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Perspective

Delivering effectively on large engineering projects

Guru Madhavan*, Alton D. Romig Jr, Richard A. Meserve and Donald C. Winter

National Academy of Engineering, Washington, DC 20001, USA
*To whom correspondence should be addressed: Email: gmadhavan@nae.edu
Edited By: Cristina Amon

Introduction

In 1982 the city of Boston began planning a tunnel project, which rerouted the city's central artery, I-93, into a 1.5-mile tunnel running underneath downtown. The project, known universally as "the Big Dig," was originally expected to cost $2.8 billion and be completed by 1998. Instead, construction dragged on until 2007, and the final cost, which will not be completely paid until 2038, is expected to reach $22 billion, including interest.

Fifteen years later, in 1997, construction began on the National Ignition Facility at Lawrence Livermore National Laboratory, a facility in California designed to create the conditions necessary for nuclear fusion to occur within a small, confined space. It was estimated that the project would cost $1.1 billion and be complete within five to seven years. The construction took twice as long as expected, with the facility finally being completed in 2009 for $3.5 billion.

In 2006, when the Honolulu High-Capacity Transit Corridor project, a 20-mile rail transit line through the paradise city, was in the planning stages, the final cost was estimated to be $4 billion. A recent estimate is that it will ultimately cost $12.4 billion when it is completed in 2031 (1). A project to build two nuclear reactors at the Alvin W. Vogtle Electric Generating Plant in Georgia doubled in cost and was delayed by over five years from the estimates when the project was approved. And the project involving two reactor units at Virgil C. Summer Nuclear Generating Station was canceled after uncontrollable cost overruns (2).

These experiences are not anomalies. Large-scale engineering projects—generally called "megaprojects," with a price tag of $1 billion or more—have a history of taking longer and costing more to build than originally expected. Much research has examined how likely large projects are to experience cost overruns and longer-than-expected times to completion. A widely cited estimate is that 90% of all large projects cost more than originally expected and that about 90% of these large projects are finished behind schedule (3). Other observers have come up with different estimates. Still, even the most confident find that at least 50% of large projects cost more than expected. It's been observed that "performance in megaproject management is strikingly poor and has not improved for the 70-year period for which comparable data are available, at least not when measured in terms of cost overruns, schedule delays, and benefit shortfalls" (3). And unless something major changes, we can expect that cost overruns and construction delays will continue to plague a significant percentage of large engineering projects.

The stakes are significant. Globally some $6 trillion to $9 trillion is spent each year on large-scale projects—approximating the entire US federal budget, or about 8% of the whole world's gross domestic product (GDP)—with spending as a percent of global GDP increasing yearly (3). The challenge is particularly significant for the United States given the recent passage of the $1 trillion bill to improve infrastructure. Unless practical measures can consistently bring large projects to completion on time, on budget, and with the expected benefits, vast sums may be wasted, and some important large-scale projects may never be completed. For these reasons, it is vital to develop clearer answers to two basic questions about large projects and their implications for engineering: What causes the cost overruns and delays that plague them, and what can be done to avoid or minimize them in the future? We discuss these as "problems" and "possibilities," respectively, in this perspective.

Problems

Much effort has gone into examining why completing large projects on time and on budget should be so difficult. Although the details vary from project to project, the broad outlines of the causes are clear. To begin with, the sheer size of these projects creates various challenges. For example, a $1 billion-plus project with multiple stakeholders, each with its own often-conflicting goals and a design that attempts to make everyone happy, will often have weaknesses that only become apparent over time. Furthermore, there is often pressure to get started on a project quickly—for instance, because of worries that support will dissipate if too much time passes without any sign of progress—which can lead to moving forward before all the factors have been considered and the design finalized, on the assumption that the details can be worked out later. In such cases, issues that might have been caught in the design phase if more time had been taken may not become obvious until the project is underway, construction has started, and a significant amount of money has already been spent. But because of the investment and commitment that large projects require, they tend to develop a momentum

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that keeps them going even after major problems appear. This is how a $1 billion budget turns into $3 billion or more over time. The complexity of large projects introduces an entirely different set of problems. These projects have numerous components that depend upon each other and tend to interact in difficult-to-predict ways; such unforeseen interactions can lead to emergent behaviors that require a rethinking and redesigning of the project, leading to delays and cost increases.

