint venture __________________

7B. List below the name of each partner and the reason (s) it had for participating in the project. (CIRCLE ALL THAT APPLY)

	__________ Partner	__________ Partner	__________ Partner
Limit financial risk	1	1	1
Share resources	2	2	2
Access to raw materials	3	3	3
Technology transfer	4	4	4
Government incentives/ regulations	5	5	5
Other (PLEASE SPECIFY)	8	8	8

Partner 1 __________ __________ __________

Partner 2 __________ __________ __________

Partner 3 __________ __________ __________

7C. Did the fact that this was a joint venture pose any special management problems?

YES .... 1 (go to question 7D)
NO .... 0 (go to question 7E)

7D. Please explain the nature of these problems.

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

7E. Please provide any additional information you have about this joint venture (e.g., the nature of the agreement among the partners, any reports of dissatisfaction by the partners).

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

8. Is this project located in a remote area?

YES 1
NO 0

9. What infrastructure had to be constructed for the project?
(CIRCLE ALL THAT APPLY)

Roads	1
Sewage treatment	2
Water supply	3
Railway	4
Port facilities	5
Temporary housing (e.g., labor camps)	6
Permanent Housing	7
Communications systems (e.g. telephone lines)	10
Airplane runways or heliport	11
Medical Facilities	12
Not applicable - no infrastructure development development	99
Other (PLEASE SPECIFY)	8

____

10A. Did local climate significantly affect construction costs or schedule?

YES ..... 1 (GO TO QUESTION 10B)
NO ..... 0 (GO TO QUESTION 10C)

10B. (IF YES) In what way?

____

Source (s) _ _ _ _ _
_ _ _ _ _
_ _ _ _ _

10C. Was it possible for construction to proceed year round?

YES 1
NO 0

11A. Does this project embody any first-of-a-kind technology?

YES ..... 1 (GO TO QUESTION 11B)
NO ..... 0 (GO TO QUESTION 11C)

11B. (IF YES) Briefly describe this technology.

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

11C. Has either the owner/operator or the prime contractor built this type of unit before?

YES ..... 1 How many?________
NO 0

12. Is this project unique in any of the following ways? (CIRCLE ALL THAT APPLY)

Size	1
Climate or environmental conditions at the site	2
Unusual materials or construction methods	3
Other unique physical features	8

(PLEASE SPECIFY)________________________________

____

No unique physical features........................99

13A. Is there any direct governmental involvement in this project's financing or management?

YES ..... 1 (GO TO 13B)
NO ..... 0 (GO TO 14A)

13B. (IF YES) describe the nature of that involvement (which government agencies, type of involvement - investor, loan guarantor, owner/operator)

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

14A. Did any of the following significantly affect project schedules or costs? (CIRCLE ALL THAT APPLY)

Environmental regulations	1
Public Health and Safety standards	2
Government regulations on labor or procurements	3
Other governmental regulations or standards	8
No significant effect	99

14B. FOR ITEMS CIRCLED, please explain the nature of the regulation and its effect on project cost or schedule?

____

14C. Please summarize any discussion you may have about how project relationships with governmental agencies (and their regulations) were handled.

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

15A. What were the **peak labor force requirements** for this project?

Number of men working on-site________________________

(IF AVAILABLE) **Total** number of man-hours to complete project ____________________________hrs.

Source _ _ _ _ _

(IF AVAILABLE) Number of **engineering** man-hours to complete project____________________________hrs.

Source _ _ _ _ _

(IF AVAILABLE) Number of **construction** man-hours to complete project____________________________hrs.

Source _ _ _ _ _

15B. Did labor have to be recruited from outside the immediate local area?

YES ..... 1 (GO TO QUESTION 15C)

NO ..... 0 (GO TO QUESTION 16A)

15C. (IF YES) Indicate the approximate proportion recruited outside and any other information you might have found about recruitment efforts outside the local area.

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

16A. During project construction, were there any serious **labor** shortages?

YES ..... 1 (GO TO QUESTION 16B)
NO ..... 0 (GO TO QUESTION 17A)

16B. (IF YES) please explain their nature, including the types of labor that were in short supply (i.e., engineering/ technical, skilled craft, construction labor).

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

17A. During project construction, were there any serious **labor** stoppages or unrest?

YES ..... 1 (go to question 17B)

NO ..... 0 (go to question 18)

17B. (IF YES) please describe them (how many, why they occurred how long they lasted on average, and whether or not they shut down the project.)

