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A growing number of infrastructure projects are being proposed and built throughout the world. A megaproject is an investment of $1B or more to build the physical infrastructures that enable people, resources, and information to move within buildings and between locations throughout the world. Organizations responsible for producing megaprojects face a "performance paradox." Despite the growth in number and opportunities to benefit from learning, megaprojects continue to have poor performance records.[1] Most are unsuccessful measured against their original time, cost, quality, and safety objectives, as well as their expected revenue predictions.

The construction of airport infrastructure provides examples of how megaprojects can go wrong. When Denver's $5B international airport opened in 1995, it was almost 200 per cent over the original budget, 16 months late, and passenger traffic achieved only half the predicted revenues. The opening of the airport was plagued by problems with the baggage handling system, which was eventually abandoned in August 2005. Although Hong Kong's $20B Chek Lap Kok airport opened on time in July 1998, severe disruptions were experienced for six months after opening due to computer problems with the baggage handling system.

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Recent research has identified the challenges and risks associated with managing megaprojects.[2] However, there is little by way of a blueprint for their success. Our analysis of the London Heathrow Terminal 5 project enabled us to develop a systems integration model illustrating how organizations learn to overcome difficulties in megaproject performance. Each megaproject has its own internal economy, governance structure, and system of production established on a temporary basis.[3] The typical outcome is made up of millions of components, designed and produced by many different companies. Although the goal of a megaproject is to create a unique product, the processes involved in its production can be progressively standardized, simplified, and repeated to improve performance.

The model identifies six processes required to execute a megaproject:

- systems integration to coordinate the design, engineering, integration, and delivery of a fully functioning operational system;
- project and program management to support an integrated supply chain;
- digital design technologies to support design, construction, integration, and maintenance activities;
- off-site fabrication, pre-assembly, and modular production, to improve productivity, predictability, and health and safety;
- just-in-time logistics to coordinate the supply of materials, to increase speed and efficiency; and
- operational integration to undertake systems tests, trials, and preparation for hand-over to operations

These processes form a system of production that is coordinated and controlled by a systems integrator. This organization must establish the project governance structure, assume responsibility for risk, work with partners in integrated project teams, and lead a transient network of external suppliers consisting of dozens of first-tier suppliers, hundreds of contractors, and thousands of subcontractors. Our research illustrates how systems integrators seek to improve megaproject performance by learning to implement innovations based on the "recombination" and "replication" of a system of production processes.

In each megaproject, there is discontinuity between the processes required to deliver the "project" and those involved in the "operation" of the end result. Ironically, the troubled opening of T5 provides added confirmation to our argument that organizations must ensure that all six processes are well planned and executed. The disjointed hand-over to operation violated processes and behavior that led to success in earlier phases of design, construction, and integration on T5.

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Research Approach

The research was based on a single case study of the T5 project, involving two embedded subunits of analysis: an in-depth industrial collaboration with two leading organizations—BAA and Laing O'Rourke (LOR).[4] The client, BAA, formerly the state-owned British Airports Authority, is a highly regulated independent airport operator. It owns and operates Heathrow Airport and managed the T5 project. BAA recognized that in order to expand Heathrow it needed to find a better way to manage megaprojects at one of the world's busiest airports. LOR, one of several T5 contractors, developed new capabilities that enabled it to learn from T5, adapting and developing approaches for its other megaprojects, such as the $20B Al Raha Beach City in Abu Dhabi.

An inductive research approach was used, iterating between empirical findings and concepts, to draw inferences about the processes required to deliver megaprojects to meet cost, time, budget, quality, and other targets.[5] We recognize the difficulties of building theory from a single case study and suggest that the framework is treated as a proposition, for further rigorous testing and refinement on multiple case studies and surveys of megaprojects.[6] The case was selected because we had unusual research access to explore a significant phenomenon, providing conceptual insights about how two different organizations learn and innovate to improve megaproject performance.[7]

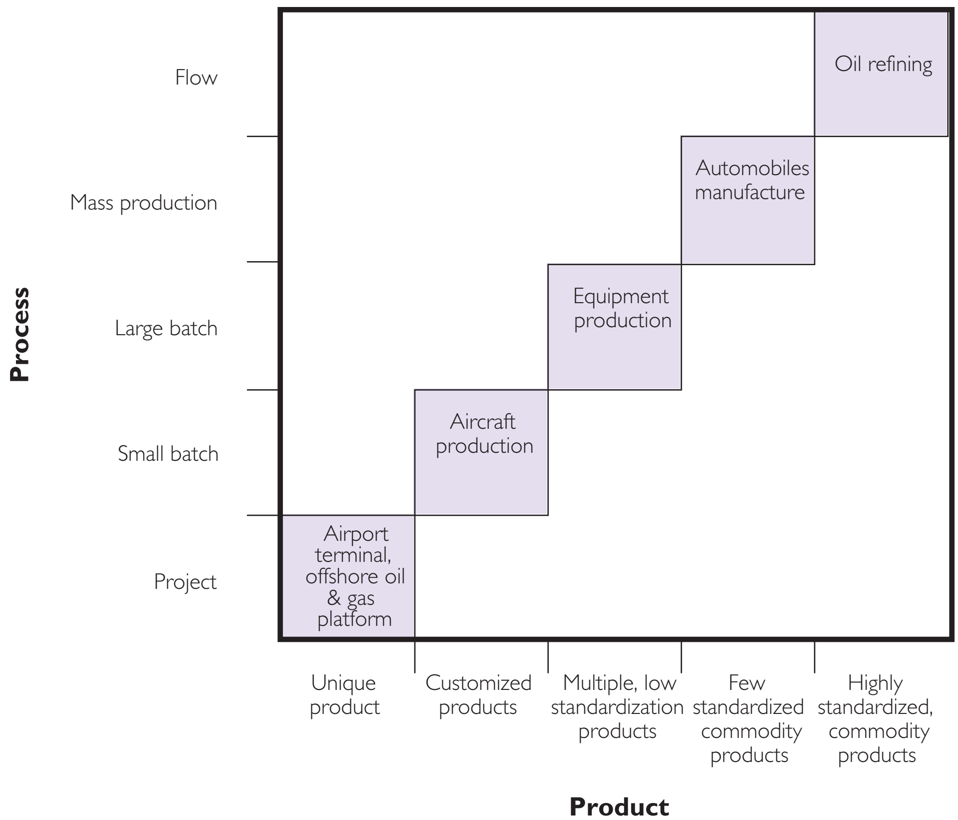
We worked closely with senior managers from BAA and LOR to identify and clarify the key research problem. The research explored how the two organizations attempted to learn during and after the T5 project, using the experience to improve megaproject performance. We gathered data through observations, archival records, and over 50 interviews with senior managers on the project, past and present project directors, and senior project managers from BAA and LOR, including LOR's Chief Operating Officer and Chairman, and BAA's former T5 Project Directors. Interviews took place between June 2005 and January 2007. Follow-up interviews were held in October and November 2007, and July and October 2008.

Project as Process

Our challenge was to understand how megaprojects can be improved through learning and innovation. A simple distinction is made between projects and operations. Whereas projects involve non-routine tasks to produce unique outcomes, operations refer to the repetitive activities performed in the production of standardized products and services in high volumes.[8] Recent research recognizes that while the outcome of a project is unique, processes can be standardized to enhance performance.[9] It also underlines the possibilities of using learning from project experiences to create replicable processes.[10]

The literature on industrial organization explains how performance is improved through learning and innovation in products and processes.[11] We adapted the product-process matrix to locate project-based activities and out-