In short, the size and complexity of large projects create challenges that are different qualitatively and quantitatively from those encountered in smaller projects. These challenges must be understood and dealt with if the issues with large projects are to be successfully addressed. The challenges can be classified into three broad categories. First, technical challenges make designing, building, and maintaining large projects much more difficult than with smaller, less ambitious projects. Second, large projects' size, cost, and complexity lead to various organizational, political, and social problems that can hinder the projects' development, construction, and operation. And third, many engineers, design organizations, and construction firms do not have the training, expertise, or experience necessary for dealing effectively with large projects.

Technical challenges

The size and, particularly, the complexity of large projects pose technical challenges that are qualitatively different from the sorts of challenges that engineers encounter in less substantial projects. Of these two factors, complexity lies at the root of the most challenging design issues. In technical terms, complexity is different from merely complicated. A Rube Goldberg device with multiple components connected in a series (levers, balls rolling down chutes, etc.), where an action in one component triggers an action in the next line, is complicated but not complex. The outcome is the same each time. A complex system, by contrast, has components that interact in ways that make the system's behavior difficult to predict. A failure in one component, for instance, can lead the entire system to behave in completely unforeseen ways or even fail catastrophically, as when frozen O-rings led to the explosion of the *Challenger* space shuttle.

Because of such complexity, large projects have inevitable unpredictability, which can have various consequences. It can force cost overruns and delays, for instance, when previously unforeseen problems with a design come to light. Complexity is a major reason that so many of these large projects follow what has been termed the "break-fix" pattern: The project gets started with great optimism but without a complete understanding of what will be required for it to become fully operational. Then, the uncertainties catch up at some point, and the project "breaks" in some way or another, requiring a "fix," i.e. a redesign or reorganization. Because of the time, money, and political capital already invested in the project, a "break" seldom leads to the project's cancellation but will lead to the project taking longer to finish and costing more than anticipated.

One characteristic of unsuccessful megaprojects is that the projects are allowed to start before their designs are complete. Then as problems arise, delays become the norm, creating project management risks. Moreover, the crucial need to complete the program planning effort to enable reliable cost and schedule estimates is often under appreciated. A proper program plan should identify the various activities needed to support developmental and verification activities. It should incorporate a risk management program detailing activities that reduce the likelihood and (or) consequences of failures resulting from inexecutable designs, unavailability of parts or personnel, or incomplete engineering development and verification and validation efforts.

These technical challenges are not insurmountable, and they could be effectively dealt with in a perfect world. Unfortunately, the situations in which large projects are built are generally far from ideal. The technical challenges are exacerbated by various other issues involving these projects' organizational, political, social, and professional environments.

Organizational, political, and social factors

Factors external to the engineering design process shape a project in many ways. Political considerations and public opinion will influence a project's requirements and impose a cost, timeline, and location constraints. Organizational factors can affect how well the design and construction organizations collaborate to bring the project to fruition. Psychological factors, such as the reluctance to walk away from sunk cost, can sway decisions about continuing a foundering project. Such factors influence any technology, of course. Still, they tend to have a particularly large role in large projects because the larger uncertainties inherent in large projects open the door to nontechnical factors shaping the outcomes (4).

A good example is the influence wielded by the so-called "sublimes." Large projects exert a powerful attraction on people in industrialized societies. Their size and power evoke a sense of awe and wonder accompanied by a sense of pride that such an impressive object was designed and built by humans. Such feelings of awe and appreciation are referred to as the *technological sublime* (5, 6) and are akin to the sensations triggered by the grandeur of nature, such as the power and beauty of Niagara Falls or the magnitude of the Grand Canyon. The difference is, of course, that while people do not have the ability to create Niagara Falls, they can, with enough effort and resources, build a Three Gorges Dam.