____

18. Please provide any additional information you can on project labor conditions (e.g., nature of training provided project workers, turn-over rates, etc.)

____

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

19A. Number of subcontractors ____________

19B. Number of suppliers ____________

20A. During project construction, were there any serious equipment shortages?

YES ..... 1 (GO TO QUESTION 20B)
NO ..... 0 GO TO QUESTION 21)

20B. (IF YES) please describe these shortages. What items were in short supply, what were the causes of the shortages, and what were their effects on project schedule and cost?

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

21A. During the project, how many people served as project manager?

Number of project managers __________

21B. (IF MORE THAN ONE PERSON SERVED AS PROJECT MANAGER) was turnover the result of any problems with the project?

YES ..... 1 (GO TO QUESTION 21C)
NO ..... 0 (GO TO QUESTION 22)

21C. Please explain any turnover in project management.

____

22A. When did detailed engineering for this project begin?

________ month ________ year

22B. When did project construction end?

________ month ________ year

22C. When did the project begin start-up (i.e., was mechanically completed)

________ month ________ year

22D. Is this a modular or phased construction project?

YES ..... 1 (GO TO QUESTION 22E)
NO ..... 0 (GO TO QUESTION 22F)

22E. Which project components were completed by the end construction and start-up dates listed in Questions 22B and 22C?

____

22F. What was the total planned schedule from the beginning of detailed engineering through start-up?

Months ____ (planned) Date of plan/article: mo___ yr___ Source _ _ _ _ _

Months ____ (planned) Date of plan/article: mo___ yr___ Source _ _ _ _ _

Months ___ (planned) Date of plan/article: mo___ yr___ Source _ _ _ _ _

Months ___ (planned) Date of plan/article: mo___ yr___ Source _ _ _ _ _

Months ___ (planned) Date of plan/article: mo___ yr___ Source _ _ _ _ _

22G. What was the total actual schedule from the beginning of detailed engineering through start-up?

Months ___________(actual) Source _ _ _ _ _

Months ___________(actual) Source _ _ _ _ _

Months ___________(actual) Source _ _ _ _ _

23. (IF ANY SCHEDULE DELAYS OR SLIPPAGES) what were the reasons?

____

Source _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

No schedule delays or slippage.....99

24. What was the **actual total capital cost** of this project in "as spent" dollars?

Total actual cost $________million Source - - - - -

Total actual cost $________million Source - - - - -

Total actual cost $________million Source - - - - -

Total actual cost $________million Source - - - - -

Total actual cost $________million Source - - - - -

25. What was the **initial estimate** of the total capital cost of this project?

Total estimated cost $________million

Date of estimate/article ___ ____ Source _ _ _ _ _
mo yr
Escalation/Inflation factor included in estimate _____ _____
yes no
(IF YES) Date to which escalation valid ______ ______
mo yr

(REPEATED)

26. Please list all other estimates of total capital cost that were reported on the project prior to its completion. List them in chronological order from the earliest one (after the initial estimate) to the most recent.

Total estimated cost $________million

Date of estimate/article ___ ____ Source _ _ _ _ _
mo yr
Escalation/Inflation factor included in estimate _____ _____
yes no
(IF YES) Date to which escalation valid ______ ______
mo yr

(REPEATED 6 TIMES)

27. Please list all other estimates of total capital cost that were reported on the project prior to its completion. List them in chronological order from the earliest one (after the initial estimate) to the most recent.

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

28. Please list below any other available information on cost -- e.g., the estimated and actual costs of major project components, initial design costs, etc. (Attach copies of any detailed cost information available).

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

29. Has the project always produced/operated in the way intended?

YES ..... 1 (GO TO QUESTION 31A)
NO ..... 0 GO TO QUESTION 29B)

29B. (IF NOT) describe any problems (e.g., in type or rate of production).

____

Source (s) _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

30A. Have there been any major breakdowns or failures since the project began start-up?

YES ..... 1 (GO TO QUESTION 30B)
NO ..... 0 (GO TO QUESTION 31A)

30B. (IF YES) Describe them. Were these due to equipment difficulties or other problems?

____

Source (s) _ _ _ _ _
_ _ _ _ _
_ _ _ _ _

31A. Is this project currently generating profits at the level originally expected?

YES ..... 1 (GO TO QUESTION 31B)
NO ..... 0 (GO TO QUESTION 31C)

31B. (IF YES) Is this due to favorable conditions external to the project (e.g., the rise in world oil prices)?

