ACQUISITION INNOVATION RESEARCH CENTER

The Future of Megaproject Management *Executive Summary, Findings, and Recommendations*

EXECUTIVE SUMMARY

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ACRONYMS AND ABBREVIATIONS

AI	Artificial Intelligence
AIRC	Acquisition Innovation Research Center
CJADC2	Combined Joint All-Domain Command and Control
DAU	Defense Acquisition University
DE	Digital Engineering
DoD	Department of Defense
FCS	Future Combat System
FLRAA	Future Long-Range Assault Aircraft
LLM	Large Language Model
MDAP	Major Defense Acquisition Program
ML	Machine Learning
MOSA	Modular Open Systems Approach
OUSD(A&S)	Office of the Under Secretary of Defense for Acquisition and Sustainment
OUSD(R&E)	Office of the Under Secretary of Defense for Research and Engineering
PERT	Program Evaluation and Review Technique
PM	Project Management
PMI	Project Management Institute
SERC	Systems Engineering Research Center
TRL	Technology Readiness Level

INTRODUCTION

Defense acquisition key leaders and practitioners (e.g., project managers, systems engineers, financial officers, contracting officers, and logisticians) are expected to manage large-scale megaprojects (measured by size, complexity, quantity, and scale) to acquire defense infrastructures or warfighting capabilities. According to the Oxford Handbook of Megaproject Management (Flyvbjerg & Gardner, 2014), megaprojects are "large-scale, complex ventures that typically cost $1 billion or more, take many years to develop and build, involve multiple public and private stakeholders, are transformational, and impact millions of people" (Flyvbjerg, 2017). Megaprojects are also often mega-systems that operate with dimensions of operational uncertainty, behavioral complexity, pluralistic decision-making, and volatility of the external environment (Stevens, 2010). Furthermore, megaprojects often combine uncertainty with the difficulties of long-time horizons and nonstandard technologies (Lenfle & Loch, 2017). The Department of Defense (DoD) has long-been a sponsor of megaprojects and continues to transition from more standalone platform centric systems to mega-systems. Megaproject failures and successes from commercial programs offer lessons learned for improving the performance of Major Defense Acquisition Programs (MDAPs), which are often megaprojects and also may be useful for smaller, less complex acquisitions.

DERIVED COMMON ANALYTICAL CHARACTERISTICS OF MEGAPROJECTS

Megaprojects share some common characteristics beyond cost (Flyvbjerg, 2017):

- Large scale, with complex interfaces
- High behavioral and structural complexity, which drives uncertainty and management of uncertainty
- Often use non-standard technology & design
- Often result in transformational outcomes for users and communities
- Have long planning horizons and project scope changes significantly over time
- Project decisions are pluralistic, with multi-stakeholder influence and decision-making
- Exist in and are affected by complex external environments and often experience over-commitment and optimism bias in their planning
- Lack of causality in planning and execution due to complexity, and success/failure is difficult to predict
- Require specialized enterprise leadership skills

Most megaprojects have "fat tails" – numerous projects exceed average overruns. There is no normal distribution for megaprojects, so buffers based on domain driven averages are ineffective. Project management (PM) literature systemically ignores the study of fat tails in PM risk, even though their complexity requires different planning and management models than smaller more certain projects.

Megaprojects, as with many large, complex systems, traditionally have a lower-than-desired success rate. Research by Bent Flyvbjerg, a leading scholar in megaproject management from the University of Oxford (UK), suggests that around 8.5% of megaprojects are completed on time and within budget while delivering the intended benefits. This means that approximately 90% of megaprojects fail in *at least* one key aspect: cost, schedule, or intended outcomes (Flyvberg & Gardner, 2014). As megaprojects cost billions of dollars and often involve the labor and cooperation of tens of thousands of people, improving the success rate of these projects is critical.

Flyvberg has collected extensive data on megaproject performance. Figure 1 shows cost overruns for twenty-five project types covering sixteen thousand–plus projects in the Oxford database (Flyvberg & Gardner, 2014). Overrun is measured as (a) mean cost overrun, (b) percentage of projects in the upper tail (defined as ≥ 50 percent), and (c) mean overrun in the tail. Overrun is measured in real terms. Most defense megaprojects fall into 5 categories (circled), and each of these are in areas that tend to have large mean cost overruns, and a fat-tailed cost overrun distribution.

PROJECT TYPE	(A) MEAN COST OVERRUN (%)*	(B) % OF PROJECTS IN TAIL (≥ 50% OVERRUN)	(C) MEAN OVERRUN OF PROJECTS IN TAIL (%)
Nuclear storage	238	48	427
Olympic Games	157	76	200
Nuclear power	120	55	204
Hydroelectric dams	75	37	186
IT	73	18	447
Nonhydroelectric dams	71	33	202
Buildings	62	39	206
Aerospace	60	42	119
Defense	53	21	253
Bus rapid transit	40	43	69
Rail	39	28	116
Airports	39	43	88
Tunnels	37	28	103
Oil and gas	34	19	121
Ports	32	17	183
Hospitals, health	29	13	167
Mining	27	17	129
Bridges	26	21	107
Water	20	13	124
Fossil thermal power	16	14	109