Research has shown that the technological sublime can influence decisions about large projects, both the yes/no decision on whether to proceed and the details of the projects (7). There is something incredibly appealing about creating an object that is massive, powerful, beautiful, or impressive and then bequeathing it to the world. This compelling appeal helps explain why some large projects get built when a clear-eyed economic analysis of their costs and benefits might indicate that they may not be a particularly good investment.

In addition to the technological sublime, scholar Bent Flyvbjerg has identified three other sublimes that encourage large projects. The *political sublime* refers to the good feelings that politicians get from their involvement with a large project; they can bask in the reflected glory of the project and use it for political advantage. The *economic sublime* is the financial pleasure that businesses, unions, workers, and other stakeholders receive from the large amounts of money flowing from a large project. And the *aesthetic sublime* is the pleasure associated with large, beautiful projects such as the Sydney Opera House; architects, designers, and even people not connected with the project can appreciate how a project can elevate its surroundings and serve as a landmark or monument to human imagination.

Together, these four sublimes can provide a powerful impetus to large projects and help push a close decision toward moving forward. And because there is generally a great deal of uncertainty regarding the costs, timeline, and benefits of a large project before it gets started—and often even when the project is halfway or more done—there is frequently no clear, objectively best decision.

Thus, subjectivity plays a role, and the sublimes can offset doubts or reservations about the wisdom of proceeding.

A closely related issue is the tendency of engineers and construction firms to be optimistic and overconfident in estimating how much something will cost to build and how long it will take. When a customer says that a project must be done by a certain time at a certain cost, engineers tend to believe they can do it. And construction firms have good reason to be optimistic in their estimates because more pessimistic (some would say realistic) estimates make it less likely the project will ever be built. Construction firms are not penalized for unrealistic estimates when they work on a cost-plus basis. Accepting unrealistic expectations precludes developing more realistic, executable plans, such as would be developed with a well-thought-out systems engineering effort. One result is that to get the bid, contractors often eliminate performance margins, assume the best performance, and remove things that could be considered superfluous but will be needed in certain circumstances. Advocates of other types—such as politicians wishing to build a project—also tend to establish unrealistic expectations to sell the project. They understate costs, posit unrealistic schedules, and downplay or ignore the risk to promote the project.

The ultimate result of these various factors is that questionable projects with overly optimistic budgets and schedules get approved, only to "break" at some point in development. But, as noted earlier, even major problems with a large project seldom lead to its cancellation. The incentive to proceed is very strong, partly because of how much money and time has already been invested, partly because the various sublimes are still in force, and partly simply because no one likes to admit having made a mistake. In practice, the project often moves forward, but at some point—generally past when a cancellation is a viable option—problems surface and costs spike. Cost overruns and delays—sometimes quite dramatic—are the natural outcome.

Some engineers argue that this tendency to be optimistic and enthusiastic about large projects is a good thing, as it results in the creation of many jobs and valuable creations, from the Suez Canal to the Sydney Opera House, that we are ultimately happy to have built but that would have never come into fruition if the true costs had been known ahead of time. In 1967 scholar Albert Hirschman introduced the idea of the "hiding hand," arguing that taking on technological projects with underestimated difficulties ends up triggering human ingenuity, with the result that the ingenuity makes it possible to overcome the difficulties which never would have been taken on in the first place if the magnitude of the challenge had been apparent from the beginning (8). Hirschman pointed to several examples where such ingenuity made it possible to bring projects in on time and within budget, even in the face of unforeseen difficulties. Unfortunately, experience has shown that such cases are the exception rather than the rule, and underestimated large projects generally cost much more and take longer than originally predicted (9).