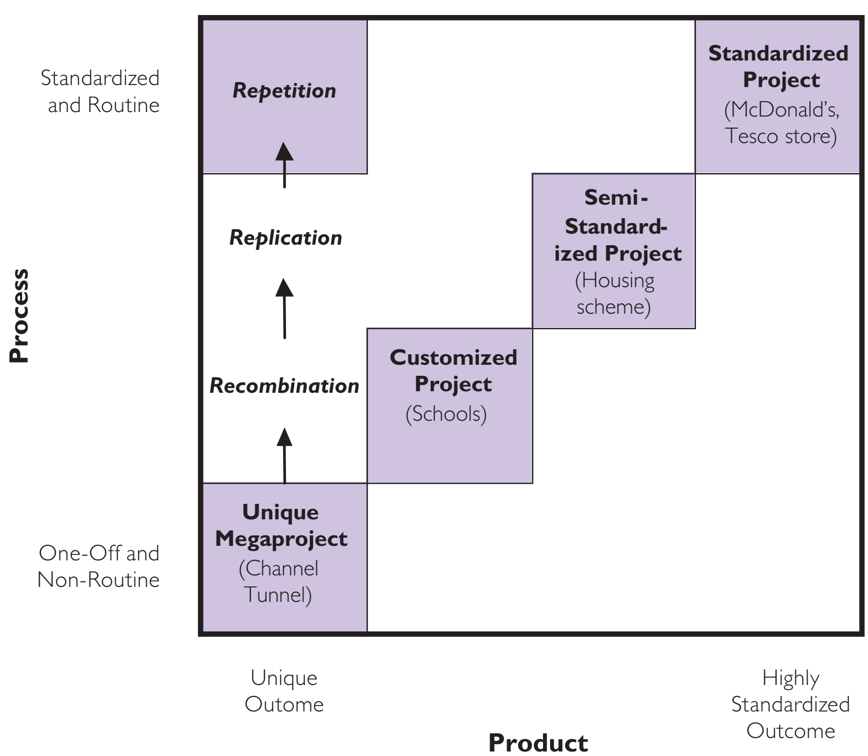
FIGURE 1. Project in the Product-Process Matrix



comes in the bottom left quadrant of Figure 1. In this classification, a megaproject is the most unique product and complex process. The dominant way of improving performance as markets expand is simply by moving progressively upwards from lower- to higher-volume standardized products and processes.[12] Project-based firms rarely move towards higher-volume automated stages because outcomes must be custom-made to each client's unique requirements and firms lack a model to transfer lessons from one project to the next.

How can the matrix help explain how organizations improve megaproject performance? Beyond a certain size, a project contains many standardized sub-processes. The volume, frequency, and predictability of project and operational tasks provides opportunities to create processes that can be structured in a controlled sequence, simplified in number, based on standardized modules, and repeated on a large-scale. Organizations can, therefore, learn from operational processes conducted at high-volume stages—such as lean production and just-in-time supply in the automobile industry—and adapt them to the requirements of megaprojects. They can also improve performance by adopting project pro-

FIGURE 2. Product and Process Innovation in Projects



cesses, ideas, and technologies developed by clients (e.g., Shell and BP) and suppliers (e.g., Bechtel) on other megaprojects.

By analyzing product and process innovation within the bottom left quadrant of Figure 2, we show that projects differ according to the degree of standardization. Product standardization depends on the extent to which a client specifies a one-off outcome. Process standardization depends on the extent to which tasks and components can be simplified and repeated.[13] In a routine project located in the top right quadrant—such as constructing a McDonald's restaurant—product and processes are highly standardized and replicable. A unique project—such as constructing the Boston Central Artery Tunnel—is located in the bottom left quadrant. Most projects lie between the two extremes and involve a combination of standardized and customized elements. The matrix helps to demonstrate that a unique outcome can be achieved using standardized processes and repetitive tasks. As Joan Woodward recognized, it is possible to achieve the "best of two production worlds—reducing production costs and still continuing to satisfy individual customers."[14]

In megaprojects, innovation focuses on the design and development of a unique product—a one-off solution tailored to a customer's specific requirements. In traditional approaches, product design is typically separated from construction—the process by which the outcome is produced. The conventional practice of procuring construction after (or while) design is finalized encourages bids from contractors who compete by offering novel processes without being able to iterate with major changes in design. By this route, contractors may achieve individual process improvements leading to isolated pockets of innovation that do not necessarily enhance overall performance of the completed project. Major benefits, however, can be gained if the lead organization in a project ensures an integrated and efficient system of iterative product-process design.[15] Early contractor involvement at the design stage is therefore more likely to result in reducing whole-life costs through the implementation of advanced, standardized, and efficient processes and sub-assemblies. Our research identifies two categories of innovation in the production system that support these improvements in megaproject processes:

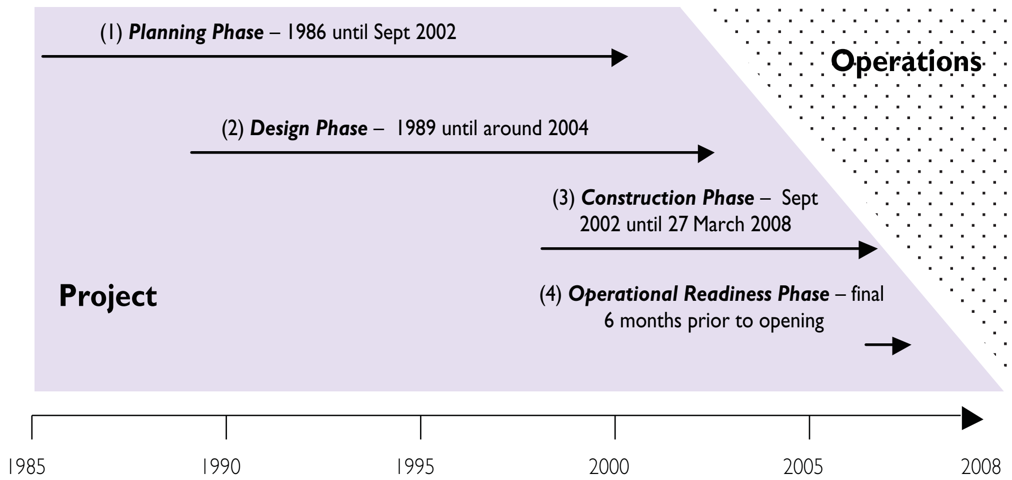
- *System Recombination*—An innovative recombination is created by learning about successful ideas, practices, and technologies from other industrial settings, combining them to achieve improvements in performance on a single breakthrough project.[16] The project organization requires considerable latitude to explore, identify, select, and experiment with new processes, technologies, operating procedures, and supplier networks.
- *System Replication*—A replication is achieved by learning how to enhance the combination of processes already implemented on a breakthrough project. Processes are rearranged, modified, and refined to create a common approach to project delivery that is reused on one or more future projects.[17] Replication improves the routines established by a breakthrough project but does not introduce the untried combinations of processes that breakthrough innovations do. Performance is improved by exploiting the learning curve advantages of a process for megaproject delivery measured against time, cost, quality, and other business objectives that are repeated on subsequent projects.[18]

Organizations can improve performance over time by implementing these innovations to move towards the ideal of megaproject efficiency: a unique outcome produced using routine and repetitive processes (the top left quadrant of the matrix).

Project Description and Challenges

A brief description of T5 illustrates the challenges involved in delivering a megaproject. BAA established the T5 project to design and build a new terminal to increase Heathrow's annual capacity from 67 million to 95 million passengers. Despite problems experienced at the opening of T5, the project achieved its goals of delivering a high-quality infrastructure on March 27, 2008 (the goal was set in 2001 for March 30, 2008), within a budget of $8.5B (established in 2003), and with an exemplary safety record.

FIGURE 3. T5 Project Life Cycle



T5 is a "system of systems" (or "array project") consisting of a cluster of different facilities organized to achieve a common purpose, such as two large terminal buildings, an air traffic control tower, road and railway transportation links, 13km of bored tunnels, airfield infrastructure, a 4,000 space multi-storey car park, and a hotel.[19] The well-known risks of cost and time overruns associated with integrating new technology on a project were minimized by the decision to use existing or well-established technologies. Where new technologies were introduced, they were first tested and proven in trial or operational environments (such as one of BAA's smaller airports) before being taken to T5.

The T5 supply chain included 80 first-tier, 500 second-tier, 2,000 third-tier, 5,000 fourth-tier, and 15,000 fifth-tier suppliers. The work program involved four main activities—Buildings; Rail and Tunnels; Infrastructure; and Systems—which were subdivided into 16 major projects and 147 sub-projects, with the smallest valued at $2m to larger projects such as the $600m Heathrow Express underground rail station.