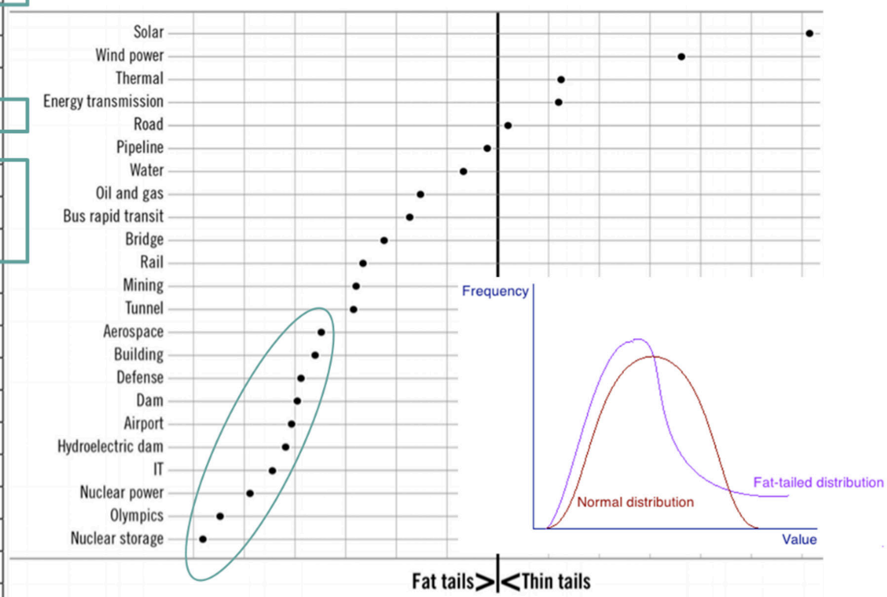

Figure 1. Megaprojects have large mean cost overruns and fat-tailed distributions.

The image on the rights shows "all the project types arranged by how "fat-tailed" they are in terms of cost—meaning how much they are in danger of the extreme cost overruns that destroy projects and careers, blow up corporations, and humiliate governments" (Flyvberg & Gardner, 2014). The most common causes of these fat-tailed behaviors are (Lenfle & Loch, 2010):

1. Underestimation of, or refusal to acknowledge uncertainty: Megaprojects are often started with an assumption that the design and project plan can be fully defined at the beginning, which is typical in project management literature. However, it is impossible to plan for all uncertainties in projects with this complexity. This leads to control conflicts on decisions around uncertainty, often compounding the risks.

2. Stakeholder neglect or mismanagement: Megaprojects/systems are coalitions of active partners and other non-active stakeholders. Stakeholder conflicts are a major source of project problems and are often unpredictable. Ignoring stakeholders or creating forced agreements are common conflict areas.

3. Inflexible contractor management: Many organizations have to cooperate; transparency, honesty and incentives are needed. But many megaprojects fail because they are bid incorrectly or dishonestly, or just "priced to win," leading to blame-placing and lawsuits. Flexible contracting strategies must be employed that emphasize uncertainty and problem-solving, and win-win leadership strategies must be developed in managing supplier interaction.

Furthermore, interactions across these causes enhance project failure models. Traditional project management and risk management practices that assume only "known-knowns" and "unknown-knowns" are ineffective in megaprojects. Megaproject leadership and management methods must shift toward managing uncertainties.

FROM MANAGING RISKS TO MANAGING UNCERTAINTIES

While project management encourages careful up-front planning of known-knowns and known-unknowns (risks), megaproject success is strongly linked to successful management of project unknown-unknowns or uncertainties. Management of project uncertainties fundamentally differs from the management of project risk. Often, projects are based on assumptions that have uncertainty, leading them to overly optimistic planning (Flyvbjerg & Gardner, 2023). While classical project management has a well-established tradition of risk management, the concept of uncertainty, particularly in large, complex projects, has not been adequately addressed in the literature or in practice. Frequently, project uncertainties and their underlying assumptions are not distinguished from project risks, despite the need for inherently different leadership and management approaches.

In this research, we developed a "Project Uncertainty Framework" from extensive literature review on both successful and non-successful megaprojects. This framework was evaluated based on historical case studies and also on the Army Future Long-Range Assault Aircraft (FLRAA) which is an existing megaproject just entering Milestone B approval - a phase of significant investment ramp-up. We used this analysis to create an initial "Megaproject Management Playbook", a set of best practices for management of uncertainty in megaprojects.

FROM PLANNING PROJECT LIFECYCLES TO PLANNING LIFECYCLE SHIFTS

Megaprojects and mega-systems tend to experience much larger shifts in their planning lifecycles than smaller projects. Flyvbjerg and Gardner use the phrase "Think Slow, Execute Fast" to describe the needed planning process in megaprojects. Doing planning as a bureaucratic process of scheduling and resource loading is necessary, but real planning involves learning through experimentation and experience. The "Think Slow" phase should plan experiments and iteration conducted when program spend rates are low, with sufficient time to mature the system concepts and identify and adjust to uncertainties. The "Execute Fast" phase recognizes that time kills megaprojects, not size. When commitments to scale up the program are made, all efforts (and funds) should be used to execute fast to reduce exposure to external disrupting factors. From complexity theory, megaprojects are subject to the concept of "equifinality": in a complex system there are multiple routes to a specific set of outcomes; more complexity needs more planning cases.

Megaprojects, because of their size and potentially transformative outcomes, are highly impacted by optimism bias and underestimation of true cost and schedule at the start. Hirshman argues that some ignorance at the start is useful because it can invoke creative approaches to success and many megaprojects have emergent benefits that cannot be known up front – what he called "The Hiding Hand" (Hirshman, 1967). If the true cost was known these projects would never have started. Flyvbjerg's data shows that in many megaprojects the expected benefits are also unrealized, and he emphasizes that this often results in "survival of the unfittest." The projects that look best on paper get funded and other less attractive but more useful projects fall to the side (Flyvbjerg, 2014). The think slow phase should rationally address the full lifecycle – not just full lifecycle costs but full lifecycle benefits.

Figure 2 overlays this model on the traditional DoD 5000 Major Capability Acquisition Process (DoDI, 2022).

