



ACQUISITION INNOVATION
RESEARCH CENTER

The Future of Megaproject Management *Full Research Results*

TECHNICAL REPORT
SEPTEMBER 2024

PRINCIPAL INVESTIGATOR

Tom McDermott, *Stevens Institute of Technology*

CO-PRINCIPAL INVESTIGATOR

Zhongyuan (Annie) Yu, *Stevens Institute of Technology*

Amro Farid, *Stevens Institute of Technology*

RESEARCH FACULTY

Dennis Folds, *Stevens Institute of Technology*

Nicole Hutchison, *Stevens Institute of Technology*

Molly Nadolski, *Stevens Institute of Technology*

AIRC FELLOW

Gordon Kranz, *Stevens Institute of Technology*

RESEARCH SCIENTIST

Megan Clifford, *Stevens Institute of Technology*

SPONSOR

**Dr. David Gallop, Director, Acquisition Workforce Educational Partnerships,
Defense Acquisition University (DAU)**

STEVENS
INSTITUTE OF TECHNOLOGY

DISTRIBUTION STATEMENT A.
Approved for public release:
distribution unlimited.

DISCLAIMER

Copyright © 2024 Stevens Institute of Technology. All rights reserved.

The Acquisition Innovation Research Center (AIRC) is a multi-university partnership led and managed by the Stevens Institute of Technology and sponsored by the U.S. Department of Defense (DoD) through the Systems Engineering Research Center (SERC)—a DoD University-Affiliated Research Center (UARC).

This material is based upon work supported, in whole or in part, by the U.S. Department of Defense through the Office of the Under Secretary of Defense for Acquisition and Sustainment (OUSD(A&S)) and the Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E)) under Contract HQ0034-19-D-0003, TO#0468.

The views, findings, conclusions, and recommendations expressed in this material are solely those of the authors and do not necessarily reflect the views or positions of the United States Government (including the Department of Defense (DoD) and any government personnel) or the Stevens Institute of Technology.

No Warranty.

This Material is furnished on an “as-is” basis. The Stevens Institute of Technology makes no warranties of any kind—either expressed or implied—as to any matter, including (but not limited to) warranty of fitness for purpose or merchantability, exclusivity, or results obtained from use of the material.

The Stevens Institute of Technology does not make any warranty of any kind with respect to freedom from patent, trademark, or copyright infringement.



TABLE OF CONTENTS

DISCLAIMER	2
TABLE OF CONTENTS	3
LIST OF FIGURES.....	6
LIST OF TABLES.....	8
RESEARCH TEAM.....	9
ACRONYMS AND ABBREVIATIONS.....	10
INTRODUCTION.....	13
DETAILED RESEARCH FINDINGS.....	13
RESEARCH OBJECTIVES.....	14
LITERATURE REVIEW.....	15
MEGAPROJECT CHARACTERISTICS	15
MANAGEMENT OF MEGAPROJECTS	19
CAUSES OF FAILURE AND ASSOCIATED DATA VISUALIZATION IN MEGAPROJECTS	21
INTEGRATION OF AI/ML AND DATA VISUALIZATION	23
LEADERSHIP	25
QUALITIES AND SKILLSETS OF LEADERS	26
THE MEGAPROJECT UNCERTAINTY FRAMEWORK.....	27
MEGAPROJECT CASE STUDIES.....	32
THE HEATHROW TERMINAL 5 CASE STUDY.....	32
THE FUTURE COMBAT SYSTEM (FCS) CASE STUDY	39
ANALYTIC METHODS TO EVALUATE MEGAPROJECTS	48
USING THE MEGAPROJECT UNCERTAINTY FRAMEWORK AS A PROJECT ASSESSMENT TOOL.....	48
DATA, AI, AND VISUALIZATION.....	50
CHARACTERISTICS OF DATA, INFORMATION, AND KNOWLEDGE IN PROJECT VISUALIZATION	50
THE TRAIN METAPHOR DISPLAY.....	52
INFRASTRUCTURE	54
TRAIN.....	55
ENVIRONMENT.....	58
STATIC REPRESENTATION OF THE TRAIN METAPHOR	59

DYNAMIC REPRESENTATION OF THE TRAIN METAPHOR.....	61
THE MEGA-PROJECT UNCERTAINTY FRAMEWORK DASHBOARD.....	63
PRIMARY VIEW.....	63
SECTION VIEW.....	65
SELECTED SECTION VIEW: STAKEHOLDER STATUS.....	66
INPUT SOURCE VIEW.....	68
DOCUMENT UPLOAD AND INTERPRETATION.....	69
WEBSITE SCRAPING.....	69
AI SYSTEM.....	70
CRITICAL SKILLS FOR MEGAPROJECT LEADERSHIP.....	73
INTRODUCTION.....	73
LITERATURE REVIEW.....	74
EXISTING FRAMEWORKS WITH RELEVANT SKILLS AND COMPETENCIES.....	74
LITERATURE ON QUALITIES & SKILLSETS OF MEGAPROJECT LEADERS.....	77
FRAMEWORK FOR MEGAPROJECT LEADERSHIP SKILLS.....	78
DOMAIN/DISCIPLINE FOUNDATIONS.....	78
PERSONAL CHARACTERISTICS.....	79
MINDSET.....	80
THINKING SKILLS.....	81
INTERPERSONAL SKILLS.....	82
ENTERPRISE TECHNICAL LEADERSHIP.....	83
SELECTING MEGAPROJECT LEADERS.....	84
TRAINING MEGAPROJECT LEADERS.....	85
CONCLUSIONS.....	86
THREE PROGRAM DESIGN STRATEGIES TO MANAGE UNCERTAINTY IN MEGAPROJECTS.....	87
QUALITATIVE & QUANTITATIVE MODELING TO CAPTURE KNOWLEDGE IN MEGAPROJECTS.....	88
TOWARDS A HETERO-FUNCTIONAL GRAPH THEORY APPROACH TO MEGAPROJECT MANAGEMENT (AMIRREZZA HOSSEINI, AMRO M. FARID).....	88
II. BACKGROUND: MODEL-BASED SYSTEMS ENGINEERING (MBSE) & HETERO-FUNCTIONAL GRAPH THEORY (HFGT).....	88
III. APPLYING THE HFGT META-ARCHITECTURE TO MEGAPROJECT MANAGEMENT.....	94

IV. ADDRESSING MEGAPROJECT MANAGEMENT THEMES.....	95
V. CONCLUSION.....	99
CONCEPT-KNOWLEDGE THEORY AS METHOD TO QUANTIFY OBTAINED KNOWLEDGE	100
CK THEORY FRAMEWORK	100
C-K THEORY FOR HEATHROW TERMINAL 5 BAGGAGE CLAIM	101
C-K THEORY FOR CONTRACTING INNOVATIVENESS AT HEATHROW T5	106
SYSTEM THEORETIC PROCESS ANALYSIS (STPA) AND STPA-SEC (SECURITY) FOR MEGAPROJECT MANAGEMENT	113
INTRODUCTION TO STPA AND STPA-SEC FOR MEGAPROJECT MANAGEMENT	113
STPA, STPA-SEC FOR TERMINAL 5	113
MODELING THE CONTROL STRUCTURE FOR HEATHROW TERMINAL 5 MANAGEMENT	118
ANALYZING SECURITY RISKS FOR T5 BHS	122
DEPLOYMENT OF T5 BHS.....	125
LESSONS LEARNED AND RECOMMENDATIONS ON STPA FROM TERMINAL 5 USE CASE.....	126
RECOMMENDATIONS FOR FUTURE RESEARCH	127
REFERENCES.....	131
PRIMARY LITERATURE REVIEW REFERENCES	131
FULL REFERENCE LIST.....	132
APPENDIX A: DETAILED MEGAPROJECT LEADERSHIP FRAMEWORK	142
PERSONAL CHARACTERISTICS	142
MINDSET	147
THINKING SKILLS.....	151
INTERPERSONAL SKILLS.....	154
ENTERPRISE TECHNICAL LEADERSHIP	157
APPENDIX B: IF AN LLM WROTE THIS REPORT	161

LIST OF FIGURES

FIGURE 1. MEGAPROJECTS HAVE LARGE MEAN COST OVERRUNS AND FAT-TAILED DISTRIBUTIONS.	17
FIGURE 2. TWO VIEWS OF MEGA-SYSTEMS FROM LITERATURE.	18
FIGURE 3. “THINK SLOW...EXECUTE FAST”.	20
FIGURE 4. “WHAT ARE THE POTENTIAL CAUSES OF FAILURE IN LARGE COMPLEX PROJECTS?”	21
FIGURE 5. “... AND DISCUSS HOW ONE CAN VISUALIZE THESE.”	22
FIGURE 6. CONTEXTS FOR MEGAPROJECT UNCERTAINTY	27
FIGURE 7. THE MEGAPROJECT UNCERTAINTY FRAMEWORK.....	28
FIGURE 8. UNCERTAINTIES IN THE STRATEGIC CONTEXT.....	30
FIGURE 9. UNCERTAINTIES IN THE SYSTEM CONTEXT.....	30
FIGURE 10. UNCERTAINTIES IN THE IMPLEMENTATION CONTEXT.....	31
FIGURE 11. UNCERTAINTIES IN THE STAKEHOLDER CONTEXT.....	31
FIGURE 12. STRATEGIES IN THE STRATEGIC AND STAKEHOLDER CONTEXTS.....	33
FIGURE 13. INTERNAL SPAN OF CONTROL.....	34
FIGURE 14. ALIGNMENT &TRUST.....	35
FIGURE 15. STRENGTH OF RELATIONSHIPS.....	36
FIGURE 16. CROSS-DOMAIN COMPLEXITY.....	37
FIGURE 17. NOVELTY/INNOVATION.....	37
FIGURE 18. STRATEGIES IN THE SYSTEM AND IMPLEMENTATION CONTEXTS.....	39
FIGURE 19. STRATEGIES IN THE SYSTEM AND IMPLEMENTATION CONTEXTS.....	40
FIGURE 20. OUTCOMES.....	41
FIGURE 21. CONCEPT PREDICTABILITY.....	41
FIGURE 22. EXTERNAL CONTEXT/MISSION.....	43
FIGURE 23. FCS LIFECYCLE SHIFTS.....	43
FIGURE 24. INTERNAL SPAN OF CONTROL.....	44
FIGURE 25. ALIGNMENT &TRUST.....	45
FIGURE 26. CROSS-DOMAIN COMPLEXITY.....	45
FIGURE 27. NOVELTY/INNOVATION.....	46
FIGURE 28. STRENGTH OF RELATIONSHIPS.....	47
FIGURE 29. TRAIN VIEWPORT.....	53

FIGURE 30. A TRAIN AT A TRAIN STATION 54

FIGURE 31. DRILL-DOWN OF A COAL CAR 55

FIGURE 32. DRILL-DOWN OF A FREIGHT CAR 56

FIGURE 33. DRILL-DOWN OF A PASSENGER CAR 57

FIGURE 34. TRAIN TRAVELING THROUGH BAD WEATHER 58

FIGURE 35. TRAIN APPROACHING A MILESTONE MARKER 60

FIGURE 36. TRAIN AT A FORK 62

FIGURE 37. THE MEGAPROJECT UNCERTAINTY FRAMEWORK DASHBOARD WITH HOVER INTERACTION 64

FIGURE 38. EXAMPLE OF A FOCUSED VIEW OF THE “OUTCOMES” SECTION IN THE MEGA-PROJECT UNCERTAINTY FRAMEWORK DASHBOARD 65

FIGURE 39. EXAMPLE OF “RELEVANT EVENTS” TABLE IN THE SUBSECTION VIEW 66

FIGURE 40. EXAMPLE OF “STAKEHOLDER” TABLE IN THE SUBSECTION VIEW 67

FIGURE 41. FULL VIEW OF THE “ALIGNMENT AND TRUST” SECTION 67

FIGURE 42. “NEWS AND MONITORING” PAGE 68

FIGURE 43. “UPOAD PDFS” PAGE 69

FIGURE 44. RAG-BASED GENERATIVE AI PROCESS FLOW 71

FIGURE 45. EXAMPLE SENTIMENT ANALYSIS OF A MEETING TRANSCRIPT 72

FIGURE 46. OVERVIEW OF THE SKILLS OUTLINED IN (PENNOTTI ET AL. 2015), BUILDING IN COMPLEXITY THROUGH THE SYSTEMS, BUSINESS, AND ENTERPRISE LENSES 76

FIGURE 47. MEGAPROJECT LEADERSHIP SKILLS MAPPED TO DAU TRAINING. 85

FIGURE 48. BLOCK DEFINITION DIAGRAM OF THE GRAPH THEORY META ARCHITECTURE. 89

FIGURE 49. (LEFT) BLOCK DEFINITION DIAGRAM OF A MULTI-LAYER NETWORK META ARCHITECTURE.
(RIGHT) AN ALTERNATIVE BLOCK DEFINITION DIAGRAM OF A MULTI-LAYER NETWORK META ARCHITECTURE. 90

FIGURE 50. A HYPOTHETICAL FOUR-LAYER NETWORK INCLUDING TRANSPORTATION, ELECTRIC POWER, WATER DISTRIBUTION, AND DECISION-MAKING ELEMENTS THAT EXHIBIT ALL EIGHT OF THE MODELING CONSTRAINTS FOUND IN MULTI-LAYER NETWORKS. [SCHOONENBERG, ET AL., 2019] 91

FIGURE 51. BLOCK DEFINITION DIAGRAM OF THE HFGT META ARCHITECTURE. 93

FIGURE 52. SNAPSHOT OF C-K THEORY FOR T5 BHS. 104

LIST OF TABLES

TABLE 1. USING THE UNCERTAINTY FRAMEWORK AS AN ASSESSMENT TOOL	48
TABLE 2. C-K THEORY CHART FOR CONTRACTING INNOVATIONS AT HEATHROW T5, IN TABLE-FORM.....	110
TABLE 3. DETAILED DESCRIPTION OF CRITICAL PERSONAL CHARACTERISTICS FOR MEGAPROEJCT LEADERSHIP	142
TABLE 4. DETAILED DESCRIPTION OF MINDSETS FOR MEGAPROEJCT LEADERSHIP	147
TABLE 5. DETAILED DESCRIPTION OF CRITICAL THINKING SKILLS FOR MEGAPROEJCT LEADERSHIP	151
TABLE 6. DETAILED DESCRIPTION OF CRITICAL INTERPERSONAL SKILLS FOR MEGAPROEJCT LEADERSHIP	154
TABLE 7. DETAILED DESCRIPTION OF CRITICAL ENTERPRISE TECHNICAL LEADERSHIP SKILLS FOR MEGAPROEJCT LEADERSHIP	157