The project life cycle included four distinct and overlapping phases (see Figure 3).[20] Although they ran concurrently, each phase required distinctive leadership, capabilities, and processes. On completion, British Airways (BA), the project user, began to transfer its entire Heathrow operations (split between Terminals 1 and 4) to T5.

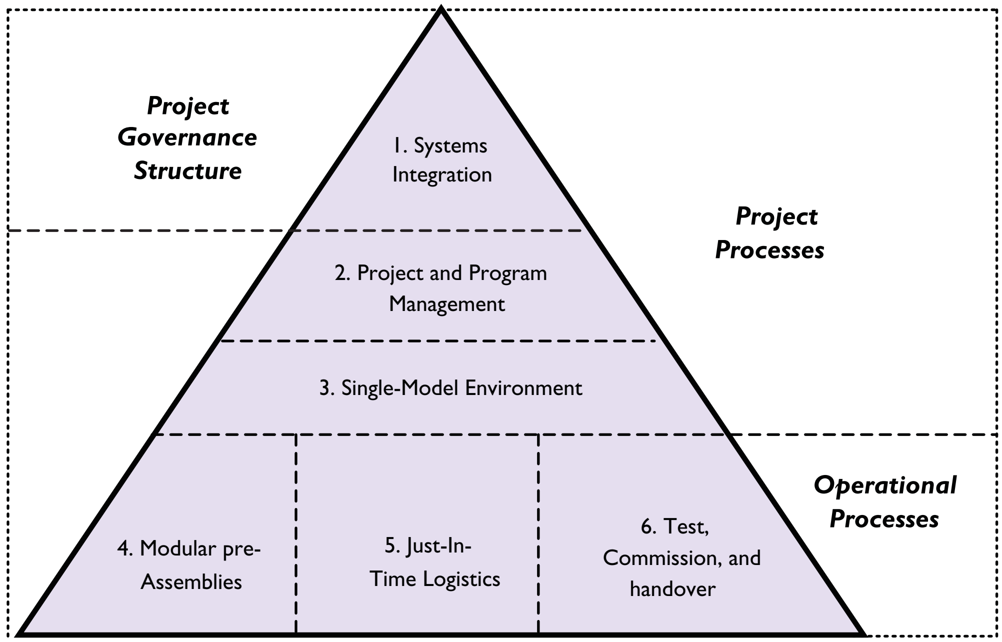
- *The planning phase* began in 1986 and included the longest public inquiry in UK planning history, from May 16, 1995 to March 17, 1999. On November 20, 2001, consent to proceed with construction was granted, subject to 700 planning conditions (such as the diversion of two rivers to meet strict environmental conditions).

- *The design phase* began in 1989 when Richard Rogers Partnership won a national competition to design T5. Using an approach called "progressive design fixity," three different designs were developed to meet the changing requirements of the client, the long public inquiry conditions, and emergent events such as 9/11 that impacted on the project during this phase.
- *The construction phase* included two sub-phases: the construction of infrastructure and buildings; and integration of systems and retail fit-out of the buildings, which started in early 2006. The project faced the logistical challenge of having only one main entrance to a site with limited space for storing materials, adjacent to Europe's busiest motorway. At its peak, the project had to cope with transporting 8,000 workers a day and nearly 250 deliveries of materials per hour.
- *The operational readiness phase* involved tests and trial "soft-openings" to prepare people, processes, systems, and facilities for the public opening. However, the project experienced difficulties when it opened on March 27, 2008. The disrupted opening cost BA $31m in the first five days. The airline misplaced over 20,000 bags and was forced to cancel 501 flights. The terminal finally achieved the first full schedule of operations 12 days after opening.

BAA had not previously managed a project or integrated a new infrastructure into its existing operations on this scale. When the decision to proceed was announced in March 2002, the budget set at $8.5B was a huge financial risk for a company with a market capitalization of around $14B. BAA's research on global megaprojects found that poor performance (such as the Channel Tunnel and London's Jubilee Line Extension) was associated with fixed-price or Private Finance Initiative (PFI) contracts, which transfer risk and responsibility to a prime contractor, with penalties incurred for delays, mistakes, and scope changes.[21] Such projects are delayed, over budget, or poorly integrated because of disputes, adversarial practices, and protracted legal battles between clients and contractors.[22]

BAA's insight was that despite efforts to transfer risk and responsibility, the client ultimately bears and pays for the risk when a megaproject runs into trouble. It decided that a radically new approach was required to deliver T5, and it developed a novel type of cost-plus incentive contract called the T5 Agreement, in which the client pays the constructor the costs incurred plus a profit margin. Unlike other forms of cost-plus contracts where the risks are *shared* between the client and contractor, BAA assumed full responsibility for the risk and worked collaboratively in integrated project teams with first-tier suppliers to create innovative solutions. This was the first time these principles were used on a large UK construction project.[23] By removing the risk from the supply chain, avoiding adversarial relationships and offering incentives to perform, the T5 contract was designed to encourage teams to work collaboratively to create innovative solutions, rather than seek additional payments or enter into legal disputes about scope changes.[24]

FIGURE 4. Processes of Megaproject Management



Systems Integration Model for Managing Megaprojects

In the immediate aftermath of the troubled opening, it would be easy to write off T5 as another megaproject failure. However, our research suggests that there is much to learn from the innovative approaches to the design and construction phases created to manage this complex and challenging project. Grounded in our study of success and failure at T5, we developed a conceptual framework to help large organizations succeed in megaproject management. The three levels in the hierarchical model presented in Figure 4 identify the project and operational processes that must be performed against time, cost, and quality targets. The model provides a framework for thinking about the challenges associated with megaprojects and practical suggestions about the combination of processes that must be put in place to improve performance. It is devised to be generic. However, it is not a one-size-fits-all approach because the processes must be arranged, integrated, and individually adjusted to fit the particular requirements of each megaproject. The processes identified in the model and the main sources of learning derived from T5 are summarized in Table 1.

Project Processes

At the highest level in the model, a systems integrator is responsible for the management and governance of the megaproject through all phases in its life cycle: planning, design, construction, and operational readiness.

TABLE 1. Megaproject Processes and Sources of Learning

Processes	Essential Tasks and Activities	Sources of Learning
Systems Integration	Coordinate system design and integration (a) bears risk (e.g. T5 project), or (b) shares risk (e.g. CTRL project) Cost-plus incentive contracts Incentives for innovation Profits shared among partners in integrated project teams Collaborative partnership approach	Oil and gas offshore oil platforms project management GSK research complex, Stevenage, UK BAA's Heathrow Express project BAA's study of every major UK construction projects over £1bn undertaken in past 10 years and every international airport opened in past 15 years
Project and Program Management	First-tier suppliers selected on past performance Consistent process of gateways and milestones to control project Framework Agreements to select and work with suppliers in integrated project teams aimed at improving productivity Concurrent engineering to integrate design, fabrication and construction. Collaborative project management software tools offering up-to-date information about scheduling, sequencing and scope changes	Car manufacturing Retailing (e.g. projects to build new supermarkets) Construction Industry Task Force Lean Manufacturing Institute Lean Construction Institute
Single-Model Environment	Single Model Environment (SME) Digital prototyping and visualization for design and construction 3D and 4D modelling, clash-detection	Nuclear industry Rolls Royce air engine design facility (building Airbus A380 engine) Rover's design collaboration centre
Modular Pre-Assemblies	Offsite manufacture of components Offsite pre-assembly Physical prototyping and testing of components and subsystems prior to erection on site	Oil and gas offshore oil platforms production Constructors on T5 (LOR, Balfour Beatty)
Just-In-Time Logistics	Materials and components delivered when on site teams need them Use of offsite consolidation centres for storage and materials handling ProjectFlow software tool to assist in management of logistics and project work	Automobile manufacturing Lean Manufacturing Institute Lean Construction Institute Constructor on T5 (LOR)
Test, Commission, and Handover	Systems testing Training and familiarization of staff with new systems Trials in preparation for handover and opening	Learning from other airport projects, e.g. Denver and Hong Kong

Systems integration is a fundamental challenge of large infrastructure projects and the firms that require and produce them across industries—such as IBM, BP, Shell, Bechtel, BAE Systems, Ericsson, and Rolls Royce. Systems integrators outsource a large portion of design, production, and construction activities while maintaining in-house capabilities to integrate components and deliver a fully functioning system against time, cost, and quality targets.[25] They should possess the engineering capabilities required to ensure that components work with sub-systems across defined interfaces and that new systems are integrated into existing operations with minimum disruption to services. They subcontract with other firms to supply components that must be designed to conform with the overall system design.[26]

It is important to integrate not only physical products and service components, but processes as well. The integration challenge is accentuated in megaprojects by the scale of the systems; the range of technologies, components, and interfaces; and the number of external suppliers whose activities must be coordinated. New technologies should be taken off the project's critical path and tested in lower risk environments prior to their integration. In many cases, systems must be integrated smoothly into infrastructure that is already operational (such as London's St. Pancras railway station redevelopment project).