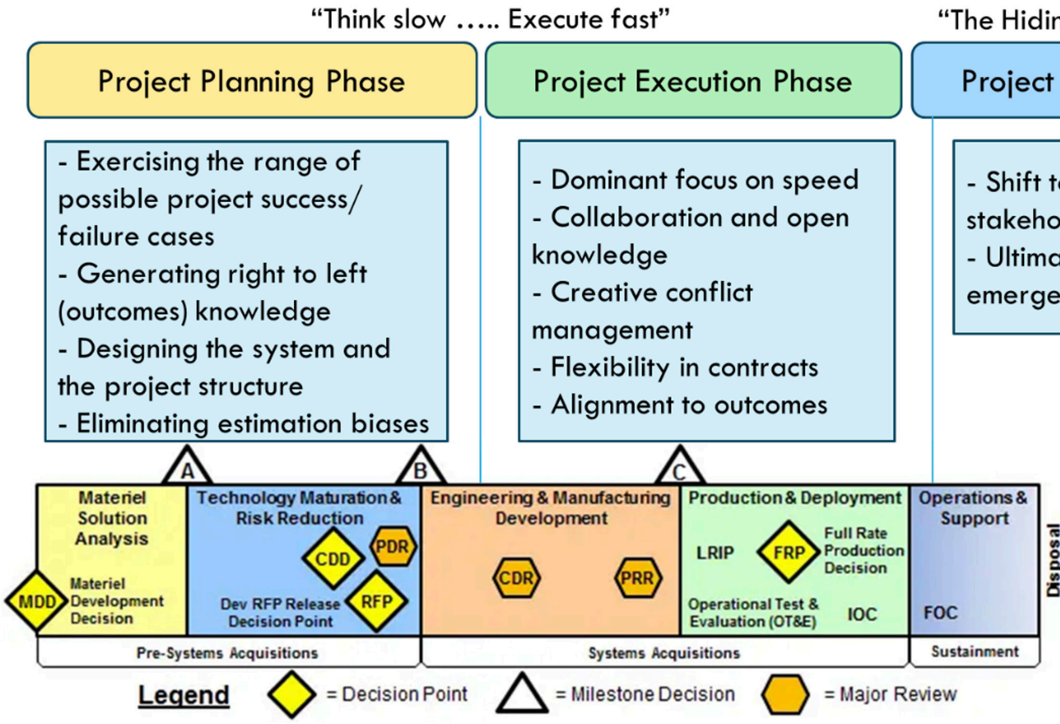

Figure 2. "Think Slow...Execute Fast".

The Milestone B decision point is the clear transition from "think slow" to "execute fast," and the decision criteria at this transition point reflects the type of data needed to successfully manage megaprojects. The question becomes: why do we see these uncertain outcomes in defense projects? And what data/indictors should have told us we would experience such large overruns? Our research indicates that the ability to continuously manage megaproject uncertainties – at the detailed level – is the prominent driver. Unfortunately, the data/indicators of uncertainty are likely to be qualitative and difficult to use as predictions of future project performance. However, there are two things a project can do to manage these uncertainties: 1) classify and track uncertainties as a program risk category, and 2) deploy advancing artificial intelligence (AI), large language model (LLM), and data visualization techniques to provide continuous situational awareness of new and progressing uncertainties. The research investigated a number of methods and tools to analyze uncertainties, which are fully documented in the report.

HOW TRANSFORMATIONAL ARE PROJECT OUTCOMES?

How transformative is the megaproject/mega-system in the operational context where it will be deployed? Figure 3 presents two evaluation rubrics – the left view is from (Stevens, 2011) and the right view is derived from (Schindler, Fadaee, & Brockington, 2021). More material project case studies like the London Olympics, the Heathrow Terminal 5 project, and the F-35 fighter aircraft differ from more transformative (or "imagined") projects like the U.S. Army Future Combat Systems (FCS), NASA's Mission to Mars, and the Defense Department's Combined Joint All-Domain Command and Control (CJADC2) projects based on how transformative they are to the operational environment and their scale of impact. These more transformational megaprojects have additional complexities that must be accounted for in planning and execution. Thus, there are two aspects of scale that drive the full lifecycle of megaprojects: how complex the project is with respect to its immediate set of stakeholders, and how transformative it might be to the broader community of stakeholders. There are many examples of both of these aspects in DoD megaprojects, and the differences should drive how we manage these megaprojects.

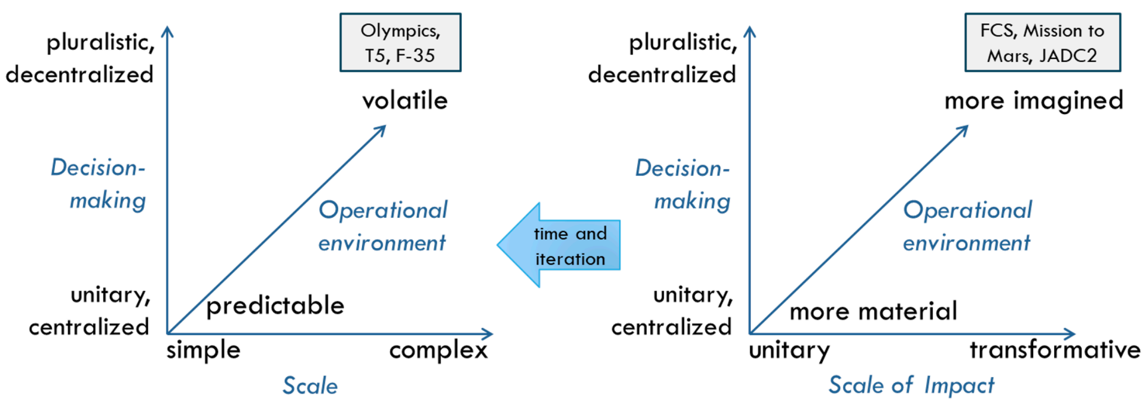

Figure 3. Two views of Mega-systems from literature.

THE MEGAPROJECT UNCERTAINTY FRAMEWORK

The research developed a megaproject uncertainty framework which is shown in Figures 4 and 5, and was adapted from a similar mega-systems classification framework in (Stevens, 2011). From (Stevens, 2011) we capture four megaproject uncertainty contexts: Strategic, Systems, Implementation, and Stakeholder.