RESEARCH TEAM

Name	Organization	Labor Category
Tom McDermott	Stevens Institute of Technology	Principal Investigator
Zhongyuan (Annie) Yu	Stevens Institute of Technology	Co-Principal Investigator
Amro Farid	Stevens Institute of Technology	Co-Principal Investigator
Dennis Folds	Stevens Institute of Technology	Research Faculty
Gordon Kranz	Stevens Institute of Technology	AIRC Fellow
Molly Nadolski	Stevens Institute of Technology	Research Faculty
Nicole Hutchison	Stevens Institute of Technology	Research Faculty
John Willison	Stevens Institute of Technology	AIRC Fellow
Megan Clifford	Stevens Institute of Technology	Research Scientist
Darian Muresan	Stevens Institute of Technology	Professor
Charles Collard	Stevens Institute of Technology	Part-time Research Scientist
Amirreza Hosseini	Stevens Institute of Technology	Doctoral Student
Lauren Kibalo	Stevens Institute of Technology	Student Research Assistant
Mikayla Mount	Stevens Institute of Technology	Student Research Assistant
Stephanie McDonough	Stevens Institute of Technology	Student Research Assistant
Harrison Huston	Stevens Institute of Technology	Student Research Assistant
Joshua Bernstein	Stevens Institute of Technology	Student Research Assistant

ACRONYMS AND ABBREVIATIONS

ACE	Advanced Collaborative Environment
AI	Artificial Intelligence
AIPT	Army Analysis Integrated Product Team
AIRC	Acquisition Innovation Research Center
AIVis	AI and Visualization
ALD	Advanced Leadership Development
AoA	Analysis of Alternatives
BAA	British Airport Authority
BA	British Airways
BHS	Baggage Handling System
BIM	Building Information Management
C-K	Concept-Knowledge
C-Space	Concept Space
CAD	Computer Aided Design
CAPE	Cost Assessment and Program Evaluation
CIPP	Continuous Improvement Project Process
CJADC2	Combined Joint All-Domain Command and Control
CoA	Courses of Action
CTD	Concept and Technology Development
DARPA	Defense Advanced Research Projects Agency
DAU	Defense Acquisition University
DE	Digital Engineering
DoD	Department of Defense
FCS	Future Combat System
FCS/OF	Future Combat System and Objective Force
FFRDCs	Federally Funded Research and Development Centers
FLRAA	Future Long-Range Assault Aircraft
GAO	Government Acquisition Office
GWOT	Global War on Terror
HFGT	Hetero-Functional Graph Theory

HMI	Human-Machine Interface
IBCT	Interim Brigade Combat Team
ICT	Information and Communication Technologies
IPT	Integrated Product Team
JCIDS	Joint Capabilities Integration Development System
K-Space	Knowledge Space
KPP	Key Performance Parameter
LLM	Large Language Model
LRM	Last Responsible Moment
LSI	Lead System Integrator
MBSE	Model Based System Engineering
MCA	Major Capability Acquisition
MDAP	Major Defense Acquisition Program
ML	Machine Learning
MOSA	Modular Open Systems Approach
NSF	National Science Foundation
OCR	Optical Character Recognition
ORD	Operational Requirements Document
OSD	Office of the Secretary of Defense
OUUSD(A&S)	Office of the Under Secretary of Defense for Acquisition and Sustainment
OUUSD(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
QRF	Quarterly Research Forum
R&D	Research and Development
RAG	Retrieval-Augmented Generation
RFID	Radio Frequency Identification
SBCT	Stryker Brigade Combat Team
SDD	System Development and Demonstration
SERC	Systems Engineering Research Center
SME	Single-Model Environment



SoS	System of Systems
STPA	System Theoretic Process Assessment
STPA-Sec	System Theoretic Process Assessment – Security
T5	Heathrow Terminal 5
T5A	T5 Agreement
TRADOC	U.S. Army Training and Doctrine Command
TRL	Technology Readiness Level
UCA	Unsafe Control Action
UML	Unified Modeling Language
VIS	Visualization

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.

DETAILED RESEARCH FINDINGS

The research team pursued multiple threads of research. This section of the report begins with the research objectives, continues with a summary of the literature review, and then presents several standalone sections on the technologies, methods and tools critical to managing the future or megaprojects. These are the key findings and recommendations encountered in this research for improving the management of, and ideally success of, DoD megaprojects.

RESEARCH OBJECTIVES

The project was organized into a set of five research tasks, each culminating in a Defense Acquisition University (DAU) sponsored Quarterly Research Forum (QRF) webinar. The QRF webinars were completed approximately once per quarter, although the research presented at each QRF encompassed the whole project. A secondary goal of the QRF webinars was to show the research in progress, so the organization and timing followed a typical 1-year research progression starting with a literature review and concluding with results.

1. The research team conducted a comprehensive literature review across the areas of mega-project management, project data collection, project data visualization, visualization effects on human decision making in complexity, and emerging artificial intelligence (AI)/machine learning (ML) project management trends. The team started with a literature review across non-DoD domains such as critical infrastructure, healthcare, finance, supply and distribution to determine standard data relationships and decision criteria that are universal versus unique by domain. The team benchmarked successful and non-successful non-DoD projects for lessons learned applicable to DoD megaprojects. (QRF 1)
2. The research team conducted a benchmark study of historical DoD mega-project management using literature, interviews with DoD and related contractor mega-project managers, and review of DoD mega-project management data (based on availability). The research team generalized the primary decision data and methods used in historical DoD mega-projects and evaluated how emerging capabilities of AI/ML technologies and large language models (LLMs) could aid in future mega-project management. From these analyses the research team baselined a set of case studies and learning outcomes that can be used to improve mega-project management in DoD programs. Two historical case studies and one future case study of an in-process DoD megaproject were used. The team applied concepts from the literature review and selected case studies to derive a classification framework for megaproject uncertainties and risks, and to investigate analysis methods and tools for managing megaprojects. (QRF 2)
3. The research team used the literature and case studies along with interviews of an active program to develop a set of lessons learned for megaproject management. From this the team identified a “playbook” of unique management methods for managing megaproject uncertainties. In the process, the team identified a number of conceptual tools to reason about project uncertainties. (QRF 3)
4. The research team applied concepts from the literature review and case studies to develop prototype AI and data visualization methods and tools that would potentially aid in megaproject management. The literature review helped to filter and identify the most effective AI/ML applications and visualization methods and tools in practical contexts for megaproject management. Two dashboard prototypes were developed to test and evaluate prototype visualization concepts. (QRF 4a)
5. The team applied concepts from the literature review and case studies to develop to develop an extended leadership competency model representing the unique leadership characteristics and skills of megaprojects. The research team developed a skills classification, a set of leadership selection criteria, and a framework for a future curricula and training program for teams of key leaders, managers, and functionals in planning, soliciting, and managing megaprojects. (QRF 4b)

LITERATURE REVIEW

The research team conducted a broad literature review in the megaproject domain. There is a small but focused body of literature on megaprojects and megaproject leadership. There is emerging literature on AI and project management. The literature review was organized into four focus areas:

Thread 1: What are the unique characteristics of a megaproject over simpler projects? What data are most critical to informing megaproject leadership of emerging uncertainties and risks? What data are most critical to stakeholder alignment? What analytical frameworks can improve planning and execution of megaprojects?

Thread 2: What are the unique characteristics of a DoD megaproject/mega-system? What are the traditional leadership characteristics of a DoD megaproject across the full system lifecycle? Are there other data that is uniquely critical? Can we compare DoD historical megaproject data to non-DoD frameworks?

Thread 3: What are emerging trends in AI/ML and data analytics that might improve insight on megaproject uncertainties and stakeholder alignment? What types of visualization (VIS) would be most important? How will effectiveness be measured?

Thread 4: What are leader/manager characteristics of a megaproject leader (general and DoD)? Can/how should existing Systems Engineering Research Center (SERC)/Acquisition Innovation Research Center (AIRC)/DAU competency frameworks be extended to support megaproject leadership?

MEGAPROJECT CHARACTERISTICS

Flyvbjerg defines megaprojects as large-scale, complex ventures that typically cost more than 1 billion US Dollars, take many years to build, involve multiple public and private stakeholders, are transformational, and impact millions of people. They differ in terms of their objectives, lead times, complexity, and stakeholder involvement, also requiring a distinct type of manager and leadership. Examples of megaprojects are high-speed rail lines, airports, the Olympics, and high-energy particle accelerators. Not only are megaprojects large, they also are constantly growing ever larger in a long historical trend. Project costs have escalated to the billions and are evolving into giga-projects and even tera-projects. Another factor that makes them different from normal projects is they have proven to be recession proof. The downturn in 2008 helped the megaprojects business grow further by giving stimulus spending on everything from transportation infrastructure to information and communication technologies (ICT). As such, they are accelerating in growth but also becoming more intertwined and interlinked in all aspects of society and our economy.

Not only are they large and constantly growing, but they are also being built in ever greater numbers at an ever-greater value. However, they are also very vulnerable to global events and things like natural disasters. Furthermore, that won't be detrimental to just the project itself but could affect the weather of entire cities, regions and nations if the megaproject fails. For example, in Hong Kong, months of obstacles during the opening of a new international airport resulted in disrupted traffic and the GNP falling for the entire city state. For Greece, a contributing factor to the country's 2011 debt default was the 2004 Olympic games in Athens, for which cost-overrun and incurred debt were so large they negatively affected the credit rating of the whole nation and weakened the economy. Flyvbjerg provides several other examples in his paper.

Flyvbjerg identifies four “sublimes”—political, technological, economic, and aesthetic—that he uses to explain the increased size and frequency of megaprojects. Taken together, they ensure that strong coalitions exist of stakeholders who benefit from megaprojects and who will therefore work for more such projects. For policymakers, investing in infrastructure megaprojects seems particularly coveted because, if done right, investing in them can improve GDP, employment, improve productivity, and many other things. However, Flyvbjerg says that is a big “if” since there are many other factors at play that are often overlooked. He argues that conventional megaproject delivery, infrastructure and other, is highly problematic with a dismal performance record in terms of actual costs and benefits.

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 (Flyvbjerg & 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.

Flyvbjerg 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 (Flyvbjerg & 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.

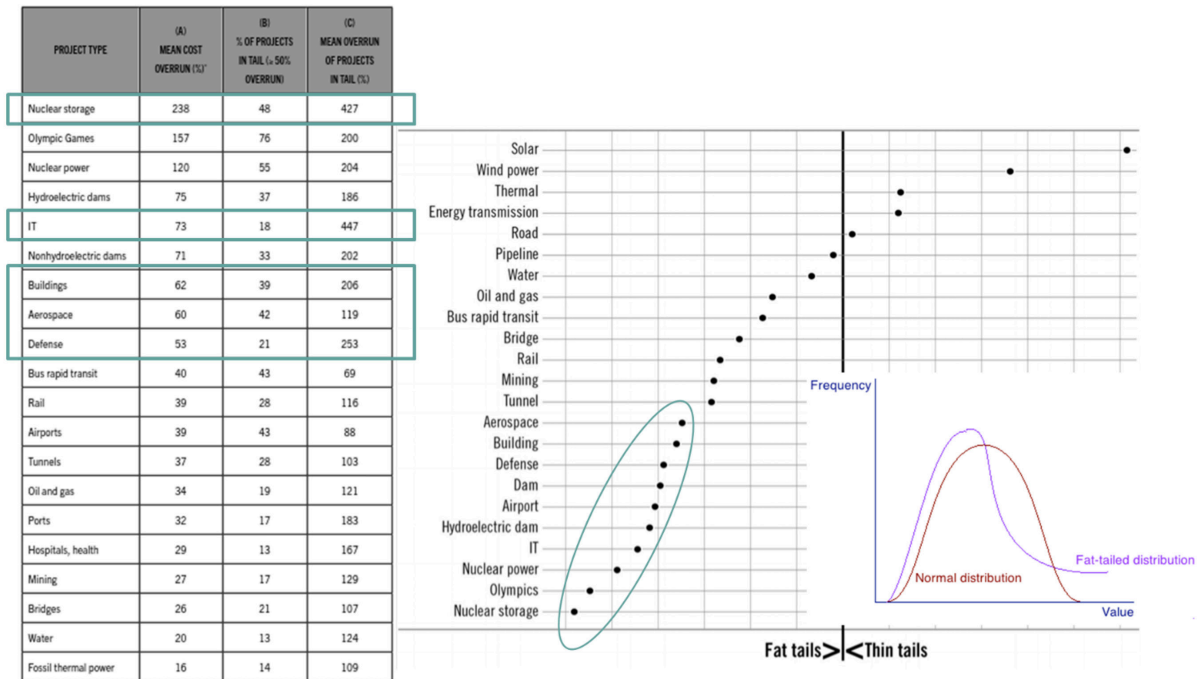


Figure 1. Megaprojects have large mean cost overruns and fat-tailed distributions.

The image on the right 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.

Megaprojects often function as mega-systems (Stevens, 2011) and are marked by operational uncertainty, behavioral complexity, pluralistic decision-making, and external environmental volatility. Megaprojects are distinct from mega-systems in that mega-systems are characterized not only by scale (larger versus smaller), complex behavior, and the fact that they cross traditional boundaries, but also by their “nestedness” (Stevens, 2016). They are composed of multiple separate systems and they constitute part of one or more even larger mega-systems. In order to achieve their objectives, they have to interact with external and related systems. “Engineering Megasystems” by Renee Stevens notes that just as systems are made up of components—subsystems—the systems can interact with related external systems to provide a desired capability. Stevens classifies three tiers: (1) the system, (2) the components of the systems (its parts), and (3) the larger system (the “containing system” in Ackoff’s terms) of which it is a part. Furthermore, at the same time a system can be part of more than one “containing system.” Therefore, a weapon system can be part of that military service’s mega-system while simultaneously be a component of the joint mega-system specific to a particular theater of operations. With a specific purpose or mission in mind, a mega-system is grown or designed, and its component system is able to act independently. As such, the likelihood of mission success increases by pursuing the mission using independent means that are effective in different operating environments (Stevens, 2016). Like megaprojects, the scale, complexity, increasing pace of technological change, and the fact that a single organization rarely owns and therefore completely controls the mega-system, presents distinct challenges for engineering mega-systems.