However, overoptimism is not the only factor leading to problems with large projects. A major one is that those in charge of designing and building large projects must deal with different constituencies with different priorities and goals. Stakeholders come from various cultures and business environments and differ in how they view performance levels and capabilities versus cost, employment, and environmental impacts. The tendency in response is to try to please everyone as much as possible, which can lead to overpromising and an inevitable failure to satisfy conflicting objectives. This can be compounded by political pressure for early demonstrations of tangible progress, such as subcontract awards, hiring of significant numbers of workers, and completion of early construction steps, which is another factor making the projects likely to get underway without proper planning and vetting. A related factor is that "buyers" of major projects do not have skilled staff to oversee design and construction. They are dependent on contractors that do not necessarily have financial "skin in the game" but do have incentives for optimism bias. Different organizational and contracting relationships may be necessary to address this problem.

The pressure to sell most programs motivates overly optimistic cost and schedule projections as much or more so than the positive inclinations of engineers. This is further compounded by the perceived need to downplay (or ignore) the developmental risks. This mentality, for instance, was evident in the Space Shuttle program, where the partially reusable launch vehicle was a compromise after the original, fully reusable, concept was rejected as unaffordable. Compared to the Apollo program, the difference between the attitude and developmental approach of the engineers was strikingly different from the continuing "sales pitch" that accompanied the shuttle development. For Apollo, no sales were needed; it was a national commitment. The engineers and project managers were willing to openly admit this was new territory that we treaded with great concern, which wasn't the case with the shuttle. To sell the program, it was perceived to be necessary to argue that the shuttle's development was a logical next step for which the community was well prepared. Worse yet was the decision to make the shuttle the sole means of access to space for the United States. This decision greatly increased the risk consequences, but no attempt was made to reduce the probability of catastrophic loss. A properly constructed development and verification plan (also known as a "DVP") would have allowed reconsideration of major design decisions. For instance, was the shuttle design that precluded uncrewed test flights prudent? But since the shuttle design could only be evaluated using piecewise verification, it was a risky approach for a totally new concept.

Another compounding factor is the regulatory process, which has become increasingly complicated. A vast number of relevant regulations means that hundreds of intervenors may be involved in a large project, each of whom must be dealt with. The schedule is dragged out, and the cost increases, leading to various other issues. Goals may change over time, making it necessary to decide whether to change the project in response or accept that the finished project will not be completely satisfactory (4). Furthermore, knowledge and practice change over time, so a solution that seemed appropriate during the original design phase may now seem obsolete, while new and improved approaches appear desirable to integrate into the project. Again, that prompts a choice between delivering a state-of-the-art project that requires redesigning and reworking or sticking with the original design and ending up with an obsolete project (10).

Professional competencies and capabilities

Most discussion concerning what goes wrong with large projects focuses on technical challenges and organizational and political shortcomings. Still, engineers and engineering organizations aren't entirely blameless. Granted, even a flawless design would be no guarantee that the construction of a large project would go smoothly, but the simple truth is that most engineers and engineering concerns are not as prepared as they should be to deal with major complex projects of the sort that are becoming more common today.

The basic problem is that few people and organizations have the experience or training to deal effectively with large projects, so they tend to learn on the job, particularly since most projects are bespoke, with major differences from other large projects that have been undertaken. Furthermore, the projects are often built with bespoke technologies and designs. Hence, the planners and designers working on them tend to see them as nonstandard and assume they will not be able to learn from the experiences of other projects (10). So avoidable mistakes get made, and whatever lessons might be learned from those mistakes seldom get passed along to those working on similar projects in the future.

A typical large engineering project requires experience and capabilities that span multiple areas including finance, economics, sociology, environmental policy, political science, cultural anthropology, behavioral sciences, and civic engagement. Still, those in charge often lack the background and training to lead a multidisciplinary project. Furthermore, the complexity of the projects makes it more important that engineers have a familiarity with the processes that will be used in their construction; without this familiarity, engineers may come up with designs that cannot be built in an affordable and timely manner. The larger and more complex the project, the more important it is for engineering managers to move between different disciplines or communicate with those of other areas of expertise combined with a willingness to seek out such communication.