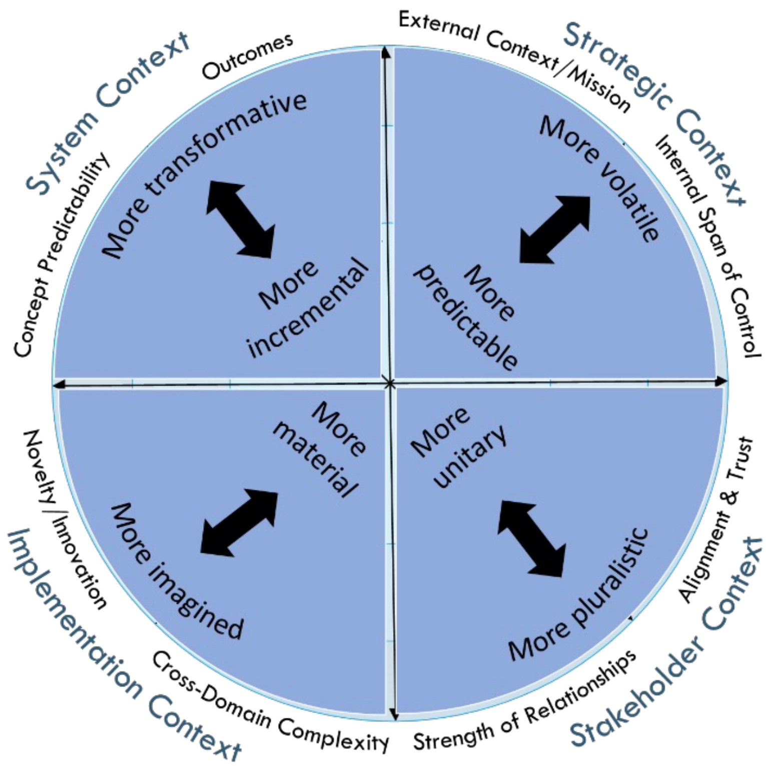

Figure 4. Contexts for Megaproject Uncertainty.

In the **Strategic Context**, megaprojects are characterized by more uncertainty in external environment and more uncertainty in internal environment. Organizational structures are more complex, and management of supply chains becomes more difficult. External stakeholders who might influence the project will need to be managed more closely as the stakes are higher.

In the **System Context**, megaprojects tend to be more transformative in the system concepts and outcomes, and more transformative in their processes. Megaprojects need to plan and execute more flexible decision-making processes. As there are many things that cannot be defined up front, critical decisions should be made later in the project, after more knowledge is accumulated.

In the **Implementation Context**, megaprojects tend to start as "more imagined" and have less knowledge of end design and less knowledge of cross-domain relationships. One must ask how imaginary vs. concrete is the implementation (at this point)? Projects should invest in flexibility to manage risk and uncertainty, particularly modularity so that "unknowns" can be separated from "knowns." Projects need to invest in digital models and environments for design and project execution so that all stakeholders at any level have system-level design visibility. Projects also need to invest in up-front experimentation and test in order to connect implementation with real-world context before commitment to scale project resources.

Finally, in the **Stakeholder Context**, megaprojects tend to have less alignment of stakeholders and need more strength in stakeholder relationships. Decision-making is more pluralistic. Projects must focus more on maintaining and sharing project knowledge. Integrated product teams are necessary to encourage multi-disciplinary and pluralistic decision-making. These projects must choose leaders with megaproject leadership skills and build their capacity.

Each of these contexts has two assessment approaches that can be used to both drive megaproject leadership principles and to select and visualize key project performance metrics. These dimensions are shown in Figure 5.

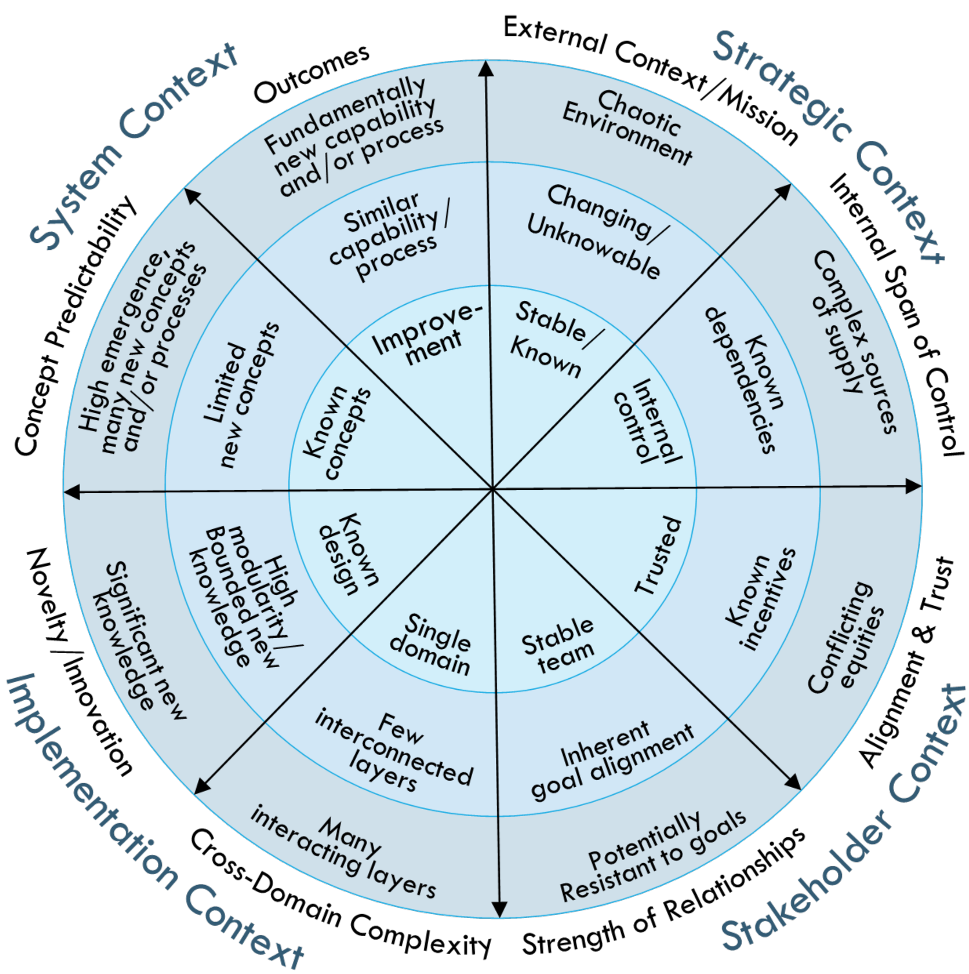

Figure 5. The Megaproject Uncertainty Framework.