How transformative is the megaproject/mega-system in the operational context where it will be deployed? Figure 2 presents two evaluation rubrics – the left view is from (Stevens, 2011) and the right view is derived from (Schindler, Fadaee, & Brockington, 2021).

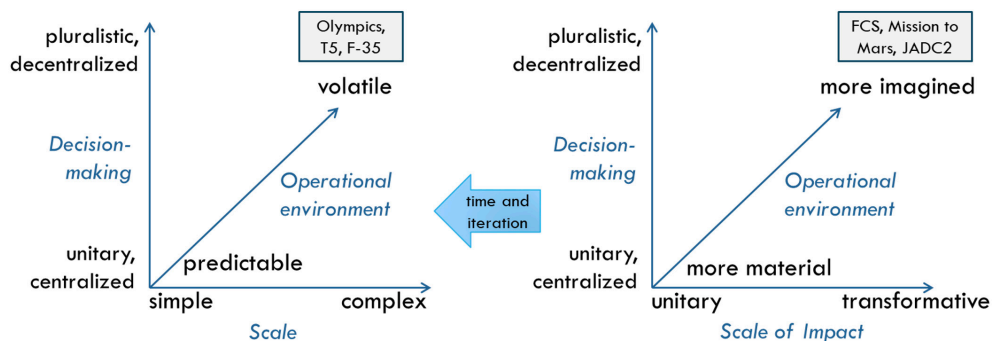


Figure 2. Two views of Mega-systems from literature.

More material project case studies like the London Olympics, the Heathrow Terminal 5 (T5) 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.

MANAGEMENT OF MEGAPROJECTS

Megaproject management success results in projects being delivered on budget, on time, and with the promised benefits (Flyvbjerg, 2014). Approximately 1/10 megaprojects are on budget, 1/10 on schedule, and 1/10 delivers the promised benefits, then approximately 1/1,000 a success, and defined as “on target” for all three (Flyvbjerg, 2014). Poor stakeholder management can lead to many serious problems in megaprojects, such as: poor scope and work definition, inadequate resources assigned to the project, poor communication, changes in the scope of work and unforeseen regulatory changes, etc. (Metar, 2021). All of these may be the major source of delays and cost overruns.

The nature of megaprojects growth means that their ecosystems will also grow bigger, and as such, the volume of project data has catapulted and data networks have also grown more interdependent. This has resulted in detailed data sets that are often scattered across the ecosystem and can be difficult to collect, integrate, and distill into insights that can inform decision making (McKinsey, 2021). While the growth in complexity increases the possibility for blind spots, innovations in project management technologies offers solutions and improvements not only in the automation of administrative and low value tasks but also in the definition and implementation of projects to ensure success with analytics-driven insights.

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

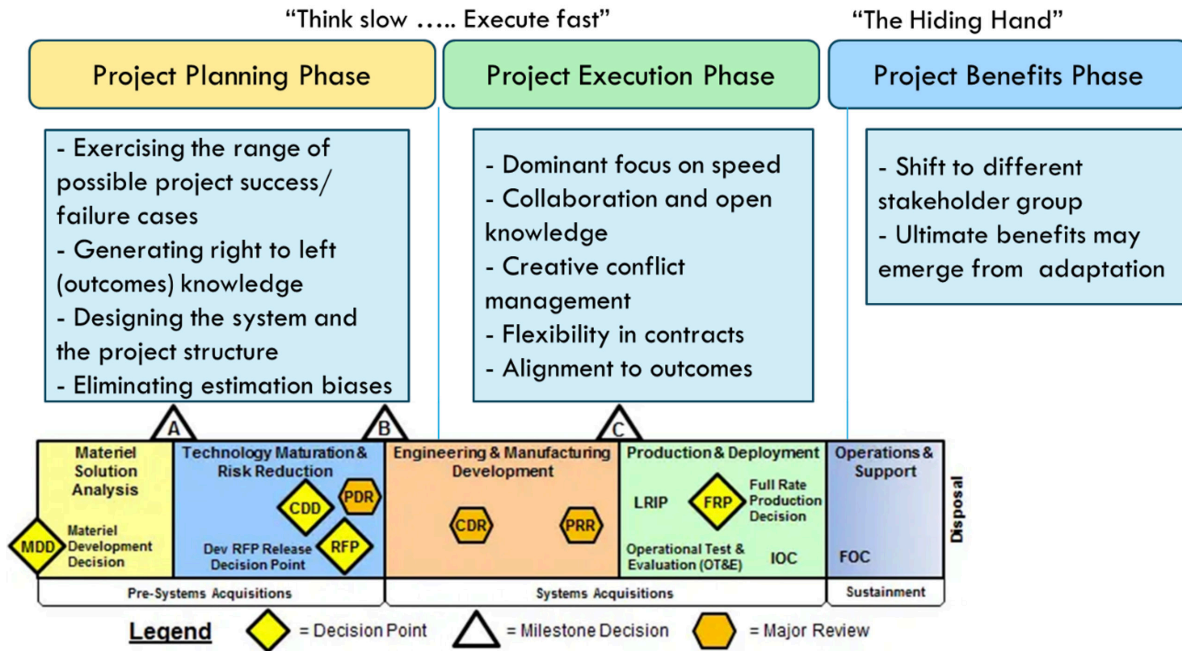


Figure 3. “Think Slow...Execute Fast”.

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/indicators 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 AI, 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 this report.

As such, while traditional project management approaches are effective in many contexts, they are inadequate when confronted with the multifaceted challenges of today’s projects. The intricacy and scale of these projects necessitates an approach that reflects complex project leadership, and involves competences such as systemic thinking, strategy, innovation, collaboration, and adaptability. In the *Megaproject leaders: Reflections on Personal Life Stories* book, the leaders interviewed stated the importance of having project culture, since it enables a meaningful connection with team members and with stakeholders that contribute to project outcomes. Examples of this would be establishing an alliance culture to help foster inter-organizational collaboration, or a sense of mission and the prestige of working on an important endeavor that benefits the nation and contributing to societal outcomes.

Most importantly, the project culture helped to create a sense of unity during difficult periods in the project, which brought people together from diverse cultural backgrounds to achieve this shared destiny. This community mission led to cohesiveness of multicultural teamwork and overall, more innovative missions. Having a unique culture built-in to the project leadership approach was seen in megaprojects such as the London T5 airport expansion, where the leadership aimed to encourage the suppliers to move away from “business as usual” to a project environment where “we all continually challenge how we can be successful.” They implemented a ‘devolved governance’ model by which it sought to empower suppliers to accelerate decision-making and problem-solving (Gil & Ward, 2011). The project’s issues, including labor disputes, technical failures, and extensive regulatory hurdles, underscore the difficulties in managing projects of such monumental scope and impact.

CAUSES OF FAILURE AND ASSOCIATED DATA VISUALIZATION IN MEGAPROJECTS

There are a large and complex set of potential causes of failure in megaprojects. The available literature has done a good job of generalizing and classifying these patterns, but very little literature exists on the detailed causes of failure necessary for megaproject managers to define the data they need to manage with. In the spirit of using AI, we prompted the public ChatGPT4o LLM to find some of these details from across the body of both project management and megaproject literature. Figure 4 shows 20 potential causes of failure in megaprojects.

1. Poor Planning:

1. Inadequate project planning and scope definition.
2. Unrealistic timelines and resource estimates.
3. Lack of contingency planning for unforeseen events.

2. Inadequate Leadership and Governance:

1. Weak project management and leadership.
2. Insufficient project governance and oversight.
3. Lack of alignment between project objectives and organizational strategy.

3. Unclear Objectives and Requirements:

1. Ambiguous or changing project requirements.
2. Inadequate stakeholder communication and involvement.
3. Misalignment between project goals and stakeholder expectations.

4. Scope Creep:

1. Uncontrolled changes in project scope.
2. Poorly managed requirements and feature additions.
3. Inability to resist external pressures for additional scope.

5. Poor Communication:

1. Ineffective communication between team members and stakeholders.
2. Lack of transparency regarding project status and issues.
3. Miscommunication leading to misunderstandings and mistakes.

6. Inadequate Resources:

1. Insufficient budget and financial resources.
2. Shortages in skilled personnel.
3. Lack of necessary equipment and technology.

7. Technical Challenges:

1. Complexity of technology and integration issues.
2. Insufficient testing and quality assurance.
3. Unexpected technical obstacles and dependencies.

8. Risk Management Failures:

1. Failure to identify and mitigate project risks.
2. Inadequate risk response planning.
3. Lack of a proactive risk management culture.

9. Poor Stakeholder Management:

1. Insufficient engagement with stakeholders.
2. Unresolved conflicts among stakeholders.
3. Failure to address stakeholder concerns and expectations.

10. Team Dynamics and Collaboration:

1. Ineffective teamwork and collaboration.
2. Lack of cohesion among team members.
3. Poorly defined roles and responsibilities.

11. Inadequate Change Management:

1. Resistance to change within the organization.
2. Poorly managed transitions and handovers.
3. Inability to adapt to evolving project requirements.

12. External Factors:

1. Political, economic, or regulatory changes.
2. Environmental factors affecting project locations.
3. Force majeure events disrupting project activities.

13. Vendor and Supplier Issues:

1. Dependence on unreliable suppliers.
2. Contractual disputes and issues.
3. Lack of contingency plans for supplier failures.

14. Ineffective Monitoring and Control:

1. Inadequate project tracking and monitoring mechanisms.
2. Failure to identify and address issues in a timely manner.
3. Lack of effective change control procedures.

15. Insufficient Training and Skill Development:

1. Lack of training programs for team members.
2. Inadequate skill development to handle new technologies.
3. Inability to adapt to evolving industry standards.

16. Legal and Compliance Challenges:

1. Non-compliance with regulatory requirements.
2. Legal disputes and issues.
3. Failure to anticipate and address legal constraints.

17. Cultural and Organizational Issues:

1. Organizational resistance to project changes.
2. Misalignment of project culture with the broader organization.
3. Lack of adaptability to diverse cultural contexts.

18. Lack of Continuous Improvement:

1. Failure to learn from past projects.
2. Inability to adapt and improve processes over time.
3. Lack of a culture of continuous improvement.

19. Financial and Economic Factors:

1. Economic downturns impacting project funding.
2. Unforeseen cost escalations.
3. Budget constraints affecting project quality and timelines.

20. Cybersecurity Threats:

1. Increasingly relevant in the digital age, potential breaches in cybersecurity can compromise project data, intellectual property, and overall project integrity.

Figure 4. “What are the potential causes of failure in large complex projects?”

We were able to find each of these causes in the literature review, but no such organized list. The challenge to megaproject leadership is to maintain situational awareness of each of these potential causes, which is probably not possible without the support of automated tools.

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.

Following this question, we used a series of prompts to get the ChatGPT4o model to identify how megaproject managers might visualize each of the potential failure causes. The results are shown in Figure 5 below. Many of the suggested visualization approaches reflect historical project management tools. In other words, LLMs are good at finding data but are not going to be innovative in their recommendations. However, these two sets of information added necessary detail to our literature review on megaproject characteristics.

- | | |
|--|---|
| <p>1. Inadequate Planning:</p> <ul style="list-style-type: none"> Visualization: Use a timeline or Gantt chart to represent project milestones and deadlines. Identify gaps or overlaps in tasks to highlight planning deficiencies. <p>2. Lack of Leadership and Governance:</p> <ul style="list-style-type: none"> Visualization: Display an organizational chart that illustrates project leadership roles and responsibilities. Highlight any gaps in decision-making or accountability. <p>3. Unclear Objectives and Requirements:</p> <ul style="list-style-type: none"> Visualization: Develop a visual hierarchy showing project goals, objectives, and key results. Ensure alignment across the entire project team. <p>4. Scope Creep:</p> <ul style="list-style-type: none"> Visualization: Use a scope change log to document and visualize changes to the project scope over time. Track the impact of each change on resources and timelines. <p>5. Ineffective Communication:</p> <ul style="list-style-type: none"> Visualization: Construct a communication flowchart, illustrating how information moves within the project. Identify bottlenecks or gaps in the communication process. <p>6. Inadequate Resources:</p> <ul style="list-style-type: none"> Visualization: Use resource allocation charts to illustrate the distribution of human, financial, and material resources. Highlight any imbalances or shortages. <p>7. Technical Challenges:</p> <ul style="list-style-type: none"> Visualization: Create a technology landscape diagram, mapping out the various tools and systems used in the project. Identify potential points of failure or integration issues. <p>8. Risk Management Failures:</p> <ul style="list-style-type: none"> Visualization: Create a risk matrix, plotting the likelihood and impact of potential risks. Use color coding to indicate the severity of each risk. <p>9. Poor Stakeholder Management:</p> <ul style="list-style-type: none"> Visualization: Develop a stakeholder map, categorizing stakeholders based on interest and influence. Ensure that key stakeholders are adequately engaged and informed. <p>10. Team Dynamics and Collaboration:</p> <ul style="list-style-type: none"> Visualization: Create a network diagram that connects team members based on collaboration and communication patterns. Nodes represent individuals, and edges represent interactions. This can help identify key influencers and communication pathways within the team. | <p>11. Inadequate Change Management:</p> <ul style="list-style-type: none"> Visualization: Create a change control process flowchart, illustrating how changes are proposed, evaluated, and implemented. Identify potential points of resistance. <p>12. External Factors:</p> <ul style="list-style-type: none"> Visualization: Use a risk heat map to illustrate the geographic and environmental risks associated with the project. Highlight areas prone to natural disasters. <p>13. Vendor and Supplier Issues:</p> <ul style="list-style-type: none"> Visualization: Create a dependency network diagram, illustrating relationships between tasks and external factors. Highlight critical dependencies and potential risks. <p>14. Ineffective Monitoring and Control:</p> <ul style="list-style-type: none"> Visualization: Create a visual dashboard that consolidates key project metrics, such as progress, budget, and milestones. Use charts, graphs, and color-coded indicators to provide a quick overview of project health. <p>15. Insufficient Training and Skill Development:</p> <ul style="list-style-type: none"> Visualization: Construct an organizational skills matrix, showing the skills and competencies of team members. Identify gaps and areas for skill development. <p>16. Legal and Compliance Challenges:</p> <ul style="list-style-type: none"> Visualization: Develop a regulatory compliance matrix, mapping out the relevant regulations and their impact on the project. Identify potential compliance risks. <p>17. Cultural and Organizational Issues:</p> <ul style="list-style-type: none"> Visualization: Develop a visual representation of the Cultural Web, a model that includes symbols and icons representing various aspects of organizational culture, such as rituals, stories, symbols, control systems, power structures, and organizational structures. <p>18. Lack of Continuous Improvement:</p> <ul style="list-style-type: none"> Visualization: Implement a Kaizen board, which is a visual representation of improvement ideas and their progress. Use columns like "Ideas," "In Progress," and "Completed" to track the evolution of improvement initiatives. <p>19. Financial and Economic Factors:</p> <ul style="list-style-type: none"> Visualization: Use a financial tracking chart to monitor project expenses against the budget. Clearly display any variances and their impact on the overall project. <p>20. Cybersecurity Threats:</p> <ul style="list-style-type: none"> Visualization: Create a visual map that categorizes and depicts various types of cybersecurity threats, including malware, phishing, DDoS attacks, and ransomware. Use color codes or symbols to represent the severity or frequency of each threat. |
|--|---|

Figure 5. "... and discuss how one can visualize these."