Clients face choices over what type of governance structure is appropriate. Megaprojects are usually managed through temporary institutional governance structures providing senior project directors autonomy and flexibility, while making effective use of resources and capabilities from their parent organizations. Decisions have to be made about how to manage project risks, the preferred contractual approach, and what tasks should be undertaken in-house or outsourced. Traditionally, in industries such as construction and defense, clients have employed external organizations (or prime contractors) as systems integrators.

A fixed-price contract may work well for routine capital projects where the risks are known and understood, but is deficient for complex and uncertain megaprojects with uncertain outcomes, where it creates unacceptable risks for clients and contractors. If the client organization assumes responsibility for systems integration, it must maintain the depth of in-house capabilities needed to lead the project, bear the risk, and work with teams to coordinate and control design and construction activities. Although this approach was used on T5, it was pioneered in the 1980s by large clients in offshore oil and gas projects such as BP, Shell, Mobil, Chevron, and Exxon.[27] However, there are limits to client-led systems integration. Unlike BAA, BP, and Shell, many clients are involved in megaprojects only on a one-off basis and have no incentive to develop strong in-house capabilities. In such cases, the client may have to consider ways of sharing the risk and the responsibilities with external partners or consultants in a joint-venture, strategic partnership or Special Purpose Vehicle —such as Rail Link Engineering, the consortium of Bechtel, Arup, Systra, and Halcrow established to run the $10.3B Channel Tunnel Rail Link project linking the UK to Europe's high-speed rail network.[28]

The middle level in the model identifies project processes that systems integrators must put in place to create an integrated chain of first-tier suppliers working with common procedures, technologies, and practices.

Project and program management processes are needed to manage the overall project and the interfaces between sub-projects through stages in its life cycle (see Table 1). These tools and techniques are focused on improving performance by reducing costs, minimizing waste, and improving safety in design and construction. A structured set of project management principles enshrined in framework agreements help the systems integrator select, manage, and work in integrated project teams with first-tier suppliers, such as architects, designers, consultants, and constructors. Long-term commitments provide the volume and security of future work needed for suppliers to invest in capability building and continuous improvement. By carefully selecting its suppliers, the client minimizes risks in other ways. Persistently poor performance will result in a supplier being replaced by another more capable firm.

Digital design and management technologies enable co-ordination of design, construction, and integration as well as virtual testing of components and systems.[29] A single-model environment (SME) using standard software replaces the numerous proprietary models developed in-house by first-tier suppliers. The SME is a real-time, computer-aided design system for digital prototyping and simulation to provide photorealistic representation of the project and "virtual walk through" of the final design. Each user with access to the digital model shares the same digital drawings and information. Interference and clashes between parts and components can be detected prior to integration. The SME can inform project management by identifying the latest date that a design decision can be made before progressing to fabrication and construction.

The goal is for digital vertical integration to be achieved through the SME, enabling architects, designers, and engineers working in separate organizations to collaborate together. This can help design and construction firms work concurrently and plan in advance how buildings and infrastructure will be assembled, providing a more accurate estimate of costs at the design stage. The usefulness of the SME extends beyond design and construction to the maintenance of the building or facility by creating a database showing the exact location of internal components (such as cabling, heating, and cooling systems).

Operational Processes

At the lowest level in the model, operational processes must be put in place to support the project during the high-volume construction and handover phases of a megaproject.

Advanced production methods must be used to reduce the costs and increase the flexibility, efficiency, and safety with which components and subsystems are installed on site.[30] Pre-assembled modular components (e.g., structural elements, cladding systems, and plant rooms) should be produced in offsite factories. Moving the pre-fabrication of major subsystems to less risky and safer production environments away from construction sites enables suppliers to assemble, test, and practice their installation before being taken to the site.[31] Construction of offshore oil and gas platforms in the North Sea during the 1970s and 1980s were instructive because of the ways in which modules had to be fabricated, assembled, and tested onshore before being floated out to offshore platforms.

Just-in-time (JIT) coordination of the supply chain is required to manage the flow of large numbers of workers and high-volumes of materials, parts, components, and subsystems procured to and from the site during construction.[32] Demand fulfillment software should be used to pre-book and prioritize the delivery of materials, components, and subsystems to the project.

Operational integration processes are required to undertake system tests, trials, training, commissioning, and handover of a fully functioning facility. Trials will indicate how people, processes, and systems interact together when the new infrastructure becomes operational. A detailed plan should provide clear guidance on the skills, training, and working practices that the customer and occupiers of the facility will need to master during the months prior to opening. Our research on T5 suggests that the real success of operational integration should be measured six to 12 months after the opening date.

How the Model Works

The model illustrates how a megaproject involves a system of production consisting of six processes that can be recombined and replicated to improve performance. The processes are linked together in a hierarchical relationship. Because the processes are closely related or dependent on each other, the performance of one process can influence the performance of others. These interconnected processes are centrally controlled and coordinated by the systems integrator—located at the top level—to enhance overall performance measured against the project objectives. The middle level encompasses standardized processes enabling the integrator to work in close cooperation with a small number of key partners to manage critically important design, engineering, and construction activities. The use of incentives in contractual arrangements enables the integrator and its partners to exercise direct control over volume-based operational activities performed by the large network of subcontractors located at the bottom level.

Although innovation is promoted within individual processes, significant improvements in overall performance can be achieved when all six processes are developed as complementary parts of an integrated production process. Unless all processes are carefully planned and executed, the poor performance of one can jeopardize the entire project.

Learning to Succeed in Megaprojects

Learning to improve megaproject performance is not easy, but it can be done. The following examples of two organizations involved in the T5 project describe how they sought to overcome management challenges by introducing recombinative and replicative innovations in their processes. They also learned to own and share risks, rather than shift them down the supply chain.

BAA's Recombination

BAA used the long planning phase of T5 to create a radical improvement in project delivery. Under Sir John Egan, BAA's CEO from 1991 to 1999, a core team of senior managers and consultants was assembled to explore alternative practices, technologies, and ideas found in other industries and megaprojects and bring them together to create a new project delivery process. BAA recognized that "doing it differently" must guide its delivery strategy.[33] It had no previous experience of undertaking a project of this size and complexity and had not integrated a new facility on this scale into its existing operations. It recognized the UK construction industry had a poor track record in megaprojects.[34] The team's knowledge of other projects contributed to BAA's decision to occupy the role of systems integrator on the project.

A separate T5 project organization was established, which operated independently of BAA's main corporate organization to provide the freedom of choice needed to promote experimentation and innovation. It formed a leadership team of about ten key individuals and around 300 staff with capabilities in design, integration, and project management, traditionally undertaken by the prime contractor.