This framework serves several purposes:

1. As a way to organize structure and learning from case studies of historical megaprojects. The framework becomes an assessment tool and lessons learned guide for these case studies. Two detailed case studies were completed using the framework. In the process, a number of conceptual tools for modeling the complexities and uncertainties of a megaproject were evaluated.

2. As a playbook for megaproject leadership and management. The framework can be used to define a series of strategies and "plays" to improve megaproject success. The research developed a set of interview questions that were applied to one DoD program of record initially and used these interviews and literature to develop an initial set of lessons learned and "plays" for megaproject leadership to use as an uncertainty management guide.

3. As a high-level visualization dashboard for future megaprojects. The framework provides a holistic visualization tool for situational awareness of data-driven uncertainties across different dimensions of megaprojects. Two prototype megaproject automated visualization tools were developed in the research, one associated with planning and structuring the program, and another associated with maintaining situational awareness of current uncertainties.

4. As a megaproject leadership model. The characteristics of successful megaproject leaders can also be mapped to the framework and be used to guide leadership selection and developmental training in this domain.

ANALYZING AND VISUALIZING MEGAPROJECT UNCERTAINTIES

Data visualization, AI, and machine learning (ML) are anticipated to be of increasing importance to megaproject success. (Gartner, 2019) predicts that by 2030, 80% of project management tasks will be automated using big data, ML, and natural language processing. Project management is becoming a target market for the growth of AI/ML applications (Balyuk, 2023). This market will start with a focus more on automating routine project management activities and not the more difficult aspects of managing through complexity and uncertainty in megaprojects. However, there are emerging commercial tools that have interesting application to megaproject challenges.

This research explored how data visualization, AI, and ML could be combined with human knowledge transfer across teams to aid in the management of DoD's largest programs (megaprojects). Megaprojects are also often mega-systems that operate with dimensions of behavioral complexity, pluralistic decision-making, criticality, and volatility of the external environment. Beyond just involving large financial resources, their complexity leads to greater uncertainty and higher risks. This research showed that AI applications, such as LLMs, can be useful in enhancing leader situational awareness of megaproject progress and potential disruptions, particularly at the tactical level.

In project management, visualization tools allow the mapping of large amounts of data to visual attributes that aid human information processing. Concepts of visual project management argue that managing the complexity of project data requires visualization of patterns that can be evaluated with speed and by multiple stakeholders. Many project management dashboard tools have very prescriptive views and limited ability to contextually arrange informational views into meaningful stories. Megaproject leaders often aggregate this information into periodic reports or presentation slides to effectively convey the "story" that leadership wants to tell with the data. This approach is both highly inefficient and highly subject to leadership bias in interpretation of the data and information (McDermott & Freeman, 2019). The research identified and prototyped two approaches for more automated, flexible and holistic information presentation – the Project Uncertainty Dashboard and the Metaphoric Display.

The Project Management Institute (PMI) found that organizations that are effective at knowledge transfer improve their project outcomes by 35% and that 34% of unsuccessful projects are adversely affected by lack of timely or accurate knowledge transfer (PMI, 2015). Megaproject literature cites communication, emotional intelligence, and stakeholder management skills as key attributes of megaproject leaders. As project complexity and criticality increases, the role of communication and knowledge transfer in social networks becomes more critical, and the ability to visualize knowledge (as opposed to information) becomes paramount to project communication and stakeholder negotiation. Success in megaprojects is based on how the role of human management and decision-making addresses project complexity, uncertainty, and stakeholder conflict from inception to completion. The relationship between knowledge transfer and project success, combined with dimensions of project complexity, requires different ways to visualize and manage the dynamics of a mega-project. The primary project data visualization challenge is to support the combination of qualitative or heuristic decisions that must be made in conjunction with quantitative data driven decisions (McDermott & Freeman, 2019).

For experienced megaproject leaders, integration of project data, information, and knowledge is a highly intuitive process. Much of the quantitative data available to leadership is historical, there is a lot of useful data that is hidden from both the analysis tools and the management teams, and for predictive analysis, qualitative data (what people are saying about uncertainties) is as important as quantitative.

Traditional tools of visual project management produce visualization of patterns that can be evaluated with speed and by multiple stakeholders. Visualization approaches common across the project management domain work well for simpler projects but become overwhelmed as complexity increases. In addition, few of these approaches support visualization of knowledge. (Lengler and Eppler, 2007) categorized project visualization types into a progression of forms that are useful to represent data, information, and higher-level forms that support conceptual knowledge. Four of these types are:

- Data visualization – visualizing quantitative data. Examples are matrices, line charts, scatterplots.
- Information visualization – visualizing representations of data in forms to amplify cognition. Data is transformed into images, often interactive. Examples are spider charts and flow charts.
- Concept visualization – visualizing and elaborating qualitative concepts, ideas, plans, and analyses. Examples are mind maps, causal chains, program evaluation and review technique (PERT) and Gantt charts, and swim lane diagrams.
- Metaphor visualization – positioning information graphically to organize and structure information, using metaphor to provide insight about the displayed information. Examples are metro or tube maps, bridge maps, and funnels.

In this research, we investigated two innovative approaches to project management visualization, supported by LLMs. Each of these visualization approaches assess both qualitative and quantitative project information. The first is a dashboard that combines data, information, and concepts, while the second is a metaphoric display.

THE MEGA-PROJECT UNCERTAINTY FRAMEWORK DASHBOARD

The first visualization transforms the Project Uncertainty Framework into an information-rich interactive dashboard. Through this visualization, for example, we can monitor stakeholder satisfaction/alignment and the influence of relevant events on the project. Through automated and integrated tracing of requirements to implementation, we gain invaluable insights into project dynamics and enhance adaptability. The dashboard is similar in form and in use to a traditional project risk rubric and in fact should be integrated with risk management as one source of information. The dashboard uses AI and LLMs to track both internal and external program potential uncertainties. The top-level dashboard is shown in Figure 6 below. The data in this figure is notional at this point.