Similarly, however competent, most engineers are not used to thinking about complexity and emergent behavior in their designs. Standard engineering design assumes that one can completely specify a built object's behavior—give or take a certain small uncertainty that is calculated straightforwardly—and that failures can similarly be anticipated, at least statistically speaking, by examining a design's potential failure modes. However, because of their complexity, large projects break these rules. Major failures are much more likely to occur due to an unanticipated response to a rare, but not completely unlikely, series of events. Engineers who are not attuned to the complexity of a system and its possible consequences can easily develop a design, particularly in a large, multi-component, multi-constituent system, that will perform as planned in most situations but break down spectacularly when events align in just the wrong way.

Possibilities

In thinking about what is required to deal with the multiple issues affecting large projects, it is helpful to categorize the solutions in a way that is parallel to the categorization of the problems: technical approaches, social–political–organizational approaches, and ways to better prepare engineers and engineering organizations to deal with large projects.

Technical approaches

Many of the technical problems that plague large projects can be traced back to the complexity of the projects; this complexity makes it difficult to predict performance accurately or to anticipate ways that the project might break down or fail to perform as expected. Thus, not surprisingly, most of the technical approaches suggested for lessening the cost overruns, time delays, and other issues associated with a large project involve finding ways to ease the effects of its complexity.

Certain design choices, for instance, can reduce the complexity of a project and thus lessen the chances of emergent behaviors or an unanticipated series of events occurring that leads to failure. An example of such a design would be one in which a large project is broken into multiple pieces with minimal interaction. This approach helps in various ways. It lowers the demands placed on engineers by reducing the complexity of the overall project—in particular, removing or minimizing the interactions that must be considered, allowing engineers to focus on the designs of the various pieces individually. Furthermore, different parts of a project will have different constraints and requirements. For instance, some will need to change rapidly, while others will have great inertia. By deconstructing the project into functional subsystems that can become mostly stand-alone, the engineers can allow each subsystem to behave most effectively for that subsystem. Even with such a "modular approach," risks can be reduced only if the interactions between the various modules can be accurately foreseen. For instance, the space shuttle was designed in a modular fashion, yet the unanticipated interactions at launch led to failure. It becomes crucial for some team members to analyze the entire project holistically to ensure any integral effects are considered. This approach should help facilitate the most promising opportunities for improvement.

Other ways to deal with complexity include incorporating sufficient design margins to protect the project from unanticipated behaviors and avoid adverse events so that, even if unanticipated behaviors emerge, the consequences will not be disastrous. The typical approach in engineering is to design a system that will "behave" in a desired way. But it is also important to design systems to prevent undesirable behaviors, focusing on only the desired behavior results in designs that are more prone to unplanned adverse behaviors.

More generally, effective systems engineering competencies and capabilities are vital to designing and operating large projects that perform as desired. This broader view is crucial to developing designs that consider the overall complexity of a project and how the various components of a design interact with one another.

Finally, developing the proper performance measures for a large project is crucial in ensuring that the project will behave in the most valuable ways for its users. Most users will not be engineers, and their systems of value are not those of engineers; instead, they care about how well the built product performs its mission, not *how* it performs its mission. Engineers, in contrast, value technical aspects of that performance and thus tend to focus on technical performance rather than operational performance measures. In other words, they may measure the system's success in terms of technical measures rather than what is important to users. Therefore, they may end up building a system that fails to live up to expectations. To counter this tendency, engineers should learn what users think is important and create operational performance measures that reflect those values. This type of explicit focus on the needs of the users—and on how the meeting of those needs is measured—remains important: a large project that is technically sound but does not provide sufficient value to its users can be almost as much a failure as a large project that proves to be technically flawed.

Social, political, and organizational approaches

Allowing large projects to occur with different groups taking on different aspects with minimal interaction is a recipe for problems to appear in the interstices, which no one notices until it is too late. Instituting a holistic approach to a large project is an organizational issue. An effective project manager, for instance, can ensure that the different components of a project are well coordinated and that the people in charge of those components are in close communication.