INTEGRATION OF AI/ML AND DATA VISUALIZATION

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 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.

Research by Gartner predicts that major change is coming to project management tasks, stating that by 2030, 80% of project management tasks will be run by AI, powered by big data, ML, and natural language processing. By modernizing project management through application of AI and big data innovations, it could improve the success ratio in megaprojects and have positive implications through testing, risk management, machine-learning prioritization, virtual assisting, and more. When the correct data is available, ML can detect patterns that can't be discerned by other means and can vastly exceed human accuracy in making predictions (Nieto-Rodriguez and Vargas, 2023). While these technologies will impact how projects are managed, they will also impact how we train and coach teams as well as foster the transition and implementation of the technologies.

The integration of AI/ML with advanced visualization tools not only deepens the understanding of complex project data but also fosters a proactive, data-driven approach to project management. Our comprehensive analysis reveals a significant paradigm shift towards more visually-oriented, intelligent project management practices that promise enhanced clarity and strategic alignment, ultimately improving decision-making across various industries. AI and ML are redefining project oversight, enabling a dynamic and interconnected management style that leverages real-time data to boost transparency and response rates. For instance, the Heathrow T5 project, a hallmark of mega-project complexity with its multitude of interlinked subprojects, serves as a potent example of where the application of AI/ML could have proactively identified and mitigated risks, highlighting the transformative potential of these technologies in managing projects of monumental scale and significance. With predictive analytics, these technologies are poised to play a critical role in the operational aspects of mega-projects, as corroborated by forecasts suggesting a surge in AI/ML adoption in the coming years (Balyuk, 2023).

Furthermore, GenAI transcends traditional analytical tools by offering a nuanced approach to project oversight through three core functions: Assistance, Augmentation, and Automation. These functions collectively enrich the project lifecycle by streamlining operations and enhancing decision-making, thereby shaping a new horizon for project management that is intuitive, efficient, and adaptive. Assistance through GenAI provides essential support by automating routine tasks and generating preliminary analyses, thereby freeing up time for project managers to focus on strategic planning. This shift towards a GenAI-driven model promises a future where project management is not only more agile and intelligent but also more attuned to the nuanced demands of large-scale projects.

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.

The novelty of our work lies in its integration of sophisticated data visualization tools with AI and ML to create more dynamic and responsive project management practices. These practices are designed to not only anticipate and mitigate risks but also to enhance decision-making processes, thereby aligning project management strategies more closely with long-term organizational goals. The importance of this work cannot be overstated, as it provides a blueprint for future mega-project management strategies, potentially revolutionizing the field.

LEADERSHIP

While traditional project management approaches are effective in many contexts, they are inadequate when confronted with the multifaceted challenges of today's projects. The intricacy and scale of these projects necessitates an approach that reflects complex project leadership, and involves competences such as systemic thinking, strategy, innovation, collaboration, and adaptability. In the *Megaproject leaders: Reflections on Personal Life Stories* book, the leaders interviewed stated the importance of having project culture, since it enables a meaningful connection with team members and with stakeholders that contribute to project outcomes. Examples of this would be establishing an alliance culture to help foster inter-organizational collaboration, or a sense of mission and the prestige of working on an important endeavor that benefits the nation and contributing to societal outcomes.

Most importantly, the project culture helped to create a sense of unity during difficult periods in the project, which brought people together from diverse cultural backgrounds to achieve this shared destiny. This community mission led to cohesiveness of multicultural teamwork and overall, more innovative missions. Having a unique culture built-in to the project leadership approach was seen in megaprojects such as the London T5 airport expansion, for example, where the leadership aimed to encourage the suppliers to move away from "business as usual" to a project environment where "we all continually challenge how we can be successful." They implemented a 'devolved governance' model by which it sought to empower suppliers to accelerate decision-making and problem-solving (Gil & Ward, 2011).

Effective front-end planning is also critical for megaprojects. It should identify high risk conditions and the appropriate methods to address those issues when/if they arise. The project team needs to clearly define the technical data, business/commercial data, site data, and execution data required prior to commencing with the plan (Hallock & Zack Jr, 2018). The project team also needs to be sensitive to optimism bias and develop auditable trails and cold eyes review to ensure the planning is realistic (Hallock & Zack Jr, 2018).

In reality, megaprojects are produced by a network, not by a single organization. It includes a group of key stakeholders with their own goals and strategies, which includes public and private entities such as a meta-organization representing governments, land and resource ownership, public interest and local communities. With all these stakeholders, consensus is still needed to bring the project to fruition. Agreements are reached through dialogue as much as through mutual bargaining and compromise-seeking between these often-conflicting groups, with each committed to different time and cost baselines and holding different ideas of efficiency and effectiveness (Lundrigan, Gil, Puranam, 2014). Lundrigan et al. argue that the disappointing and controversial (under) performance of mega-projects may be a result of how their organizational structure develops, rather than due to any agency or competence related failure per se.

QUALITIES AND SKILLSETS OF LEADERS

Any review of literature on megaproject leaders must start with Merrow and Nandurdikar's book, *Leading Complex Projects* (2018). This book provides insights into managing large-scale, complex projects taken from a quantitative analysis of leadership in the oil and gas industry. The book discusses the unique challenges of such projects, emphasizing the need for strong leadership, effective communication, and rigorous planning. Key themes include: managing uncertainty, stakeholder engagement, decision-making under pressure, and balancing short-term objectives with long-term goals. The authors offer practical strategies based on research findings to help project leaders improve performance, mitigate risks, and navigate the complexities inherent in large, high-stakes projects.

- Historically, excellent program managers have been selected as megaproject leaders. But success in a first complex project is a good indicator for success in a second. "It is not even clear that a long career progression in smaller, less-complex is of any substantial value to the complex project leader at all."
- Skillsets for PMs overlap with megaproject leadership – but there are very different emphases.
- Most effective megaproject leaders have had:
 - » Broad and varied jobs - most successful megaproject leaders have depth in the domain of the project but have worked more broadly and become generalists.
 - » Making timely decisions under conditions of uncertainty.
 - » Opportunity to watch others lead complex projects.
 - » Experience sorting out difficult interpersonal situations.
 - » Many come from engineering (most megaprojects are engineered systems).
- Critical skills for megaproject leaders include:
 - » They are highly open to new experiences, self-disciplined, engaging, stable, and test high in emotional intelligence (the five-factor model).
 - » Project management remains important but in the context of cooperation and not in transactional methods (as it is usually employed).
 - » They prefer to manage people, create alignment, and focus on communications over on work processes.
 - » They are highly aware of their own abilities for learning.

THE MEGAPROJECT UNCERTAINTY FRAMEWORK

The research developed a megaproject uncertainty framework which is shown in Figures 6 and 7, and was adapted from a similar mega-systems classification framework in (Stevens, 2011). From (Stevens, 2011) we capture four megaproject uncertainty contexts shown in Figure 6: Strategic, Systems, Implementation, and Stakeholder.

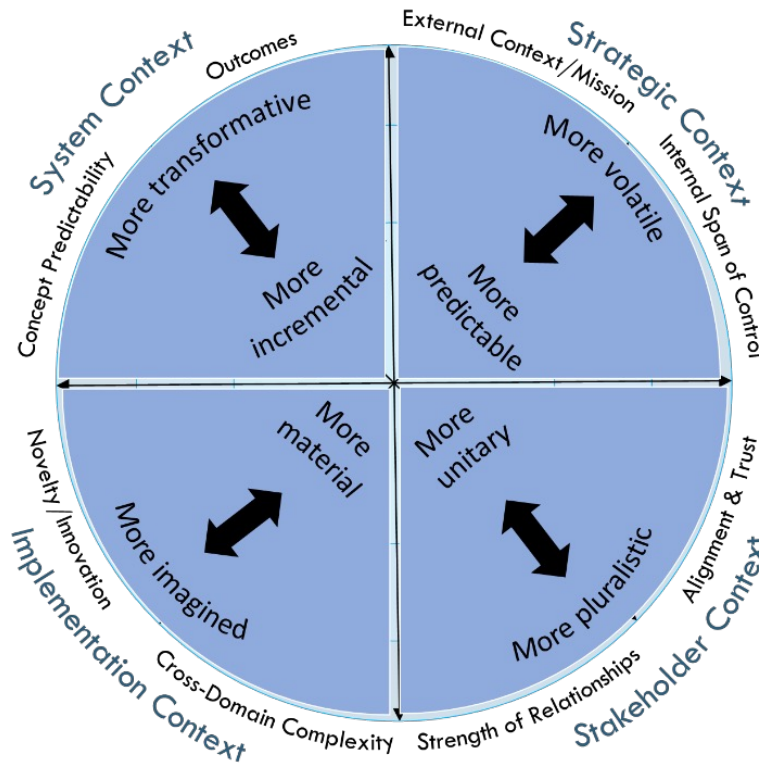


Figure 6. Contexts for Megaproject Uncertainty

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 7.

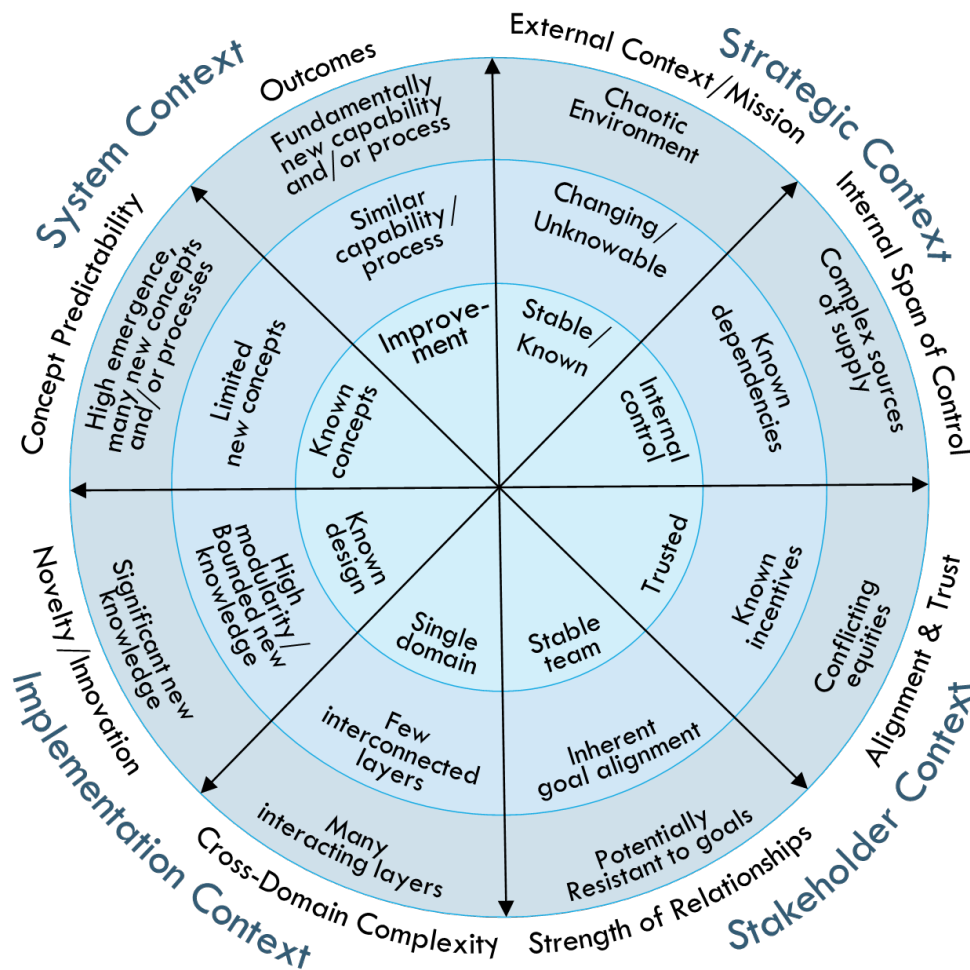


Figure 7. The Megaproject Uncertainty Framework

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.

Early in the research, the framework was derived in order to categorize more deeply the types of project uncertainties, methods or “hedges” to counter them, and examples of analytics that might be used to track them. This was the foundational categorization that was used to drive the rest of the research on the project. These were summarized in a set of visuals presented at QRF 1.

Uncertainties in the **Strategic Context** exist in both the external environment of the project and in the internal environment – the supply chain. For example, in the external context, often changing political environments can impact support for the project, including budgets and favorable incentives. Improving the exchange of knowledge on project uncertainties can impact project stakeholder support, which may improve and erode support. These are illustrated in Figure 8.