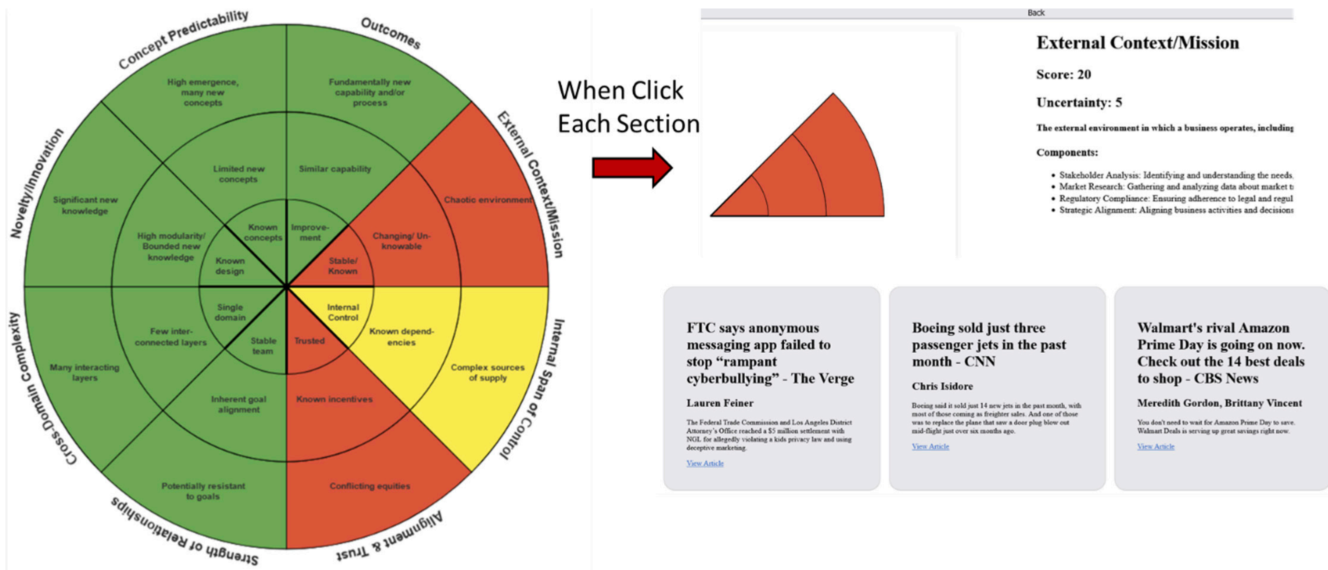

Figure 6. The Megaproject Uncertainty Framework Dashboard.

THE TRAIN METAPHOR MEGAPROJECT MANAGEMENT DISPLAY

The second visualization introduces a metaphoric display, the train metaphor, which illustrates project progression amidst challenges and milestones. Metaphors can serve as effective tools in visualizing abstract and interconnected concepts, fostering a shared vision, and facilitating discussions among team members and stakeholders. Metaphors are often found in megaproject leadership communication, with references to the Manhattan Project or the Apollo mission as typical ways for leadership to convey the importance of innovation or project execution to their teams. Metaphoric displays are also very familiar, the desktop metaphor exists in almost every computer display including IoS and Windows (think of the items arranged around the perimeter of the typical computer display desktop, such as file drawers, toolboxes, and a clock). They are also familiar to display data in project management, many tools support dashboard views of project data built to resemble automotive dashboards. Metaphors are used to both organize information in a familiar intuitive way and to focus attention on immediate needs.

We were not able to find any literature or examples of metaphoric displays used to specifically help manage the structural and dynamic complexity of megaproject planning and execution. Visualization of the complex phenomena of interest in mega-project management is a challenge. A number of potential metaphors were explored on the project as candidates for visualization aids. These included agricultural and biological metaphors, as well as physical construction or assembly metaphors. The railway operations metaphor ("train metaphor") emerged as best suited for this use among the candidates that were considered. Figure 7 illustrates a project train with various cars. In our train metaphor, the engine represents project leadership (stakeholder context), the cars depict project components (implementation context), signposts project milestones (system context), and the passengers embody stakeholders (strategic context), all navigating the project's timeline track.

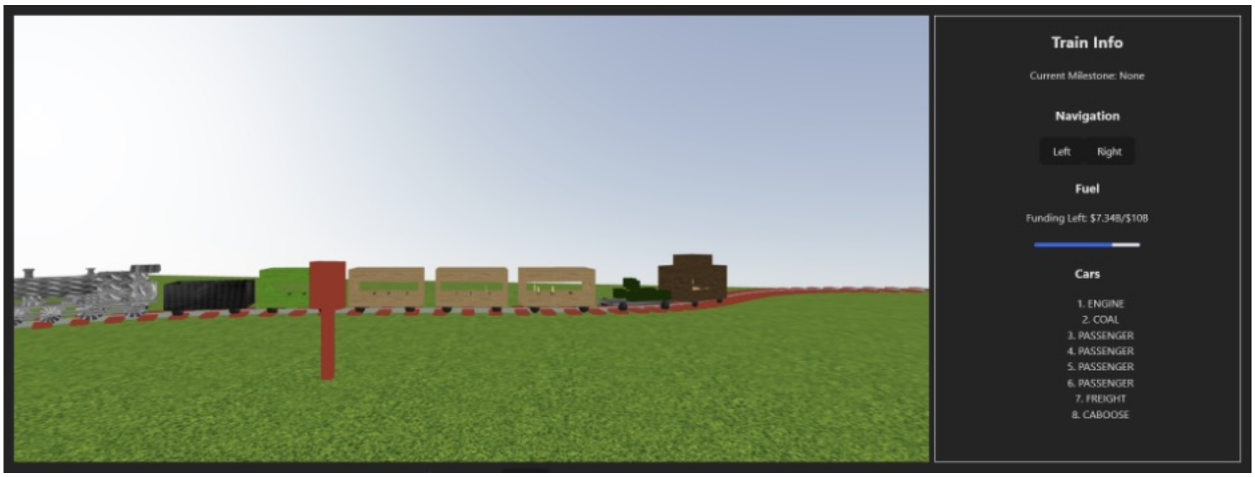

Figure 7. The Megaproject Train Metaphor Display Prototype.