Several members of BAA's original team—Simon Murray, Group Technical Director; Michael Forster, Design Director; and Andrew Wolstenholme, T5 Project Manager—previously worked for Arup, the consulting engineering design firm, on a megaproject (valued at c$1.5B) to build the pharmaceutical research facility for Glaxo (now GSK) at Stevenage in the UK. This "team of three" played a vital role in bringing the GSK experience of risk-bearing, co-located integrated project team working, and open-book cost-reimbursable contracts to BAA's $600m Heathrow Express Rail Link project.[35]

The Heathrow Express project ran into trouble on October 21, 1994, when one of the main tunnels collapsed. BAA decided not to resort to the standard industry practice of suing the contractor, Balfour Beatty, for breach of contract. Adopting key lessons from the GSK project, BAA made a decision to assume responsibility for risk on the project and work as a partner with suppliers in integrated project teams. Efforts to recover the tunnel and rescue the project were successful. The project achieved its new target date and opened for service in June 1998. BAA's approach to risk and use of integrated teams working on Heathrow Express "was proof of concept that the T5 agreement could work."[36] Senior managers involved in the project ensured that lessons from Heathrow Express were used in the preparations for T5, despite the prevailing view at the time that T5 was "special and one-off, so don't bother us with that process."[37]

BAA's T5 delivery strategy was informed by a systematic benchmarking study, undertaken between 2000 and 2002, of every major UK construction project over $2B undertaken in the past 10 years and every international airport opened over the previous 15 years. The research found that no UK construction project had been successfully delivered on time, within budget, to quality, and few projects had good safety records. The study of 12 major airport programs concluded that without a radically different approach, the T5 project would be $2B over budget, delivered one year late, and result in two deaths.

BAA's study identified two areas that contributed to the poor performance of megaprojects: lack of collaboration among project partners; and clients' reluctance to assume responsibility for project risks. BAA's research specifically identified poor systems delivery and integration during the final stage of project execution as a major reason why international airports failed to open on time. It concluded that transferring the risk to the contractor offered no real protection for the client. The only way to succeed on T5 was to change the "rules of the game" by establishing a new governance structure and commercial principles embodied in the T5 Agreement.

Although T5 was designed to be a unique showpiece, BAA recognized that the processes involved in its delivery could be standardized and simplified to improve performance. When Egan joined BAA from his previous position as CEO of Jaguar Motorcars, he found that BAA had no standardized process for project delivery. As one of BAA's senior managers explained, every project was treated as a "blank sheet of paper" and the newly assembled project team tended "to think it through from first principles over and over again."[38] Egan recognized that the assumption that every project is unique was the main obstacle to productivity improvements. He instructed BAA to adopt successful lean production techniques found in automobile, retailing, and other high-volume industries to achieve an orderly, predictable, and replicable approach to project design and delivery.[39]

BAA's Continuous Improvement Project Process (CIPP) was developed to provide a set of standardized and repeatable time-sequenced tasks, milestones, and stage-gates to deliver cost-effective and profitable projects through the application of best practices across BAA's capital projects valued between $4M-$20M. Egan wanted to adopt the component-led design used to build Tesco's standardized retail outlets so that BAA's buildings could be designed by "mixing and matching Lego-like components."[40] Standardized designs (e.g., for offices and car parks) and modular components were used across routine projects at lower cost than bespoke solutions, enabling BAA to exploit the learning curve advantages of "design it once, build it multiple times."

Although CIPP was primarily intended to improve the delivery of capital projects, the longer-term objective was to create standardized processes in preparation for T5.[41] Framework suppliers worked in integrated project teams using CIPP processes on BAA's projects well before the T5 project started, which helped to make them "match fit" for T5. It also helped BAA to understand the capability of its suppliers and their ability to work under the environment of co-operation, trust, and open-book accounting later used on T5.

The project processes for delivering T5 were codified in the "T5 Handbook" and designed to be reused on BAA's next major infrastructure project—the $2.3B Heathrow East project. Originally devised in 1996 as precursor to the

T5 Agreement, this visionary document outlined the "processes"—including the lines of reporting, responsibilities, and accountabilities—to be used on T5. The T5 Agreement was a legal document, based on the processes outlined in the Handbook, which promoted "collaborative behaviors" that would enable suppliers to work effectively in integrated project teams.[42] The successful implementation of the T5 processes depended on BAA's continuous efforts to break with the "old rules of commercial contracting" and traditional construction industry practices. Although many first-tier suppliers understood the benefits of collaborative relationships, some traditional contractors were unwilling or unable to change their behavior. A large change program was put in place to educate the supply chain and foster the collaborative behaviors that underpin T5 processes. Such efforts were critical to the successful execution of the project because "you can write the most fantastic process in the world, but if you don't tackle the behavior of individuals who are expected to deliver it, then you're probably not going to succeed."[43]

In preparing for T5, Norman Haste, T5's first Project Director, recognized that many projects failed because of insufficient investment in the design phase: this is "when you achieve your biggest wins. You're never going to achieve them during the construction phase."[44] He was responsible for developing BAA's SME, which enabled designs developed by various integrated project teams to fit within the overall T5 program objectives. Efforts were made to learn from other firms that had pioneered SME visualization technology.[45] BAA had to make continuous refinements to the SME to ensure that it was implemented and used effectively during the execution of the T5 project.

Operational processes successfully used on other megaprojects, in mass production industries, and on other airports were adapted to the requirements of T5. The access constraints and confined working areas meant that the T5 site was analogous to an offshore oil and gas platform. Recognizing that the failure to complete one component or section on time would delay the entire project, BAA used pre-assembly and pre-fabrication techniques to enable suppliers to manufacture, assemble and test components and practice their installation before being taken to the site. Once each trial was completed, the subsystem—such as a section of the T5 roof or the air traffic control tower—was disassembled and transported in the largest possible section to the Heathrow site for final assembly. Around 70% of mechanical and electrical engineering components were manufactured and assembled off-site.

JIT logistics were used to maintain an efficient schedule of large volumes of construction materials and components moving through the single entrance to the site. This logistics operation was supported by the establishment of two dedicated consolidation centers for storage and materials handling located close to the main site at Colnbrook and Heathrow South.

A joint BAA and BA team worked together over three years to ensure that systems, people, and processes were ready and working in preparation for the T5 opening date. Research conducted by BAA's Head of Systems into airport projects found that in airports such as Hong Kong and Denver it was the system integration challenges that delayed the opening date.[46] In the final phase of the five-year construction program, the "finish-build" team completed systems integration and retail fit out. The "start-operate commission" team then worked during six months of systems testing and operational trials prior to opening, including 72 proving trials each involving up to 2,500 people who tested how T5 would work in practice. BAA was fully aware that the opening could be disrupted by a "passive operator who will just stand back," rather than one who "gets in early, operates early, steals this off you, takes all the learning, does the final commission, and witnesses all the testing."[47] However, these careful preparations did not prevent problems from arising during the opening of the terminal. Several factors contributed to the chaotic opening, including rumors of sabotage by disgruntled former BA employees. But, the root cause of the problem was the decision to press ahead with the opening in the knowledge that BA's staff had insufficient training and familiarity with the terminal's facilities and baggage handling system.[48] The disastrous opening of T5 could have been avoided through "better preparation and more effective joint working" between BAA and BA.[49]

Despite these operational problems, the T5 project achieved its design and construction performance targets for cost, time, quality, and safety. During the construction phase, BAA had to overcome decades of established practices, entrenched behaviors, and the industry's traditional resistance to new ideas and practices originating from outside the world of construction. In the UK, the T5 project became a change program of industry-wide scale. However, it is unclear whether the valuable experience gained on T5 will be transferred to BAA's next megaproject. Ferrovial, the Spanish infrastructure company that took ownership of BAA in 2006, has put in place a new contractual arrangement to build the Heathrow East Terminal, involving Ferrovial's construction arm and a few "complex framework suppliers," such as LOR, Carillion, and Balfour Beatty.

LOR's Replication

LOR used lessons from the construction of T5 to create a replicable approach for delivering megaprojects. LOR was formed in November 2001, just prior to construction of T5, when O'Rourke acquired Laing, a large civil engineering contractor. The acquisition formed a large-scale firm that has grown from an original combined turnover of $1B in 2001 to around $8B in 2008. LOR participates in megaprojects around the world such as Dubai Airport, Al Raha Beach City, and the London 2012 Olympics.

Prior to the creation of LOR, Laing and O'Rourke as separate entities had gained experience working in the 1990s as first-tier framework suppliers in integrated project teams on BAA's capital projects program. During this time, both companies became familiar with processes later used on T5. Laing had its own in-house SME technologies and specialist visualization team. BAA's partnership approach was a "culture shock" and steep learning curve for O'Rourke—a traditional construction firm with little or no experience with collaborative team working.[50] Using the CIPP project management process, O'Rourke developed the capabilities to design standardized components for BAA's car parks. Productivity improved as O'Rourke reused its standardized product design on projects at BAA's airports in Glasgow, Edinburgh and Gatwick.