The internal context of the megaproject is associated with its supply chain and uncertainties exist in the span of control a project has over its sources of supply. Much of the megaproject literature suggests that incentive structures are necessary to manage these relationships and encourage joint project problem solving.

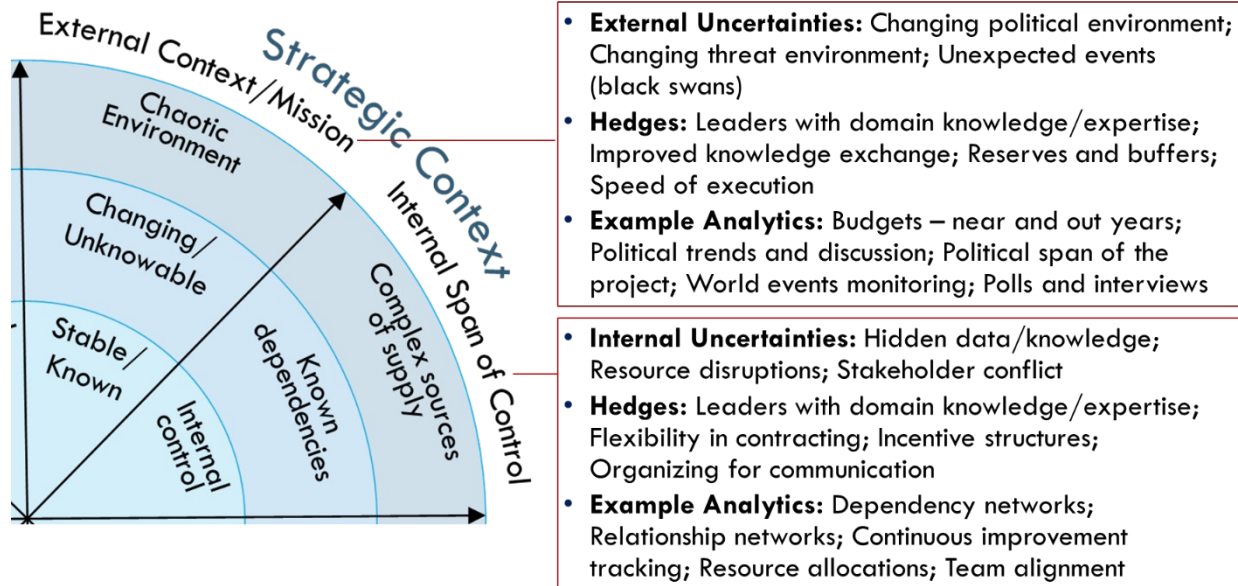


Figure 8. Uncertainties in the Strategic Context

In the **System Context**, megaprojects tend to be more transformative in the system concepts and outcomes, and more transformative in their processes. System and process transformation must evolve/iterate together. This is where uncertainties in the transformative nature of projects must be addressed, which should consider both the scale of the project and its realized systems. This is illustrated in Figure 9.

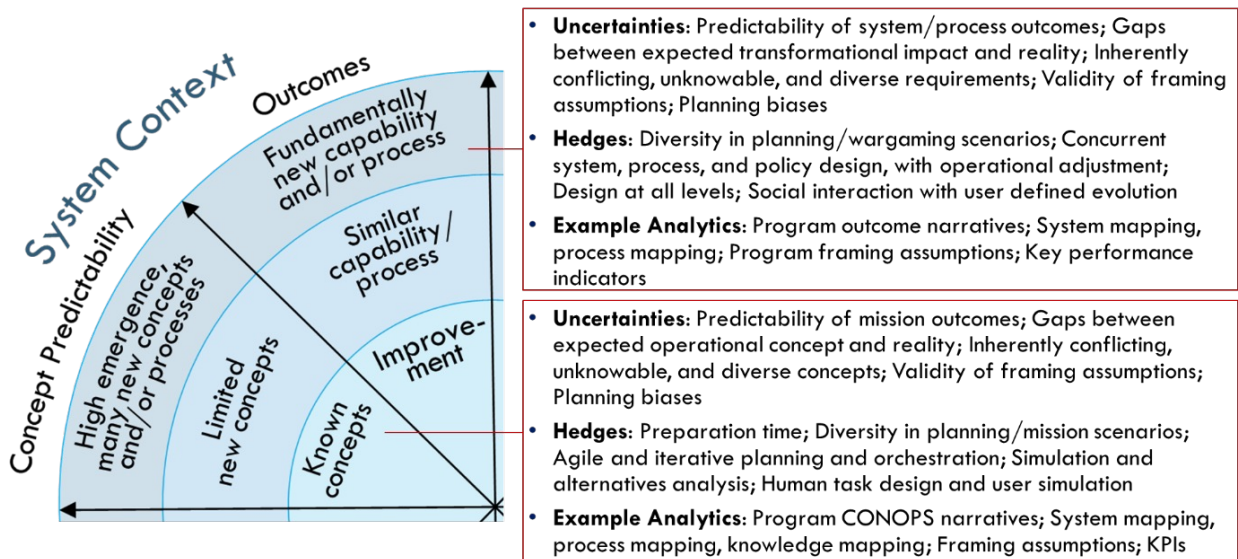


Figure 9. Uncertainties in the System Context.

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)? There is a need for increased knowledge generation opportunities. This is illustrated in Figure 10.

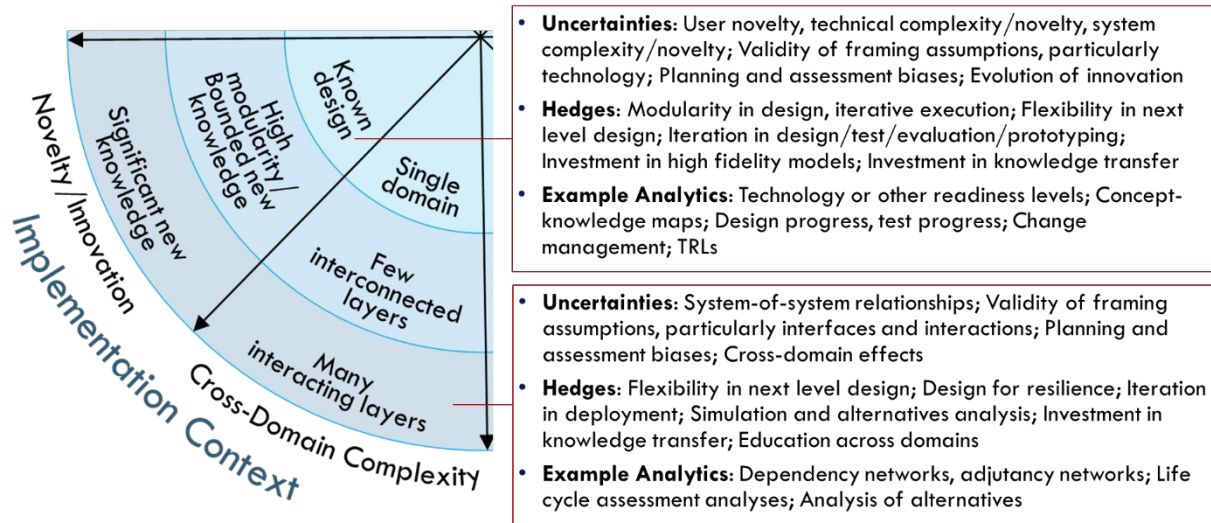


Figure 10. Uncertainties in the Implementation Context

In the **Stakeholder Context**, megaprojects tend to have less alignment of stakeholders and need more strength in stakeholder relationships. Decision-making is more pluralistic. There is a need to move from project management and focus on planning to project leadership and focus on stakeholders. This is illustrated in Figure 11.

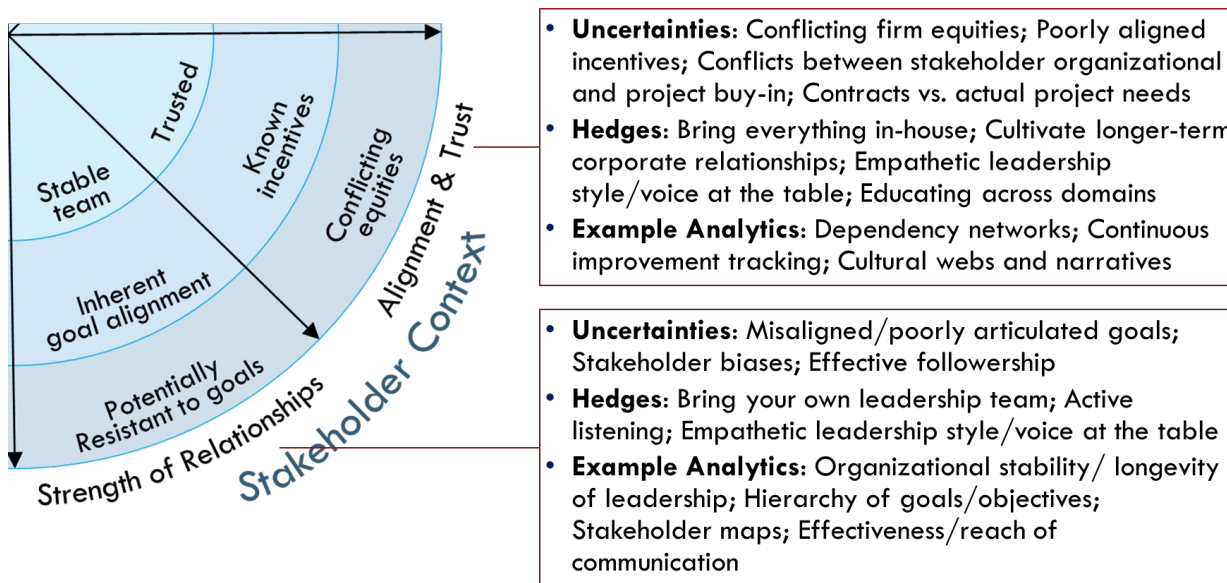


Figure 11. Uncertainties in the Stakeholder Context

MEGAPROJECT CASE STUDIES

Two historical case studies were analyzed and used as part of an observational study and to select analytical tools for megaproject planning and execution. This led to an approach to use the Megaproject Uncertainty Framework as an assessment tool to be used to evaluate ongoing megaprojects. The assessment process was tested on the U.S. Army Future Long Range Assault Aircraft (FLRAA) project which was transitioning through DoD Milestone B (the transition from “think slow” to “execute fast” in megaproject literature). A set of assessment questions for each uncertainty dimension was developed and used both with literature and the Army program. This generated a set of lessons learned that were used to categorize 12 sets of “plays” in a potential playbook for megaproject management.

There are a large number of case studies of failed and successful megaprojects in literature. Most are associated with commercial megaprojects. We selected two exemplars, one from commercial and one from DoD, primarily because these two projects had the largest body of literature. The commercial project was the Heathrow T5 project, a shining example of a successful megaproject, while the DoD project was the Army Future Combat Systems (FCS), notable for its lack of success. These two projects allowed us to characterize the Megaproject Uncertainty Framework and formed the basis for our lessons learned study. The two case studies were presented at QRF 2.

THE HEATHROW TERMINAL 5 CASE STUDY

Heathrow T5 was a £4.2 billion infrastructure project at Heathrow Airport, London, with the project started in November 2001 and the terminal opening in 2008. The T5 project was Europe’s largest and most complex project, it included 16 major projects and 147 subprojects. At any one time, the project employed up to 6,000 workers and as many as 60,000 people will have been involved in the project over its lifetime. The goal of the project was to increase the airport’s current capacity of 67 million passengers a year to 95 million passengers a year.

British Airports Authority (BAA), the project management organization leading the project, developed a whole new approach to project management and project delivery to deliver T5 safely, on time and within budget. Much of this focused on new ways for managing the Strategic and Stakeholder Contexts for the project, in particular establishing an environment for more flexibility in supplier contracting and more pluralistic decision making across the supplier base. Some of these are shown in Figure 12.

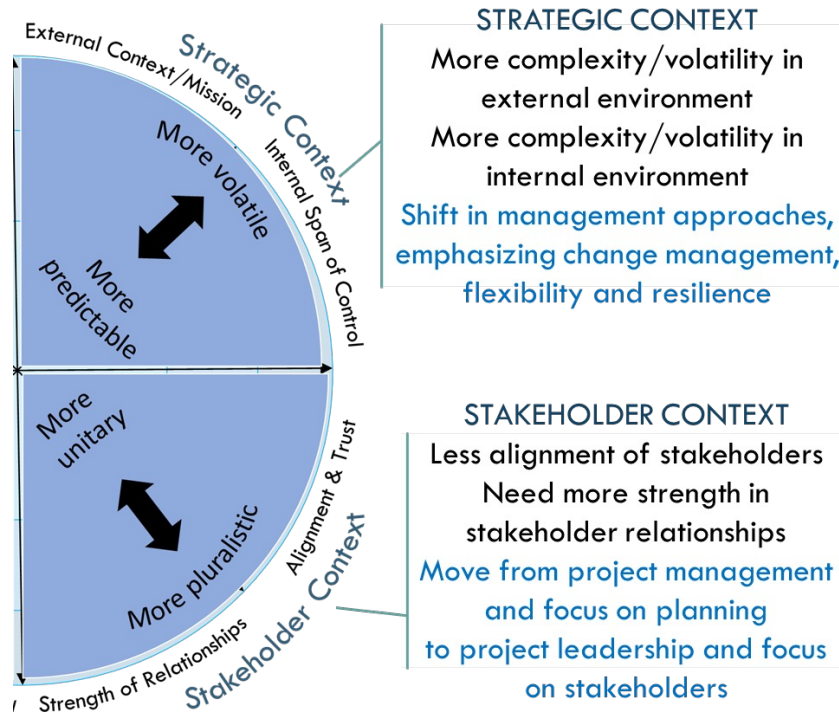


Figure 12. Strategies in the Strategic and Stakeholder Contexts

BAA created its innovation in project management by learning from and recombining a variety of practices, technologies, and ideas already found on other projects (both within BAA and elsewhere) and in other industries. Partly facilitated by the long and drawn-out public enquiry into T5 (started in 1995) they were able to undergo a strategic program of learning and development to build up the necessary capability. BAA attempted to learn internally from within the group, from previous and on-going capital projects, externally from other worldwide airport projects, projects in other sectors, and leading-edge practices in supply chain management and project management.