Using modern software integration concepts, it is conceivable that the train metaphor display can be integrated with static and real-time display feeds as a highly intuitive and abstract form of project leadership dashboard. For example, stakeholder satisfaction can quickly be assessed by zooming into one of the passenger cars and can be automatically integrated with stakeholder interaction calendars to plan an emergency visit. Key design components and critical decisions can be tracked as components in freight cars and color-coded as to time criticality, aiding "last responsible moment" decision-making.

USE OF LLMS

Both visualizations leverage LLMs to enhance understanding and decision-making. In this research we used both publicly available (OpenAI) and custom LLMs to collect, analyze, and feed each of the display prototypes. The goal is to gain early warning of critical data to focus management attention, such as an earnings report signaling a supplier in financial trouble, or sentiment analysis of a critical meeting signaling conflict between two suppliers that might lead to future misalignment of goals. As an early warning system to megaproject uncertainties, LLMs can be very useful in finding and analyzing information that may be otherwise hidden from megaproject leadership.

MAINTAINING FLEXIBILITY IN MEGAPROJECTS

Successful megaprojects maintain flexibility to account for project uncertainties and their impacts to project cost, schedule, and outcomes. The goal is to maintain a balance between project requirements, technologies, and affordability at all phases. In a megaproject the client has a clear role to manage risk and uncertainty and set up a flexible decision environment that will enable project success. Most important is to maintain flexibility across the supply chain, as contracting activities tend to limit flexibility and group problem solving across multiple suppliers.

In the Strategic Context, we found several contracting strategies from literature and interviews that aid in managing project uncertainties and provide flexibility to adjust to keep the project on track:

- Use incremental option-based contracts to co-evolve the project at the client level. The role or relationship with the client may shift across phases. Options allow the flexibility to renegotiate and redefine incentives at major program phases.

- Develop contracts that centralize risk pools at the client level to keep project funds in play rather than paying for risk up front in subcontracts. Allocating risk up-front to individual supplier contracts at every level lock up funds that might be best applied to another supplier set of activities to solve problems.

- Create a standard subcontractor contract for all key players and hold consent at the client level over these contracts. The subcontractors also will find that this makes them feel part of the overall project experience.

- In the supplier contracts include how incentives and risk pools will be used to jointly solve problems when things don't go to plan.

In the Implementation Context we found two primary strategies to invest in flexibility to manage risks and uncertainty:

1. Deploy modularity
    - » Create modularity in design, modularity isolates necessary knowledge
    - » Enforce modularity in build, simplifies integration and test
2. Minimize technology novelty
    - » Used existing or well-established technologies as much as possible
    - » Do not carry low-Technology Readiness Level (TRL) technologies past any critical design decision points
    - » Validate critical technologies early with realistic field experiments

SELECTING AND PREPARING FUTURE MEGAPROJECT LEADERS

The final goal of this research task feeds back into education. Much of the megaproject literature confirms that managing megaprojects requires a unique set of skills above and beyond normal project management skills. The DoD needs a set of leadership selection criteria and new training courses to efficiently and effectively train leaders and program teams to plan for, solicit, manage, and execute megaprojects. There were five major leadership capabilities that stood out as necessary for the successful completion of megaprojects. These are the abilities to:

- Manage Diverse Stakeholders
- Manage Complexity
- Manage Uncertainty
- Create Flexibility
- Manage Risk

The research team created a leadership selection and skills framework, as shown in Figure 8.

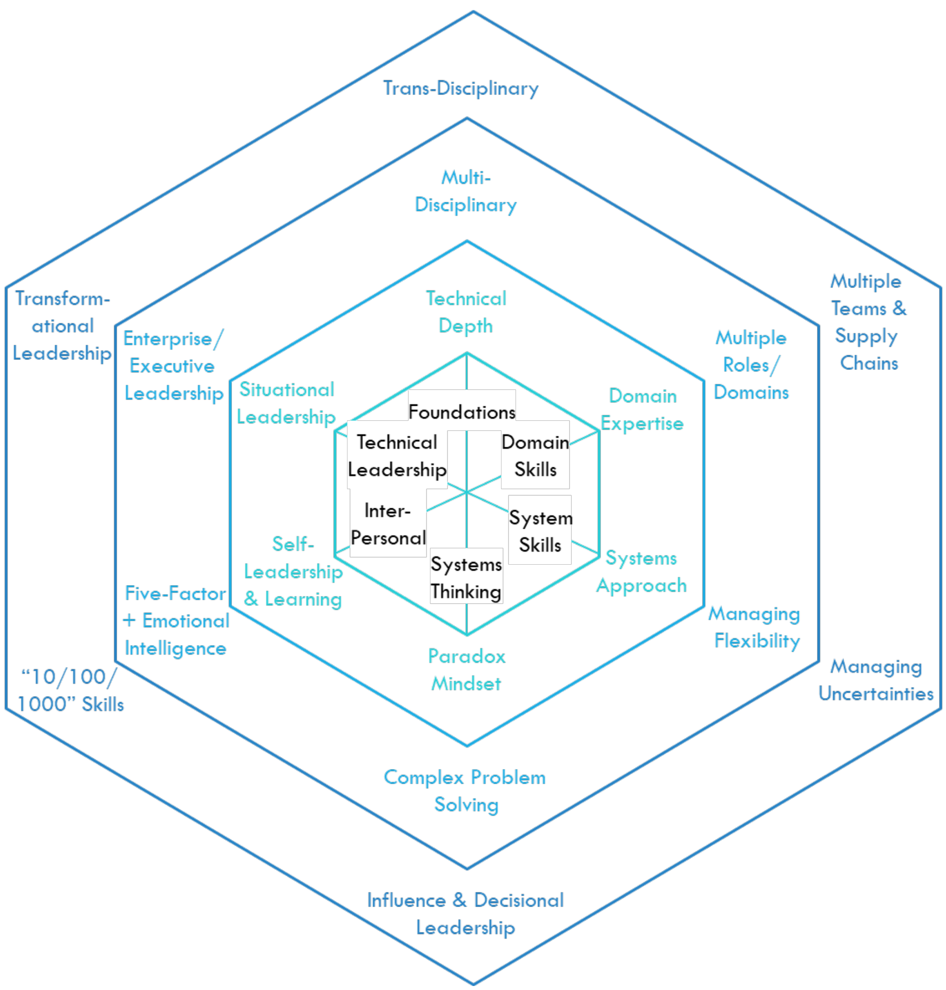

Figure 8. The Megaproject Leadership Selection and Skills Framework.