When T5 construction started in July 2002, LOR was responsible for a large proportion of the T5 building work, such as concrete structures, a six-platform rail system, and the management of all site logistics. By removing risk from the supply chain, the T5 Agreement created an environment that helped LOR understand the advantages of collaborative behavior and encouraged it to develop several process innovations used on T5. However, LOR's initial experience with co-located integrated project team working did not run smoothly. In a team led by LOR, Mott MacDonald had fallen behind in delivering design drawings for the production of pre-fabricated concrete reinforcement sub-assemblies. LOR faced the possibility of failing to achieve the project's objectives and asked BAA to intervene. However, BAA instructed LOR to find a way of solving the problem within the spirit of the T5 Agreement. LOR and Mott MacDonald had to overcome considerable resistance to integrated team working. By communicating and reinforcing the importance of collaborative behaviors, the two organizations worked together to create a solution using 3D modeling—rather than physical prototypes—to produce digital prototype designs for concrete sub-assemblies.[51]

In collaboration with BAA, LOR helped to develop the JIT logistics for T5. Mike Robins, Head of the LOR T5 project, assembled a core team to develop tools, processes, and logistics for T5. In previous projects, Laing purchased materials as cheaply as possible, shipped them to the workforce, and built infrastructure using traditional, craft-based, on-site construction techniques. LOR calculated that this approach would require a large workforce of over 5,000 workers and vehicles would have to travel through the site entrance every 10 seconds. This option was not possible because there was only one site entrance and the planning restrictions meant that deliveries were not permitted during rush hour.

LOR devised a logistics technique using a "consolidation" facility so that large volumes of materials and components could be taken from suppliers, placed in temporary storage, and then delivered on site as and when required. It proposed that the Colnbrook Centre be used as a bulk facility to deliver materials and components on a just-in-time basis. A software tool called ProjectFlow was adapted from high-volume manufacturing to meet the project's needs for JIT deliveries.[52] The tool was used in conjunction with the SME to visualize how designs would be implemented on site or built as pre-fabricated sub-assemblies, by reproducing the actual construction and erection sequences performed on the project.

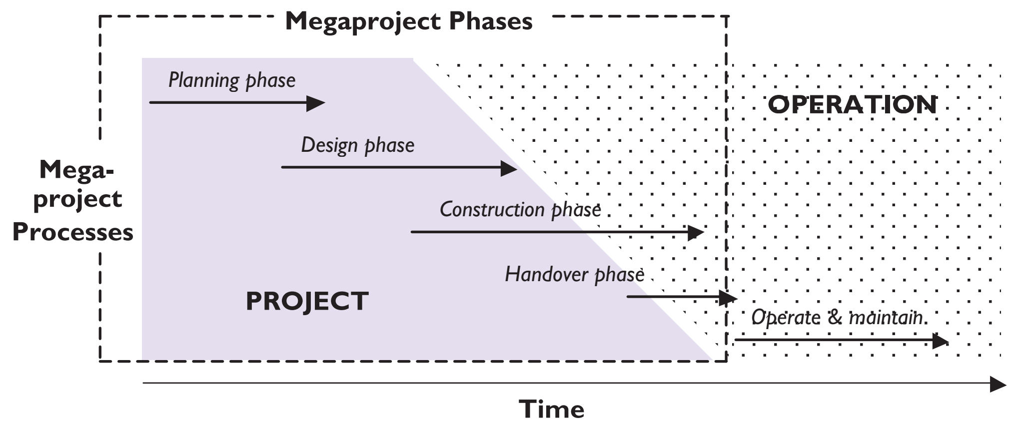
While T5 construction was underway, LOR saw an opportunity to transfer knowledge gained on T5 to another megaproject. Members of LOR's T5 project reused processes when they were assigned to work on a target-cost contract, the Channel Tunnel Rail Link terminal at St. Pancras station in London, which opened on November 14, 2007. Although not based on the same risk-bearing agreement as T5, the St. Pancras project suggested that elements of the T5 approach could be re-used on target-cost "pain/gain share" contracts, where the client and contractors share the risks and rewards of effective project delivery. Digital prototyping, ProjectFlow, off-site fabrication, and integrated project team working were re-used by LOR's project managers on the St. Pancras project.

Such informal initiatives to transfer lessons from T5 were superseded by LOR's strategic decision to pursue systematic use of the knowledge gained on T5 by developing a common approach including: integrated project team working, project management processes (similar to BAA's CIPP), component-led design based on modular components, standardized products, and digital modeling technologies. Two former T5 Project Directors and other BAA staff were recruited to facilitate the transfer of design, construction, and management expertise. LOR established an approach called "Radical at Design and Delivery" (R@DD) to capture and transfer lessons from T5. In 2005, a knowledge-sharing portal was created to support the use of this knowledge. ProjectFlow was used on all subsequent LOR projects in the company's civil engineering and infrastructure businesses. A Collaboration Centre was established at LOR's HQ in Dartford in 2006 to provide digital models of infrastructure schemes, designs, construction details, and methods. LOR also attempted to forge new collaborative relationships with first-tier suppliers and consultants, with the aim of avoiding adversarial practices, in a program called "Building Constructive Relations."

The main challenge facing LOR has been to develop the capabilities required to become a systems integrator on future megaprojects, the role performed by BAA on T5. This is a difficult transition for a construction firm that has to convince its clients to make "a leap of faith to engage, not with a designer, not with an architect, but somebody who can manage the whole process. And perhaps we should change that name to integrator."[53] In order to manage the whole systems integration process, LOR's initial moves beyond its traditional base in construction focused on developing capabilities in front-end project planning, feasibility studies, and design. More recently, it has attempted to develop capabilities to operate and maintain facilities.[54]

LOR recognized that its role as systems integrator on megaprojects depends on the requirements and capabilities of its clients. On T5, the client was the project manager and systems integrator. However, unless clients develop strong sophisticated in-house capabilities—comparable to BAA—it is possible that full replication of the T5 approach will fail. On other projects, LOR performs systems integration on behalf of the client. For example, the new Grandstand at Ascot Racecourse built by LOR suggests that the T5 approach can be used by a client with limited in-house project management capabilities, undertaking a major one-off infrastructure project.[55] This was achieved by establishing a temporary management team to represent the client, consisting of former BAA project managers and external consultants with T5 experience. This core team helped the client and LOR manage the Ascot Racecourse project using the core T5 principles of client bearing the risk and integrated project teams. The project was successfully completed in 2006 on time and within budget.

FIGURE 5. Transition from Project to Operations



Paths of Innovation in Megaprojects

The systems integration model explains how BAA and LOR innovated to improve megaproject performance. Processes must be carefully prepared, defined and codified, but improvements in performance will not be obtained without considerable efforts to promote collaborative behavior required to deliver the full potential of these innovations.

The BAA case shows how large client organizations can build in-house capabilities to increase the likelihood of success by systematically learning from and recombining successful processes practiced in other contexts. The focus of BAA's innovative efforts started at the highest level and worked progressively to the middle and lower levels in the model. During the planning phase of T5, BAA concentrated on defining its partnership approach and strategic integrator role. During the design phase, BAA introduced advanced digital technologies and continued to improve its project management capability. Many changes to the lower-level operational processes were devised in collaboration with key partners such as LOR during construction.

The troubled opening of T5 emphasizes the importance of ensuring that individual processes identified in our model are carefully planned and executed as a system.[56] This includes the difficult transition from project to operational processes—Figure 5. Ferrovial has an opportunity to capitalize on the T5 experience, but it is not clear whether the new owners will reuse the T5 project delivery model on future projects to redevelop the rest of Heathrow Airport.

The LOR case reveals that an organization can use the knowledge gained during the implementation of a breakthrough project to create a replicable approach to megaproject delivery. LOR started out at the lowest level in the model and used the learning gained over time to progress to the middle, aspiring to the highest level. During the T5 project, LOR created and applied a number of innovations in individual operational (e.g., JIT logistics) and project processes (e.g., integrated project teams, project collaboration software, and digital technologies). Lessons that LOR subsequently took from T5 enabled it to attempt innovation at the top level by exploring alternative ways of performing systems integration.