Research by John Egan on the relationship between automotive and aerospace manufacturing and construction processes found that firms should focus more strongly on customer needs, integrating processes and teams, and on quality rather than cost. Under John Egan’s guidance, BAA’s senior managers began applying the principles laid out in the Egan report (1998) to improve BAA’s project processes and relationships with suppliers. By the late 1990s, BAA had made significant improvements to its project execution capabilities, reflected in a greater degree of predictability in terms of time, cost, and quality. There were four key strands to this: (1) developing new and improved project processes, (2) managing the supply chain, (3) standardization and pre-fabrication, and (4) integrated team working.

BAA built up internal capability through recruitment of world leading practitioners and external capability by the development of framework agreements tied to regular benchmarking to try to ensure continuous improvements in delivery performance.

With T5, BAA decided to bring in-house the tasks of systems integrator and project manager. They used a relational contracting strategy - the T5 Agreement (T5A) – to frame the inter-firm relationships with all the first-tier project suppliers. From a BAA's perspective, this strategy aimed to encourage the suppliers to move away from “business as usual” to a project environment where “we all continually challenge how we can be successful.”

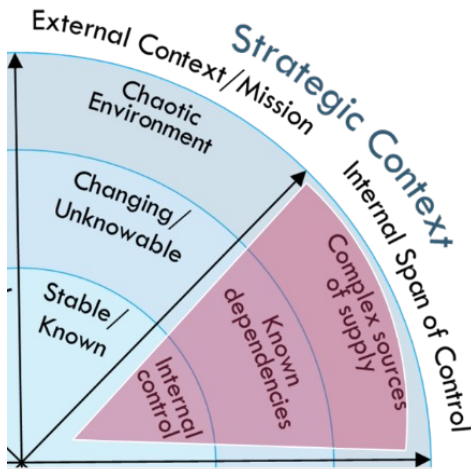


Figure 13. Internal Span of Control

One of the central features of the BAA approach is integrated team working. After the Heathrow Express Tunnel collapse in 1994, BAA chose to work with Balfour Beatty and the other main parties as partners to resolve the situation. A new contract was drawn up between BAA and Balfour Beatty which established what became known as ‘the single team’ in which all the parties worked as one team instead of a collection of separate project groups. The normal construction industry response would have been to go down the litigation route and place the blame on the main Contractor. Instead, BAA appointed a new Construction Director for the recovery project who demonstrated and promoted a culture of co-operation instead of rivalry. At one point, Heathrow Express was 24 months behind program, but eventually became operational only nine months after the original projected date.

The success of the Heathrow Express recovery project showed how partnering and trust could be made to work. 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. Much of the learning was channeled to further development of the CIPP and the integrated team working concept was applied to different clusters: the pavement team (for runways, taxiways, links and resurfacing); a team for baggage handling (clusters of suppliers); and cluster of suppliers for buildings (shell and core, fit out, etc.). The development of CIPP, the Framework Agreements, and integrated team working improved project predictability and repeatability.

BAA recognized that existing construction industry practices and its own project management processes could not cope with the complexity, scale, and risk associated with the project. BAA realized the only way to deliver T5 was to change ‘the rules of the game’ by creating a set of behaviors that allowed people to come up with innovative solutions to problems. The success of the Heathrow Express Recovery project demonstrated that such an approach could be successful. However, a more radical approach was needed to deliver T5, since a much higher level of uncertainty was involved.

The T5 experience follows a trend in successful megaprojects where complexity and uncertainty were addressed with innovation in both the system and the development and delivery processes. Across the internal project workings and supply chain, a culture of innovation and associated contract enablers for that encourage team working and pluralistic decision making, proactively working to solve problems as they arise.

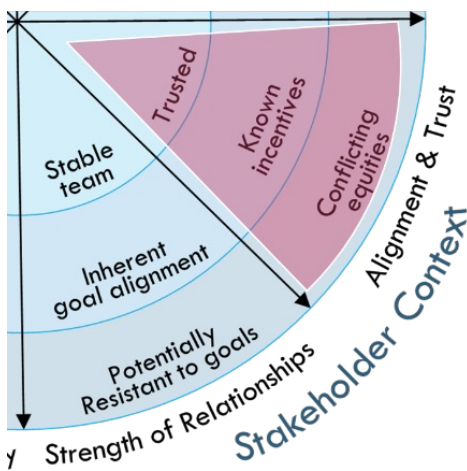


Figure 14. Alignment & Trust

In their planning studies, BAA identified two areas that would contribute to poor performance – poor collaboration and reluctance for project participants to assume responsibility for risk. Two main principles of team alignment and trust in the T5 approach stand out: the client always bears the risk, and partners are worth more than suppliers. These principles were embodied in the T5 agreement - a new form of contract developed by BAA which guarantees suppliers' profits while the client retains the risk.

A totally integrated project team was created between the client and suppliers. This was designed to mitigate conflicts between parties, which incentivized parties to collaborate and foster positive problem-solving behaviors. Suppliers, including architects, contractors, and consultants were co-located and requested to work together from the start of the project to manage risk, including with contractors who were traditionally competitors. During the construction of Heathrow's Terminal 5, the parties managed risk more collaboratively. The client, Heathrow Airport, held a comprehensive insurance policy to cover all risk. Risk was pooled into a program-wide 'risk pot' for each major component of the project to enable easier allocation based on need and greater financial control. This lowered the contractors' overall tender costs

with the risk managed actively by the entire team. It also underpinned the cultural approach which was one of partnership and transparency. BAA mandated 'open book' pricing, which involved looking in detail at suppliers' internal cost structures. Incentivization of all subcontractor pricing was necessary to achieve the intended outcomes. By using a target cost approach, contractors were aligned with BAA's goals to deliver the project successfully. The incentive fund was created from the target cost for the whole project and provided a commercial incentive for suppliers to improve on their agreed plans and increase their profit. Any outperformance against the target budgets for each sub-project was split between the contractor, BAA, and a contingency fund until the entire project was completed. Instead of a traditional client-contractor relationship, Heathrow treated the different partners like team members. It invited them to work together to solve complex issues during delivery and to help Heathrow find the technical solutions that worked best for the project as a whole.

This allowed all the parties to focus on finding ways to keep the project on schedule and within budget. That, in turn, helped the different companies meet their own obligations. This is similar to the successful alliance-contracting approach that has been used extensively in Australia on large projects, in which the project owner, designer, and contractor work under one contractual agreement to jointly deliver the project.

BAA managed conflicting equities through an integrated product team that worked together on-site and a relational contract (T5 agreement) for use with its tier 1 suppliers, including architects and engineering design consultants, and general and specialized contractors and manufacturers.

This model is familiar to DoD acquisition contracting, it was developed by looking at aerospace contracts. However, in the T5 megaproject, BAA had full decision authority over the supply chain and held the full risk pool. This is often split in DoD projects with the Lead System Integrator (LSI) managing the supply chain and the government holding the risk pool.

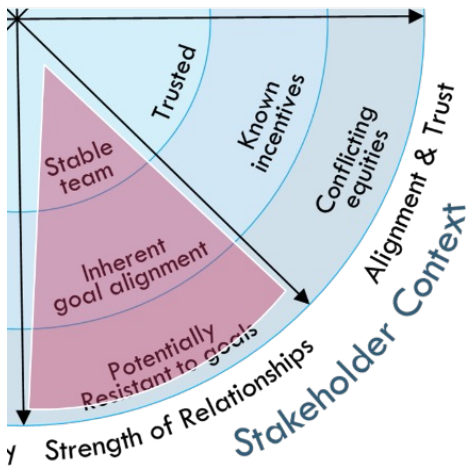


Figure 15. Strength of Relationships

BAA deemed the T5 Agreement fundamental for encouraging the T5 suppliers to achieve “exceptional performance (...), new standards, both in the building of the facilities and in the built facilities.” Hence, the T5 agreement – the “absolute bedrock of getting the relationships right” in BAA terms – aimed at creating incentives for “positive problem-solving behaviors that would not allow things to go wrong in the first place”. It discarded confrontational clauses seeking to pass the blame and recover money from suppliers if things went wrong. In its contract with the tier 1 contractors, BAA stipulated its expectations on how tier 2 suppliers were to be engaged to ensure that its approach was carried downstream throughout the project supply chain.

For example, when T5 construction started in July 2002, Laing O’ Rourke (LOR) Civil Engineering Ltd. 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.

The strong leadership of BAA’s CEO was key to the T5’s success, with the ability to create a coherent vision aided by the use of key performance indicators to measure success. Organizational change programs also helped lead this mega-project to accomplishment. In addition, the in-house project management capability of BAA was an important consideration in the success of the delivery model. BAA was able to establish a consistent leadership team and a “T5 culture” that emphasized problem solving and rewarded innovation and deconfliction of work that spanned the entire 7-year project. In contrast, this consistency of leadership at both the government and LSI levels is seldom seen in DoD megaprojects.

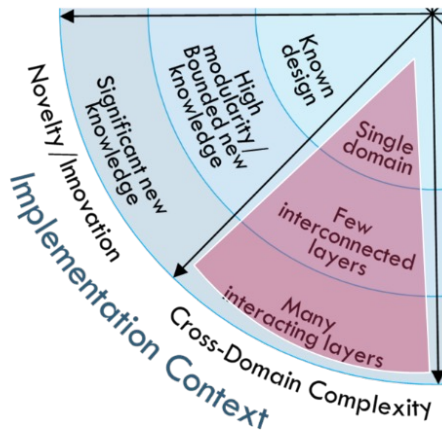


Figure 16. Cross-Domain Complexity

This does not mean that the T5 project lacked technical challenges. T5 is a “system of systems (SoS)” 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 multistory car park, and a hotel. During the design phase, BAA introduced advanced digital technologies and continued to improve its project management capability. T5 involves 180 IT suppliers and ran 163 IT systems, 546 interfaces, more than 9,000 connected devices, 2,100 PCs and “enough cable to lay to Istanbul and back”.

During construction, it was projected to contain 175 lifts, 131 escalators and 18km of conveyor belts for baggage handling. [British Airways CIO Paul] Coby says that even the construction of T5 involved: “creating a small town with a full telecommunications network for the construction workers, merely to enable the terminal to be built.” The Heathrow T5 project was a megaproject constrained by a very difficult logistics and construction environment based on location and use. It had a very long planning period, which the lead system integrator

(LSI) used to devise a different approach to manage the traditional complexity of supplier relationships and uncertainties on a complex construction site. It was not particularly driven by technological uncertainties but made use of emerging technologies to reduce risk in the construction. The team made great use of offsite staging of construction segments to minimize the number of people and resources on the site.

The roof on the main building of Heathrow’s Terminal 5 was completed in March 2005. Given that at 400 by 150 meters, this is the largest single span roof in Europe, it was a tricky operation. The six sections each weighing 2,500 tons had to be jacked up over a 10-month period. To minimize any chance of mishaps, BAA did a dummy run in Yorkshire to see whether the concept was feasible. According to Mike Forster, the BAA’s development and design director, the test in Yorkshire, which cost £2.4m ‘saved three months work on the Heathrow site and taught us all kinds of things about tolerances and sequencing’.

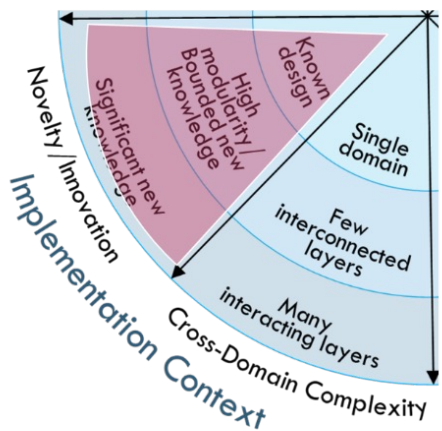


Figure 17. Novelty/Innovation

Digital design and management technologies enable co-ordination of design, construction, and integration as well as virtual testing of components and systems. BAA hired Excitech as the computer-aided design (CAD) and asset management consultant. A single-model environment (SME) using standard 4D Building Information Management (BIM) software replaced 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. This helped 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. Excitech’s 9-person team worked with over 25 separate design teams including education and cultural transformation. 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). Efforts were made to learn from other firms that had pioneered SME visualization technology. 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.

The trial and testing regime involved favoring already-established technologies, to lower research and development (R&D) costs. Any 'new' technology was first tested on BAA's smaller airports. 70% of mechanical and electrical engineering components were manufactured off site.

Despite the innovative processes, the T5 project still had major issues at the opening of the terminal. 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." However, these careful preparations did not prevent problems from arising during the opening of the terminal. Several factors contributed to the chaotic opening, but the root cause of the problem was the decision to press ahead with the opening in the knowledge that British Airway's (BA's) staff had insufficient training and familiarity with the terminal's facilities and baggage handling system.

The problematic opening of T5 could have been avoided through "better preparation and more effective joint working" between BAA and BA. However, delaying the opening did not make sense, as the cost to British Airways of delaying would have been "significantly greater than the cost incurred as a result of the problems that we encountered in the first few days."

The T5 project demonstrated the power of digital integration of systems and workflows and led to future initiatives in the UK such as the BIM Task Group and Digital Built Britain that provide standards for digital integration across public sector projects. The DoD is attempting a much broader use of digital methods for collaboration and teaming with its Digital Engineering Strategy.

Summary: The T5 project will long be viewed as a success due to the unique "T5 Agreement" which incorporated unheard of (at the time) flexibility into the supply chain and contracting relationships. It was transformational (in its industry) in its project management approach, but less transformational in its system context than many megaprojects that are also mega-systems. It pioneered use of CAD models and BIM as a digital means for transparency and collaboration in design. Unlike typical DoD megaprojects, the T5 project had relatively little direct government participation and oversight once it was given go-ahead, and BAA as primary investor was free to set requirements and manage the supply chain as they saw fit. It finished on time and under budget, although significant technical problems with installed systems had to be corrected after the terminal opened.

THE FUTURE COMBAT SYSTEM (FCS) CASE STUDY

FCS was selected both as a megaproject and because it accentuated the mega-system aspects of the uncertainty framework, noted in the Executive Summary as Figure 2.