YES ..... 1 (GO TO QUESTION 32)
NO ..... 0 "

31C. (IF NOT) Why is this the case? Please indicate if lower than expected profitability is due to adverse conditions external to the project (e.g., world market decline in the price of some minerals).

____

Source (s) _ _ _ _ _
_ _ _ _ _
_ _ _ _ _

32. Please summarize below any additional information about project management that you found in your reading. We are particularly interested in any management problems encountered on the project, how these were addressed, and whether any new or innovative approaches to project management were used.

    If you have found any detailed discussion of the project's management structure, please summarize it here and attach a copy of the article (s) to this worksheet.

Source(s) - - - - -

- - - - -

- - - - -

33. In addition to the factors already asked about is there any other evidence you can identify that suggests this project was particularly successful or unsuccessful?

Sources _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

34. In this space, include any additional information about the project that you think would help us in understanding the management of Mega projects and the determinants of project success.

Sources _ _ _ _ _

_ _ _ _ _

_ _ _ _ _

Coder _ _

Appendix C

STATISTICAL DIAGNOSTICS

Although the summary regression statistics such as the F-statistic, R^2, MSE, and T-statistics are useful and necessary ways of judging the adequacy of a regression model, they are not sufficient. In addition, it is important to assure that:

- There are no violations of ordinary least-squares (OLS) assumptions.
- There is no multicollinearity among independent variables.
- There are no influential observations.

These are discussed in turn below.

REGRESSION ASSUMPTIONS

When the residuals are plotted against the independent variables in the cost growth and schedule models, there is no discernible pattern that would suggest homoscedasticity. No variables are excluded from the models that are significantly correlated with the errors (residuals). Thus, the models are "full-rank" with respect to all data available.

MULTICOLLINEARITY

If independent variables are highly correlated, the goodness-of-fit can be substantially inflated. Table C.1 presents the correlation matrices for the cost growth and schedule slip independent variables. (No matrix is presented for the performance model because only one independent variable was used.) Note that the highest correlation coefficient is less than .52, well below the point at which multicollinearity problems arise.

Table C.1

CORRELATIONS OF INDEPENDENT VARIABLES

Cost Growth Model (obs. = 47)

	regscale	pubsect	nat-tech	foak	tempinf	perminf
regscale	1.0000					
pubsect	−0.3660	1.0000				
material	0.0422	0.1421	1.0000			
foak	0.1860	−0.3439	0.0778	1.0000		
infra	0.3408	−0.0957	0.3330	0.3350	1.0000	
perminf	0.2120	−0.0012	0.0471	0.1625	0.5033	1.0000

regscale: Regulatory problems scale
pubsect: Project is wholly owned by the public sector
mat-tech: Project uses new materials or techniques of construction
foak: Project uses first-of-a-kind technology
tempinf: Project entailed temporary project infrastructure
perminf: Project entailed permanent infrastructure

Schedule Slippage Model (obs. = 38)

	regscale	foak	mat-tech	extract
regscale	1.0000			
foak	−0.0069	1.0000		
mat-tech	−0.1167	0.0419	1.0000	
extract	0.1296	0.3601	0.0104	1.0000
shortlab	0.5211	−0.1515	0.0419	−0.1173

extract: Minerals-extraction project
shortlab: Shortages of labor occurred during construction

INFLUENTIAL OBSERVATIONS

It is possible, and especially so in relatively small datasets such as this one, for individual observations (i.e., projects) to affect regression results. Sometimes such observations are "outliers" in the sense of the dependent variable; sometimes they fit the model perfectly. But when influential observations are excluded, the model changes significantly.

To detect the possible presence of influential observations, we examined the "Cook's Distance" (D) for each observation.[1] In the cost growth equation, none of the 47 observations for which data were available were influential according to the Cook criterion. However, for the schedule slip model, two (and only two) observations were clearly identified as influential and were excluded from the final model. These were the Union Oil shale facility and the Syncrude oil sands facility. The presence of these two projects in the model causes the effect of minerals-extraction projects to be exaggerated. Interestingly, these two projects are very similar in terms of their schedule results. Both projects were completed close to schedule despite being highly innovative. Both, however, suffered very long and difficult startups. If we had been able to measure the project schedules until the end of startup, it is very unlikely that either of these observations would be influential.

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[1] See R. Dennis Cook, "Detection of Influential Observations in Linear Regression," *Technometrics*, Vol. 19, No. 1, February 1977.

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