LOR has attempted to use the cumulative knowledge of processes in our model to devise a common approach for delivering megaprojects, which can be tailored to the needs and capabilities of different clients. In megaprojects such as T5, LOR worked in a partnership with a sophisticated and capable client that took a coordinating role in the project, performing systems integration and bearing the risks. In other projects where the client has limited in-house capabilities, LOR has assumed responsibility for systems integration, working with first-tier suppliers in different forms of partnership, risk sharing, and contractual arrangements.

Conclusion

To achieve success in megaproject management, organizations must be willing to abandon the widely held view that projects are entirely unique endeavors. Improvements in megaproject productivity, safety, and quality can be obtained by selecting successful processes used in other contexts and recombining them in a system to improve efficiency and effectiveness in project design and execution. Alternatively, an organization can adopt, refine, and extend an existing combination of processes implemented on a breakthrough project to develop a common approach that can be replicated across other megaprojects. In either case, strong leadership with a coherent vision as well as the use of performance indicators and organizational change programs are essential to support the new behaviors required for successful outcomes.

In spite of the disruptions that occurred when T5 opened, this study has enabled us to develop a conceptual model to help organizations strive to overcome the poor performance found in many megaprojects. One or more of the processes had been used individually or perfected on other projects prior to their recombination on T5. What is distinctive about T5 is that it illustrates how all six processes have been brought together as a system, providing a conducive environment needed to focus on innovation and performance benefits, rather than passing-off risk. However, there is no simple recipe for success. Organizations will have to overcome considerable resistance to new ways of working, from relationships and behaviors that they may encounter in the traditional worlds of construction and project management.

Notes

1. Bent Flyvbjerg, Nils Bruzeius and Werner Rothengatter, *Megaprojects and Risk: An Anatomy of Ambition* (Cambridge: Cambridge University Press, 2003).
2. Flyvbjerg et al., op. cit.; Roger Miller and Donald R. Lessard, *The Strategic Management of Large Engineering Projects: Shaping Institutions, Risks, and Governance* (Cambridge, MA: MIT Press, 2000).

3. We thank Michael Schrage for suggesting that we think of megaprojects as having their own economy, with governance structures and transaction costs. Our work builds on Pascale Michaud's pioneering research on the governance of major projects throughout the world.
4. On embedded units within a single case, see Robert K. Yin, *Case Study Research: Design and Methods* (London: Sage, 2003).
5. Inductive research is useful to generate conceptual insights when there is limited theoretical knowledge about a particular phenomenon. Nicolaj Siggelkow, "Persuasion with Case Studies," *Academy of Management Journal,* 50/1 (February 2007): 20-24.
6. Andrew Van de Ven, *Engaged Scholarship: A Guide to Organizational and Social Research* (Oxford: Oxford University Press, 2007).
7. We used "theoretical sampling" to select a revelatory case that provided an unusual opportunity to examine the dynamics of learning and innovation in a megaproject. See Kathleen M. Eisenhardt and Melissa E. Graebner, "Theory Building from Cases: Opportunities and Challenges," *Academy of Management Journal,* 50/1 (February 2007): 25-32.
8. Arthur L. Stinchcombe and Carol A. Heimer, *Organization Theory and Project Management: Administering Uncertainty in Norwegian Offshore Oil* (Oslo: Norwegian University Press, 1985); Rodney Turner, *The Handbook of Project-Based Management: Improving the Processes for Achieving Strategic Objectives* (London: McGraw-Hill, 1999); Jeffrey K. Pinto, *Project Management: Achieving Competitive Advantage* (Upper Saddle River, NJ: Pearson/Prentice Hall, 2007).
9. Standardized processes include the Project Management Body of Knowledge Guide developed by the Project Management Institute. See also Andrew Davies and Michael Hobday, *The Business of Projects: Managing Innovation in Complex Products and Systems* (Cambridge: Cambridge University Press, 2005); Aaron J. Shenhar and Dov Dvir, *Reinventing Project Management: The Diamond Approach to Successful Growth and Innovation* (Boston, MA: Harvard Business School Press, 2007).
10. A growing body of literature on projects recognizes the role of learning in securing improvements in performance. See Anne Keegan and Rodney J. Turner, "Quantity versus Quality in Project-Based Learning Practices," *Management Learning*, 32/1 (March 2001): 77-98; Jörg Sydow, Lars Lindkvist, and Robert DeFillippi, "Project-Based Organizations, Embeddedness, and Repositories of Knowledge: Editorial," *Organization Studies,* 25/9 (Special Issue 2005): 1475-1489.
11. Classifications of industrial organizations into systems of production show how improvements in performance are driven by the "standardization, specification, and simplification" of production processes and tasks. See Joan Woodward, *Industrial Organization: Theory and Practice* (Oxford: Oxford University Press, 1965, 1994). The product and process innovation matrix was developed by Robert H. Hayes and Steven C. Wheelwright, *Restoring our Competitive Edge: Competing through Manufacturing* (New York, NY: Wiley and Sons, 1984). Major product innovation usually involves corresponding changes in processes, and vice versa. See Steven C. Wheelwright and Kim B. Clark, "Creating Project Plans to Focus Product Development," *Harvard Business Review*, 70/2 (March/April 1992): 67-83.
12. As Peter Drucker recognized, the key management challenge facing firms as they progress to high-volume stages is to "learn how to do new things rather than learn how to do the old things better." See Peter Drucker, *The Practice of Management* (New York, NY: Harper and Row, 1954). The drive to innovate in this way lies behind the evolution of the product life cycle, from an early fluid phase of product innovation to high-volume mature phases. See James M. Utterback, *Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change* (Boston, MA: Harvard Business School Press, 1994).
13. A unique task usually involves experimentation with uncertain results, whereas repetitive tasks enable predictability and the formation of institutional routines. When an organization performs a unique task, members of the project have little prior knowledge about how to proceed. When an organization performs a repetitive task, members of the team use existing routines, processes and institutionalized procedures to guide their actions. Project tasks are often codified in a firm's in-house project management manual. See Rolf A. Lundin and Anders Söderholm, "A Theory of the Temporary Organization," *Scandinavian Journal of Management,* 11/4 (1995): 437-455.
14. Woodward, op. cit. See also Jayashankar M. Swaminathan, "Enabling Customization Using Standardized Operations," *California Management Review,* 43/3 (Spring 2001): 125-135.
15. See Peter W.G. Morris, *The Management of Projects* (London: Thomas Telford, 1994).
16. See Andrew Hargadon, "Firms as Knowledge Brokers: Lessons in Pursuing Continuous Innovation," *California Management Review*, 40/3 (Spring 1998): 209-227; Andrew Hargadon,