As shown in Figure 18, these drove the left-hand side of the uncertainty framework (system context and implementation context) to focus less on the scale of the megaproject and mega-system, and more on the “scale of impact” that might be realized. FCS had major uncertainties in all eight dimensions of the framework, but its failure is probably mostly attributable to the transformative nature of the project goals – the difference between imagined scale of impact and reality. It is a good illustration of uncertainties in the system and implementation contexts.

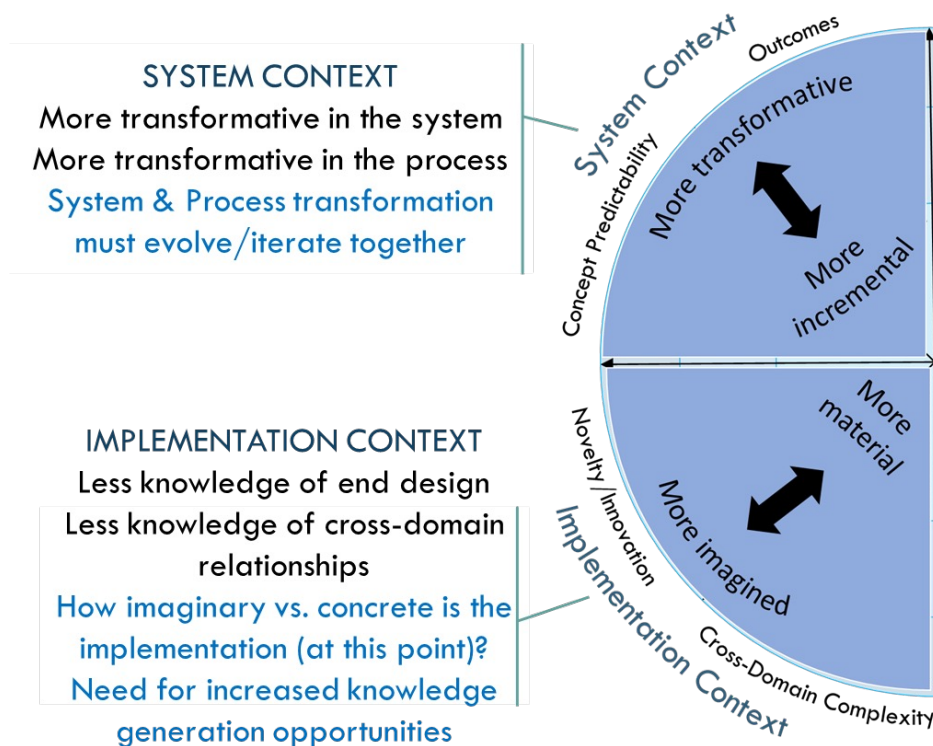
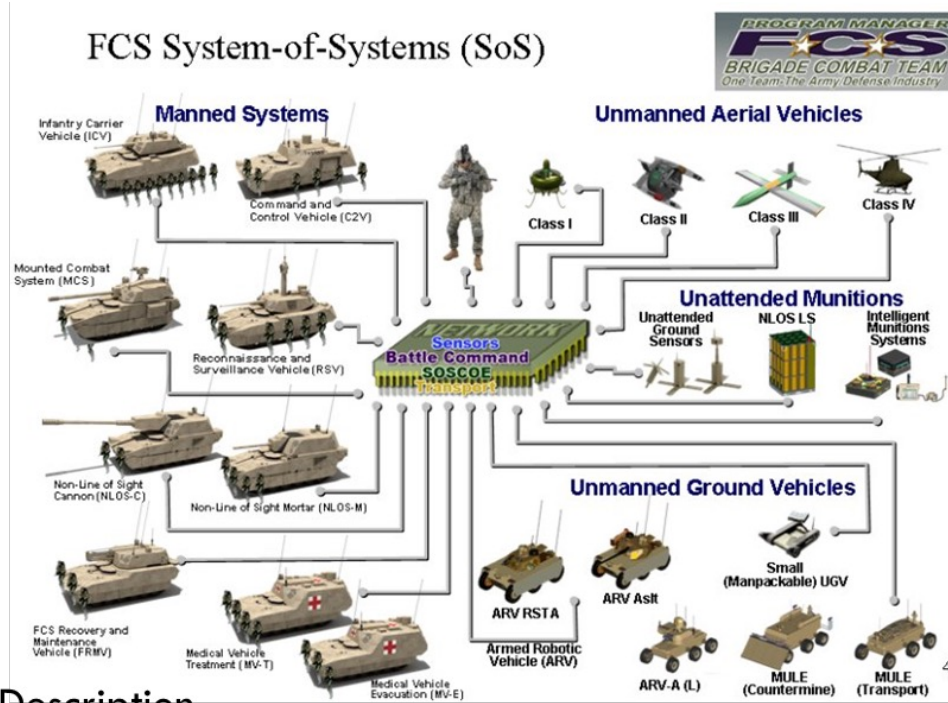


Figure 18. Strategies in the System and Implementation Contexts

The FCS project started as an exploratory project driven by a vision of modularization of Army forces into Brigade Combat Teams. In January 2000, the FCS Army Analysis Integrated Product Team (AIPT), sponsored by the FCS Program Manager of the Defense Advanced Research Projects Agency (DARPA), initiated a unique analysis that was largely a collaboration of Army analytic organizations and the four industry teams contracted by DARPA to perform FCS concept exploration and design. From April 2000 to October 2001, industry and Army analysts worked side-by-side to evaluate emerging concepts for FCS. This effort helped shape the concepts of the Army and the FCS Lead System Integrator (LSI) and was foundational for the Analysis of Alternatives (AoA) conducted during FCS Concept and Technology Development (CTD). From May 2004 to October 2004, the AoA Update analysis built upon the innovative methodologies wargamed and modeled in the AoA and Key Performance Parameter (KPP) analysis. More than 2,000 total scenario hours were simulated for the record, and 10,000 more were devoted to preparation and analysis support. A diverse and highly qualified study team from across the Army, supported by Federally Funded Research and Development Centers (FFRDCs) and industry and led by the FCS Lead System Integrator, performed the update. It was further distinguished by its inclusion of the FCS LSI. These helped establish the transformational vision of FCS. The FCS Family of Systems is shown in Figure 19.



Description

- 1) FCS will consist of a **family of** advanced, networked air- and ground-based maneuver, maneuver support and sustainment **systems**.
- 2) It employs a **revolutionary**, integrated **architecture** to help meet the future Joint and Army commanders' requirements.
- 3) The FCS-equipped brigade encompasses more than a new set of capabilities; this organization reflects a **fundamentally transformed method of combat**.
- 4) The FCS program is the **centerpiece of DOTMLPF** (doctrine, organization, training, materiel, leader development, personnel and facilities) solutions for the Future Force.

Figure 19. Strategies in the System and Implementation Contexts

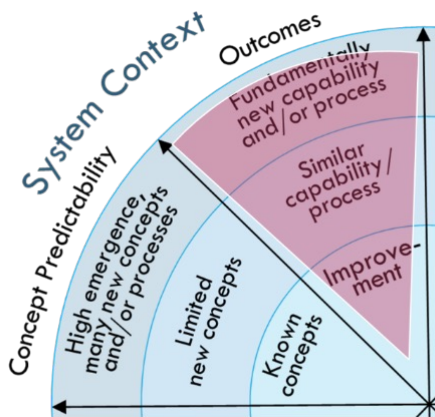


Figure 20. Outcomes

The concept of air mechanization was a significant departure from prior Army schemes of maneuver, and with it came considerable technological, operational, and financial hurdles that would need to be overcome.

The fact that “the Army had sat on the sidelines during the successful 78-day air campaign over Yugoslavia, never sending a single unit into combat” drove urgency of the program and request for more transformational capabilities. The Army envisioned a transformational set of technologies that would make the Army “light enough to deploy, lethal enough to fight and win, survivable enough to return safely home . . . to sustain themselves whatever the mission.” The new force structure would consist of lighter, more mobile manned, unmanned, and robotic vehicles designed to track and outmaneuver enemies through effective information sharing.

These weapon systems were to be a fraction of the weight of current weapons, yet as lethal and survivable. FCS’ lightweight and small size were critical to meeting the Army’s goals of deploying faster and being more transportable for big or small military operations. (C-130 Transportable). Rather than rely on heavy armor to withstand an enemy attack, FCS’ systems were to be designed to depend on superior communications to kill the enemy before being detected.

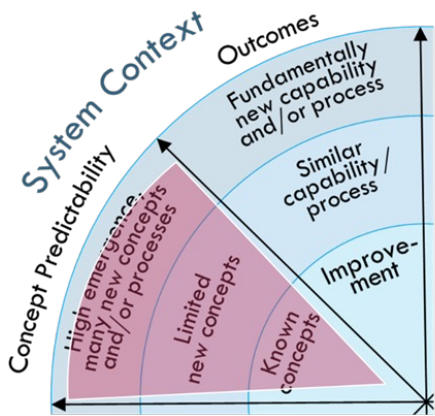


Figure 21. Concept Predictability

The FCS concept represented a significant change to current Army operational concepts. “Fundamentally, the FCS concept of operation was to replace mass with superior information—allowing soldiers to see and hit the enemy first rather than to rely on heavy armor to withstand a hit. This solution attempts to address a mismatch that has posed a dilemma to the Army for decades: the Army’s heavy forces had the necessary firepower needed to win but required extensive support and too much time to deploy while its light forces could deploy rapidly but lacked firepower. If the Future Force becomes a reality, then the Army would be better organized, staffed, equipped, and trained for prompt and sustained land combat, qualities intended to ensure that it would dominate over evolving, sophisticated threats. The Future Force is to be offensively oriented and will employ revolutionary concepts of operations, enabled by new technology. The Army envisions a new way of fighting that depends on networking the force, which involves linking people, platforms, weapons, and sensors seamlessly together in a system-of-systems.”

If successful, the FCS system-of-systems concept would integrate individual capabilities of weapons and platforms, thus facilitating interoperability and open system designs. This would represent significant improvement over the traditional approach of building superior individual weapons that must be retrofitted and netted together after the fact. This transformation, in terms of both operations and equipment, is under way with the full cooperation of the Army warfighter community.

“When technology permits, we will erase the distinctions which exist today between heavy and light forces,” transforming the Army into a “strategically responsive force that is dominant across the full spectrum of operations.”

Army's view hinged on exploiting changes in military information technologies to change the way the Army would fight. The Army developed the Force XXI concept through deliberate experimentation and unit design reviews, and installed a technological focus in the conceptual model offered by U.S. Army Training and Doctrine Command (TRADOC). The TRADOC model was evolutionary in title but recognized the at times revolutionary effects technological developments might have on an Army when seen in retrospect.

Wargames were used to showcase new operational concepts. In the strictest sense, these games cannot be considered "experiments." Rather, they were opportunities to vet and discuss possible new Army systems and operational concepts through the development of insights and issues. The assumptions made by the Army concerning the future environment were critical to the design and operation of the FCS. These wargames focused on high-intensity conventional combat with the United States (and its coalition partners) fighting against an aggressive, well-armed regional power, this changed in 2004 with the Global War on Terror (GWOT). A key feature in all of the AAN/Objective Force games was the assumed need to commit ground forces (in particular the Army) very early in a crisis. A fundamental assumption was made that very high-speed deployment and immediate engagement of Army forces was required to preclude the enemy from "setting" into defensive positions.

Army AAN/Objective Force thinking about "situational awareness" largely mirrored broader DoD assumptions that future U.S. forces would have unprecedented levels of knowledge of their operational environment. The optimistic assumptions of tactical-level (including down to the company and platoon echelons) situational awareness seemed to enable the use of lightweight FCS vehicles. A light force that would be much more deployable and yet be as lethal and survivable as a heavy force was so powerful an idea that it became the dominant theme.

This transformation, due to its complexity and uncertainty, was scheduled to take place over the course of three decades, with the first FCS-equipped objective force unit reportedly becoming operational in 2011 and the entire force transformed by 2032. In order to mitigate the risk associated with the Objective Force and to address the near-term need for more deployable and capable units, the Army's transformation plan called for the development of brigade-sized units called the Interim Force in both the active Army and the Army National Guard. These Interim Brigade Combat Teams (IBCTs) were the predecessors to the Army's current Stryker Brigade Combat Teams (SBCTs).

The FCS program suffered from a mismatch in the transformative goals of the vision of the program, and the ability of technologies (and budgets) to realize that vision, and the processes for defining and scheduling a Major Defense Acquisition Program.

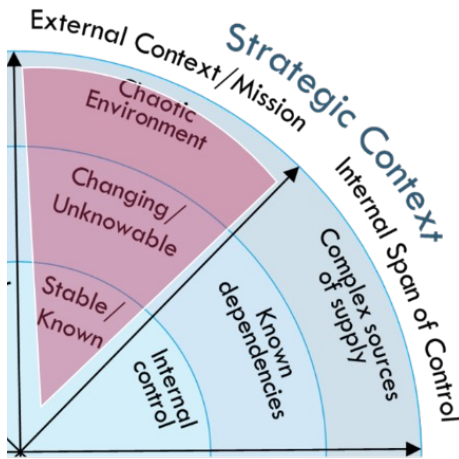


Figure 22. External Context/Mission

However, the DoD Joint Capabilities Integration Development System (JCIDS) process was still used to define the requirements for the system – an equivalently transformational process was needed. By frontloading ambitious requirements on the vehicle, it made the vehicle the core engineering challenge from the outset. In hindsight, the network, which was the sine qua non for the system of systems and would have underpinned the vehicles’ revolutionary capabilities, was the first and more basic technical hurdle.

In order for the operational concept to work theoretically, C-130 transportability had to be assumed. Where does a mismatch between core operational concept and what can actually be implemented show up in the megaproject management domain? This is where the concept to business case outcome (benefit) was flawed from the start.

Insufficient analysis and mismanagement of expectations can lead to unrealistically ambitious requirements. These shortfalls resulted partly from the fact that the operational requirements document (ORD) was developed in a hurry, with too little technical analysis or understanding of how lower-level

requirements would integrate in order to achieve higher-level ones. Since this was the largest integrated set of requirements the Army had ever developed, it was extremely difficult to analyze and understand precisely how all of them would interoperate. Compressing the amount of time allotted to reach such an understanding did not help.