This framework represents a career development model starting from the center of the hexagon with foundations in "technical depth" to the outer ring with "transformational leadership." We found the leadership progression started with situational leadership which emphasizes a flexible leadership style, to enterprise/executive leadership as megaprojects are "temporary enterprises", to transformational leadership which aims to inspire and motivate followers to innovate and create the change necessary to shape the future success of the project.

KNOWLEDGE SHARING AND INNOVATION ARE KEY INGREDIENTS OF MEGAPROJECT SUCCESS

Two project management practices are essential in managing uncertain projects: knowledge sharing across teams and driving project execution using an innovation model. Although megaprojects might be the world's largest projects, they evolve in a way that is much closer to small innovation companies – through iteration and knowledge building. These are the foundations of megaproject success and the outcomes of all of the other research results:

- Uncertainties become risks and risks are mitigated when shared knowledge is created across the team. Resolution of uncertainties is an innovation process.
- Megaprojects undergo multiple lifecycle shifts as new knowledge is created and innovative approaches drive project outcomes.
- Megaprojects and mega-systems tend to have transformational outcomes to their user and larger societal structures. These outcomes must emerge from the creativity and knowledge of the team members.
- Megaproject uncertainties should be continuously tracked and analyzed to solve problems and keep the project on track. Investment in activities (experiments) to build knowledge and characterize uncertainty must be part of the evolving megaproject lifecycle.
- New and emerging AI and visualization methods and tools that focus on abstracting knowledge will over time revolutionize megaproject management.
- Megaproject management must focus on creating flexibility while also achieving project planning outcomes. Planning must adapt to new knowledge while maintaining focus on key planning outcomes critical to cost, schedule, and performance.
- Development and selection of leaders with these abilities is critical to megaproject success, and megaprojects require unique transformational leadership skills.

FINDINGS AND RECOMMENDATIONS

Below are the key findings and recommendations encountered in this research for improving the management of, and ideally success of, DoD megaprojects.

1. There is a small but systematic set of research and literature on commercial megaprojects, but no complementary set of literature exists on DoD megaprojects. Professor Bent Flyvbjerg at the University of Oxford (UK) has created a community of researchers and established a large database on commercial megaprojects with some defense projects. Many DoD MDAPs are megaprojects, and a number are mega-systems. The megaprojects literature indicates there are significant differences between the discipline of project management and the methods and skills needed to manage megaprojects. This research additionally identified unique characteristics of DoD megaprojects that warrant further study. The DoD should conduct a systematic data-driven study of all current and historical DoD megaprojects, similar to the work done by Flyvbjerg.

2. The DoD has a very strong set of risk management processes and guidance for its developmental programs. The research found that DoD practice overemphasizes risk and underemphasizes uncertainty management, which requires a different set of methods and tools. The uncertainty framework developed in this research provides a categorization of uncertainties that should be tracked in megaprojects. DoD risk management practice should be updated to extend past risks and opportunities to also cover uncertainties and assumptions, with associated management tracking. Additional research on analytical methods for managing and communication uncertainties and assumptions should be developed.

3. Megaprojects succeed or fail based on the project's ability to effectively manage complex supply chains. The research found that contract flexibility, particularly contracting mechanisms that incentivize problem solving, is a major mechanism of success. The research also found that contracting mechanisms that utilize sponsor managed risk pools also improve problem solving behaviors. The DoD should conduct additional research on historical megaproject contracting baselines and develop specific guidance for flexible contracting in megaprojects.

4. Systems engineering in DoD megaprojects is generally too focused on the material solution being developed and is insufficiently focused on the transformative impacts of those material solutions on the greater military and related systems they interact with. Highly transformative systems are repeatedly underestimated and are overly subjected to optimism bias. The DoD needs to classify project risks and uncertainties based on how transformative the project is expected to be and create unique guidance for transformative projects. CJADC2 and hypersonic weapons are two examples of ongoing transformative DoD systems in various stages of development.

5. All megaprojects that have developed transformational systems and system outcomes have also developed transformation development and procurement processes that uniquely support these outcomes. The DoD continues to apply traditional development and procurement processes to its most transformational processes, or experiments with new processes in only parts of these programs. Future DoD megaprojects should be evaluated based on the transformational qualities of the solutions and the transformational qualities of their development and acquisition processes at milestone reviews.

6. The DoD should invest in the development of AI and data visualization tools that track and provide situational awareness on megaproject uncertainties. This research found that LLMs when combined with innovative project management dashboards would have great benefit. The DoD must recognize that first, megaprojects need different management approaches than less uncertain projects, and second, that unique project management tools are both needed and possible.

7. The research strongly identified a set of unique qualities and skills associated with megaproject leadership. The DoD should develop a career development and selection process that specifically targets leadership for its largest and most complex programs and should provide extended service time rotations for these individuals. The DoD should develop an evaluation and training program to certify megaproject leadership.

8. Digital Engineering (DE) in the form of shared program models have repeatedly been shown to aid in megaproject success, when used as an authoritative source for knowledge transfer across all megaproject performers through a "single model environment". The DoD is strongly promoting digital engineering but should make it a requirement for all MDAPs. The DoD should create standardized usage of single model environments related to type of system.

9. DoD has a strong focus on Modular Open System Approaches (MOSA). MOSA and the use of modularity have been shown to reduce risk and uncertainty on megaprojects. However, DoD does not have MOSA guidance that is specific to megaprojects. The DoD should conduct additional study on the benefits of MOSA in megaprojects and develop related guidance for the use of MOSA to reduce uncertainties in megaproject management.

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