How Breakthroughs Happen: The Surprising Truth about How Companies Innovate (Boston, MA: Harvard Business School Press, 2003).
17. Replication is usually associated with fully standardized processes, such as the "McDonald's approach." See Sydney G. Winter and Gabriel Szulanski, "Replication as Strategy," *Organization Science,* 12/6 (November/December 2001): 730-743. We suggest that innovation in megaprojects involves two stages: an exploratory recombination phase when the new approach to project delivery is combined and refined during a project; and an exploitative replication phase when the project delivery approach is stabilized and reused on other projects. This entails a transition from exploratory to exploitative learning. See James G. March, "Exploration and Exploitation in Organizational Learning," *Organization Science,* 2/1 (February 1991): 71-87.
18. The learning curve advantages are cumulative, resulting in "increasing returns to experience": each increase in a firm's capability to perform an activity increases the potential returns from engaging in that activity. See Paul S. Adler and Kim B. Clark, "Behind the Learning Curve: A Sketch of the Learning Process," *Management Science,* 37/3 (March 1991): 267-281.
19. Shenhar and Dvir [op. cit.] identify four bases or dimensions of project management: technological uncertainty, system complexity, pace, and novelty.
20. Sharon Doherty, *Heathrow's Terminal 5: History in the Making* (Chichester: John Wiley & Sons, 2008).
21. In a fixed-price contract (e.g., Design and Build, or Construction Management), the client transfers responsibility for the risk of delivering—measured against time, cost, and quality objectives—to the contractor. In PFI contracts, responsibility for project performance is shifted to the contractor and the client pays for the foreseen risk at the start of the project, and pays again for subsequent scope changes. See National Audit Office, *Case Studies: Improving Public Services through Better Construction* (London: NAO, 2005).
22. The client gets an inadequate solution if the contractor tries to keep within time and budget. The contractor is encouraged to seek additional profits if the scope changes but can lose money if the project experiences unforeseen difficulties.
23. National Audit Office, op. cit.
24. Suppliers are repaid all costs on an open-book basis and incentivized to improve their performance and innovate by bonuses for exceeding target costs and completion dates. The client uses cost information from previous projects to set target costs. If the integrated project team achieves lower than the target costs, the savings are shared by the team members.
25. In a growing number of project-based industries the trend towards vertical disintegration and outsourcing has been associated with the emergence of systems integrators. See Stefano Brusoni, Andrea Prencipe, and Keith Pavitt, "Knowledge Specialization and the Boundaries of the Firm: Why Do Firms Know More than They Make?" *Administrative Science Quarterly*, 46/4 (December 2001): 597-621; Andrea Prencipe, Andrew Davies, and Michael Hobday, *The Business of Systems Integration* (Oxford: Oxford University Press, 2005); Michael Hobday, Andrew Davies, and Andrea Prencipe, "Systems Integration: A Core Capability of the Modern Corporation," *Industrial and Corporate Change*, 14/6 (December 2005): 1109-1143.
26. Systems integrator organizations were first used by the U.S. military to help clients procure weapons systems from prime contractors, Harvey M. Sapolsky, *The Polaris System Development: Bureaucratic and Programmatic Success in Government* (Cambridge, MA: Harvard University Press, 1972).
27. Lesley P. Cook, "The Offshore Supplies Industry: Fast, Continuous, and Incremental Change," Margaret Sharp, ed., *Europe and the New Technologies: Six Case Studies in Innovation and Adjustment* (London: Pinter Publishers, 1985); James Barlow, "Innovation and Learning in Complex Offshore Construction Projects," *Research Policy,* 29/7-8 (August 2000): 973-989.
28. The client that won the original bid for the CTRL project was a SPV called LCR (London and Continental Railways Limited) incorporated by eight founder members. Four members formed Rail Link Engineering (Arup, Bechtel, Halcrow, and Systra). Under a cost-plus incentive form of contract, RLE was appointed by the client to work cooperatively to achieve the project objectives and "share" the benefits of doing so.
29. See Mark Dodgson, David Gann, and Ammon Salter, *Think, Play, Do: Innovation, Technology, and Organization* (Oxford: Oxford University Press, 2005); "From Blueprint to Database," *The Economist,* Technology Quarterly, June 7, 2008; Mark Dodgson, David M. Gann, and Ammon Salter, "In Case of Fire Please Use the Elevator: Simulation Technology and Organization in Fire Engineering," *Organization Science*, 18/5 (September/October 2007): 849-865.

30. David M. Gann, *Building Innovation: Complex Constructs in a Changing World* (London: Thomas Telford, 2000); R.B. White, *Prefabrication: A History of its Development in Great Britain* (London: Her Majesty's Stationary Office, 1965).
31. These techniques emerged through many decades of attempts to standardize and prefabricate components, dating back to the construction of London's Crystal Palace in 1851. See Gann, op. cit.
32. The JIT system was originally developed and perfected by Japanese automobile producers in the 1970s and 1980s to deliver components supplied by a large network of external suppliers to the assembly line, often on an hourly basis. See James P. Womack, Daniel T. Jones, and Daniel Roos, *The Machine that Changed the World* (New York, NY: Macmillan Publishing Company, 1990).
33. Andrew Wolstenholme, Ian Fugeman, and Fiona Hammond, "Heathrow Terminal 5: Delivery Strategy," *Proceedings of the Institution of Civil Engineers—Civil Engineering*, 161/5 (2008): 10-15.
34. By the late 1990s, pressure to reform the industry from government, large clients, and contractors resulted in several influential reports, such as the Egan Report written by Sir John Egan, BAA's CEO, which identified the radical changes needed to improve the execution of construction projects. See Sir John Egan, *Rethinking Construction: The Report of the Construction Industry Task Force*, Department of Transport, Environment and Regions, 1998.
35. By 1990, the GSK project was going heavily over budget. To help bring the project back on track, senior project managers were recruited from Exxon in the U.S. with experience of delivering major oil and gas projects. They called the project to a halt and started again using a radically different approach based on co-located integrated project teams, risk-bearing, and open-book cost-reimbursable contracts, adopted from the oil and gas sector. They knew from experience that the high cost of delays associated with the construction of offshore oil and gas platforms meant that contractors were unable to provide guarantees against lateness, cost overruns, or unreliability. This is why oil company clients—such as BP, Shell, Exxon, and Chevron—had to assume responsibility for the risk of failure and to become deeply involved in design and construction phases on their megaprojects.
36. Interview with Ian Fugeman, BAA T5 Head Rails and Tunnels Projects, 2006.
37. Interview with Andrew Wolstenholme, BAA T5 Project Manager, 2006.
38. Interview with Tony Douglas, BAA T5 Project Director, 2005.
39. The lean production techniques that informed BAA's approach to project management are documented in Womack et al., op. cit.; James P. Womack and Daniel T. Jones, *Lean Thinking* (New York, NY: Simon & Schuster 1996).
40. Interview with Norman Haste, LOR's Chief Operating Officer for the Middle East and Asia (formerly BAA's T5 Project Director), 2006.
41. Interview with Simon Murray, former BAA T5 Project Director, 2005.
42. The T5 agreement was a legally-binding document drafted in a non-adversarial style to expose and manage risk rather than "transfer or bury them," promote and reward success, and create the organizational behavior required to work co-operatively in integrated project teams. The contract also addresses cultural principles—partnering, trust, and co-operation. See Wolstenholme et al., op. cit.
43. Interview with Rob Stewart, BAA T5 Head Infrastructure Projects, 2006.
44. Interview with Norman Haste, op. cit.
45. Haste drew upon his experience as the former Project Director of Sizewell B Nuclear Power Plant, which used advanced digital modeling technologies to comply with stringent safety and quality assurance standards. He visited and studied the use of digital modeling technologies at the Rolls-Royce air engine design facility in Derby—developing the Trent engine for the Airbus A380—and Rover car's design collaboration studio. Both companies used 3D technology to carry out real-time integrated design of the product and its components.
46. This was followed by a separate study undertaken by Nick Gaines, BAA's Head of T5 Systems Integration. His research identified the integration of unproven high-technology components—particularly IT systems—during the final stages of systems delivery as a major cause of project failure. As we discussed under the description of the project setting, BAA sought to avoid this problem by using only mature technology during the systems integration stage. Interview with Nick Gaines, BAA T5 Head Systems Projects, 2006.
47. Interview with Andrew Wolstenholme, op. cit.

48. Kevin Done, "BA Took 'Calculated Risk' on Terminal 5," *Financial Times,* May 8, 2008; John Williams and Kevin Done, "BA Optimistic after That Was the Week That Was," *Financial Times,* April 5, 2008.
49. House of Commons Transport Committee, "The Opening of Heathrow Terminal 5," Twelfth Report of Session 2007-8, November 3, 2008.
50. Interview with Nigel Harper, LOR Director of Performance Improvement, 2005.
51. Interview with Mike Robins, LOR Group Business Director, 2006.
52. Rather than have site deliveries controlled by a remote planning organization, project teams on site used ProjectFlow to schedule deliveries of materials and provide project teams with key information about the timetable, risk reports, and work scope, avoiding stop-start cycles and minimizing storage and waste on site.
53. Interview with Norman Haste, op. cit.
54. For an analysis of integrated solutions see Andrew Davies, Tim Brady, and Michael Hobday, "Charting a Path toward Integrated Solutions," *MIT Sloan Management Review*, 47/3 (Spring 2006): 39-48.
55. Interview with Simon Murray, op. cit.
56. After the opening date was announced in 2003, BAA had staked its reputation on T5's successful completion. However, experience suggests that one would always expect some teething problems when an airport or any other megaproject first opens. This demonstrates the importance of managing expectations so that customers, users, government bodies, the media, and other stakeholders are fully aware of the complexities involved in the transition from project to operations.