Beyond that, it is important to keep a large project's design and build phases closely connected and aligned. In most projects, design and build are separated, with one entity chosen to do the design work and another to do the construction, with both chosen according to their cost estimates. Ideally, the design and build contractors will be as closely aligned as possible. If they are two separate entities, it is useful to choose the construction company early so that it can work with the designer early in the design process. One approach is to choose the construction contractor first and have that firm choose the designer, which can help ensure a close working relationship between the two, but there would not be as much owner input into the design in that case. A second approach is to choose an overall design first but then hand over much of the detailed design work to the construction contractor, who then works with the original designer to oversee the remaining design work and ensures it agrees with the original vision. Whatever the option chosen, the goal is to have the design and construction phases done more as a collaboration rather than as separate tasks.

A related approach would use integrated engineering, procurement, and contracting (EPC) contract structures. An uncoordinated approach may work well for smaller projects with mature technologies where all the players can be trusted to work independently and come together. Still, it opens the door to various unanticipated failures in larger, complex undertakings. The culture of the organizations involved in large projects is also important. Those most likely to succeed have a constructive culture emphasizing curiosity, humility, continuous learning, innovation, and adaptability, which are vital in managing the uncertainty inherent in large projects.

Another possibility is to institute independent peer review of the completed project designs. Some elements that such reviews could consider are how a design was finalized; what late-stage design changes were made and what may be the resulting improvements or errors; the practicality of the design (from initial concept to assembly); ensuring adequate safety margins (and allowing minor modifications without requiring additional analyses and reviews) and environmental health and safety design considerations (2).

Professional competencies and capabilities

Finally, what can be done to better prepare engineers and engineering firms to deal with large projects? One key step will be to emphasize systems engineering principles across the different teams delivering on a large project. Staffing complex projects with those who are comfortable only in their own specialties is a recipe for disaster. Systems engineers are important, as are those who actively seek out and learn from those with expertise in areas different from their own. Similarly, engineering managers must appreciate the details of the construction to understand the implications of their designs on the total installed cost of a project; this will help to keep the costs of a large project as low as possible. Given that large projects can sometimes take a decade or more to complete and that technologies relevant to the project can change, flexible designs that can accommodate such changes are preferable to designs that cannot.

And perhaps the simplest—and one of the most effective—engineering-related steps that could be taken to improve large future projects would be to learn and apply the lessons of the past. As noted, because large projects are relatively rare and tend to differ from each other in significant ways, engineers working on one project seldom have the chance to apply lessons learned from working on similar projects in the past. They are starting from scratch, with little training that applies directly to massive projects. This situation calls for creating a repository containing, for instance, lists of practices to adopt and practices to avoid—along with an explanation of why some approaches work better than others—and relevant examples from previous large projects. Ultimately, such lessons and best-worst practices could be used as the basis for university courses, professional workshops, and continuing education. The establishment of these educational elements would serve as a recognition that large projects are qualitatively different from other, less ambitious projects and require a unique set of skills and competencies for those who would design, build, maintain, and operate them. The future, in which large projects will take an increasingly large role, demands nothing small.

The path ahead

Today's large projects go beyond buildings. They can include the Joint Strike Fighter aircraft program and other defense projects, dams, wind farms, high-speed rail systems, airports, major science projects, such as the James Webb Space Telescope and the National Ignition Facility; major information and communications technology systems; and even some large individual container ships and passenger cruise ships. Each initiative comes with risks and uncertainties, and we can manage only those that we are willing to acknowledge; those that we choose to ignore will haunt us.

Many evaluations over the years have shown that infrastructures of all kinds are nearing the end of their useful life (or beyond it) and that demands beyond the original expectations are being placed on them. At the same time, the consequences of climate change, including sea level rise, extreme weather (both drought and deluge), and the imperative to decarbonize our economy, make huge investments in new infrastructure a critical need. Given the immensity of the challenge, the many large projects essential to public welfare must be completed reliably, successfully, economically, equitably, and promptly. The many past failures of large projects demand more responsible forms of engineering. The profession must rise to the task.

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