Early support for the FCS program was significant from the highest levels within Army leadership and aided in calling a large and complex program into existence quickly. The drive to move FCS forward permeated the program, as pressure mounted to meet early timelines and aggressive requirements. In the end, the senior-level involvement was both good and bad for the program, negatively affecting its ability to flex in light of information about technological challenges. Lack of progress and congressional pressure put the acquisition environment in a constant state of change. This resulted in a number of megaproject lifecycle shifts and a state of constant engineering change proposals, as shown in Figure 23.

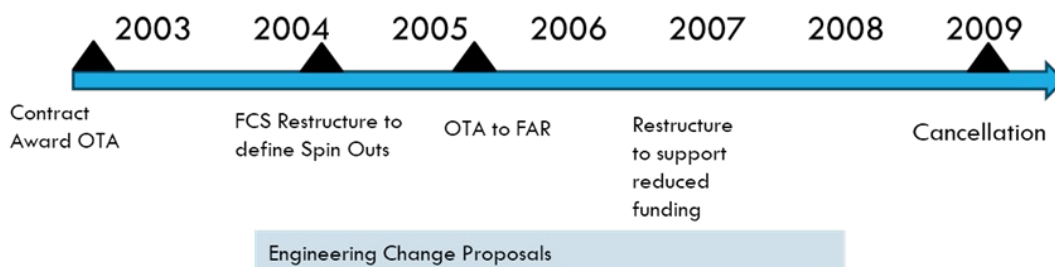


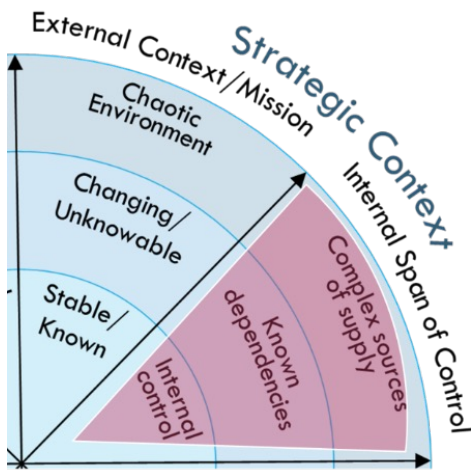
Figure 23. FCS Lifecycle Shifts

Major program shifts can cause significant turbulence and erode support for an acquisition program. The FCS program experienced turbulence as a result of multiple major Army decisions to restructure it as knowledge was gained and as operations in Iraq and Afghanistan evolved. The program was restructured two times in significant ways, changed contract types, and added “spin-outs,” all of which made more difficult an already ambitious acquisition program. These shifts, and others, made the FCS program difficult to understand and tough to manage, and in many ways sacrificed internal and external support for the effort.

Equally problematic, from a requirements perspective, were the ambitious expectations that many officials built up to Congress and the public early in the program. A common grievance was that the “propaganda campaign” rapidly outpaced delivery, making it difficult for program officials to backtrack on promised capabilities and for the user community to relax requirements.

There was significant turmoil between the vision for the program, the program requirements which are equally technical and contracts driven, and the external oversight including cost and schedule assumptions and budgeting. From the perspective of people working on the program, there was an overabundance of chaos in the contracting aspects of the effort, with numerous change proposals and reevaluation of program plan and scope. This created a great deal of uncertainty across the supplier teams.

In early March 2002, DARPA selected the Boeing/SAIC team as the LSI, giving it just over a year to prepare for Milestone B.



The Army also established a traditional Army Program Management Office to execute its oversight responsibilities. The Army’s program management strategy included enhanced oversight mechanisms for Office of the Secretary of Defense (OSD) authorities.

The Army identified three primary advantages of using the Boeing/SAIC limited LSI: access to larger pools of talent in industry, the ability to hire talent much more rapidly and efficiently, as well as the ability to award and manage multiple large technical support contracts. The Army prohibited the LSI parent organization (Boeing) from competing for any subcontracts beyond the system integration technology (System of Systems Common Operating Environment) in order to prevent conflicts of interest in second-tier competition by the LSI. A theme found throughout this study was that the Army’s intent for creating FCS was correct, but the execution was riddled with far too many challenges.

Figure 24. Internal Span of Control

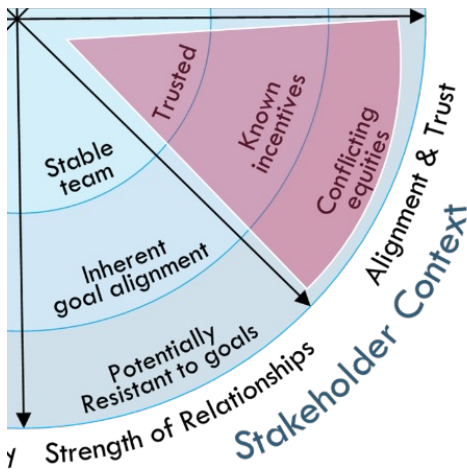


Figure 25. Alignment & Trust

Government control over significant elements of the SoS may make incentive fees inappropriate. The FCS program structure made it difficult to award the LSI less than all available performance fees. The government retained such significant control over so many of the factors that would affect FCS SoS behavior (doctrine, organization, training, system-level requirements) and because it was embedded into the integrated product team (IPT) structure with some level of authority, the LSI could always point to government actions as a proximate cause of performance issues. Performance incentives that are not tied to actual product performance may not result in effective outcomes. The ambitious performance goals and aggressive schedule for the FCS program destined it to unstable requirements. Performance incentive fees based on actual product performance cannot be realistically drafted when product requirements cannot be fixed. As the FCS case demonstrates, significant performance, cost, and schedule uncertainty needs to be mediated through contract design. This means that award and fixed fee contracts are preferable in these cases over incentive contracts. Early commitment of incentive fee reduces the available fee late in the program. Early commitment can also significantly reduce the government’s ability to motivate contractor behavior as the program enters final design and test and moves to production.

In contrast to the Heathrow T5 project, the use of fees and incentives did not serve to encourage teamwork and pluralistic decision-making, and were not employed to reduce risk on the effort.

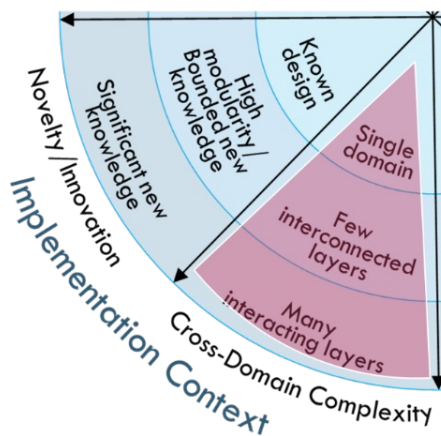


Figure 26. Cross-Domain Complexity

The Army plan included interoperability with dozens of “Complementary Programs”, some existing and some in development, that would need to be integrated into the future architecture. These added a number of dependencies and further complexity to the project. FCS was to consist of a family of advanced, networked air- and ground-based maneuver, maneuver support and sustainment systems. It employs a revolutionary, integrated architecture to help meet the future Joint and Army commanders’ requirements. Net-centric operations wherein the force is realized through the network.

A key element of the US Army’s transformation is the future combat system and objective force (FCS/OF). The FCS/OF will operate as a cohesive, mobile, lethal, survivable, and sustainable land combat force capable of rapid deployment and immediate employment upon arrival and able to defeat threats in the 2010-2025 timeframe.

It was a critical assumption that, like the C-130 requirement, tied together the underlying concept, theoretically enabling the development of vehicles that were not only lightweight but also lethal and survivable.

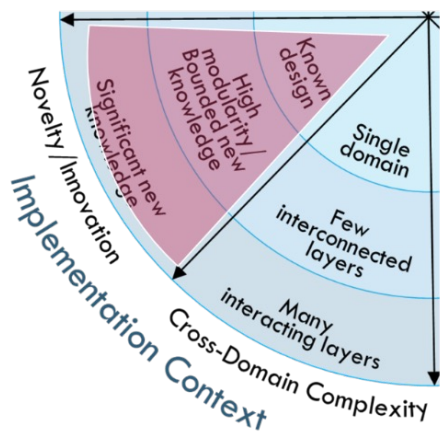


Figure 27. Novelty/Innovation

In addition, significant technology development should not occur late in acquisition programs. Technical development must be rooted in exploratory basic science and advanced development programs validated by early and realistic field experimentation with real products, and not in system development and demonstration (SDD) phases of major acquisition programs.

A 2007 Government Acquisition Office (GAO) report highlighted significant technology readiness concerns including the planned lightweight armor and active protection solutions, both critical to the Army's light forces concept. In addition, the program was dependent on technology development in its complementary programs – the JTRS and WIN-T radios – both of which were undergoing technological issues forcing additional development. In addition, there were major risks in the software development effort which the GAO report had noted had doubled in lines of code since the program's inception.

The cross-domain complexity factor highlights integration risk which occurs at the interface between systems and subsystems, while the novelty/innovation factor highlights the newness of the technologies and other implementation drivers along with the program's growth in knowledge of these innovations. As noted in the 2007 GAO report, the program still had large uncertainties in both of these factors. FCS depended on complementary programs for its networking capabilities, both of which were still in development and on the critical path to program success. A number of critical technologies were not matured, and the number of new technologies needed to execute the program were quite large. In particular, in megaprojects placing multiple technological developments on the overall project critical path should be avoided.

A widely cited success of the FCS program after it passed Milestone B was that Army TRADOC embedded official representatives throughout the LSI, its subcontractors, and Army Materiel Command facilities to help manage the effort.

The Army also established a traditional Army Program Management Office to execute its oversight responsibilities. While the LSI led the FCS system-of-systems integration, the Army PM Office maintained overall responsibility for several key activities including, but not limited to, defining operational and SoS requirements, performing overall program management and resourcing, managing the program's acquisition strategy, managing program-level cost, schedule, and performance, managing test and evaluation, and coordinating all other government agencies supporting the FCS.

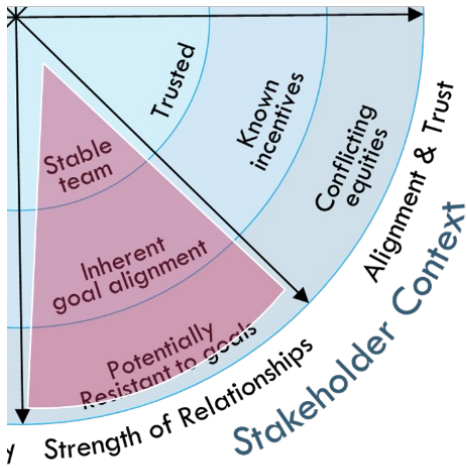


Figure 28. Strength of Relationships

The FCS established an Advanced Collaborative Environment (ACE) to provide transparency across program stakeholders. The ACE would host program documents, simulations scenarios, and virtual prototypes. It provided a single access point for program management data on risk, schedule, and technical performance. It was intended to provide up-to-date information on all aspects of program health. The ACE would provide a capability for real-time collaboration within and between the Army, OSD, contractors, and other FCS program participants. The ACE was therefore an essential tool for achieving the program's One Team approach.

Although there is not (that we could find) a historical account reflecting strength in leadership across the program, a number of lessons learned indicate the conflict between the overall vision of the program and the documented requirements for the program negatively impacted goal alignment.

Summary: The FCS program was a classic contemporary megaproject/ mega-system that envisioned highly transformative system of systems outcomes without a strong basis in reality. In the Systems Context, its end goals

were highly imaginary and its operational concepts were very transformational. This would call for a much more incremental approach to deploying systems which the Army changed to (spinouts) only after the program became inexecutable.

ANALYTIC METHODS TO EVALUATE MEGAPROJECTS

At this point the research team started to investigate a number of qualitative and quantitative analytical methods to help megaproject leadership assess uncertainties in their projects. These resulted in three areas of study:

1. Interview methods to address uncertainty in ongoing projects
2. Qualitative and quantitative modeling to capture knowledge and uncover uncertainties
3. Application of AI and visualization (AIVis) to abstract project structure, information, and knowledge for megaproject situational awareness

This section covers the interview methods and example questions, which were presented at QRF 3. The next section covers the AIVis prototype methods and tools, presented at QRF 4a, and a later section will cover the modeling approaches, which were not presented at a QRF but were studied to inform future research.

USING THE MEGAPROJECT UNCERTAINTY FRAMEWORK AS A PROJECT ASSESSMENT TOOL

The initial derivation of the project uncertainty framework was to develop an assessment tool to help megaprojects understand and manage their uncertainties. This was done through a set of questions that were used to derive uncertainties and strategies broadly from literature on megaprojects and also as an interview method to address currently executing projects. The FCS and T5 programs had the largest body of detailed lessons learned documentation. To test the framework in an ongoing megaproject, the team also conducted interviews with leadership on the U.S. Army FLRAA program. This provided a unique opportunity to assess a live program right as it is scaling from planning to execution phases. Sample questions for each area of the megaproject uncertainty framework are summarized in Table 1.

Table 1. Using the Uncertainty framework as an assessment tool.

Uncertainty Dimension	Sample Questions
Strategic Context: External Context/ Mission	<ul style="list-style-type: none"> • How would you characterize political/funding uncertainties for the program? • How certain or uncertain are overall project resources (funding, staffing, etc.)? • How aware are senior decision makers of the uncertainties that may affect the program? • What external disruptions to the program have you evaluated? In what timeframe?
Strategic Context: Internal Span of Control	<ul style="list-style-type: none"> • What are the subcontracting relationships? How is the contract structured? • Was a sharing of risk part of the contract structure/ down-select criteria? • How are contract incentives used and to what tier of the supply chain? • How are contractors engaged to address uncertainties as they arise?

Uncertainty Dimension	Sample Questions
System Context: Outcomes	<ul style="list-style-type: none"> • What fundamentally new capabilities will exist when this system is deployed? • What have you learned from prototypes and how will you use that learning? • What rough percentage of the total program cost has been spent on early stage engineering? • What data/metrics are most valuable in evaluating uncertainties in key performance attributes?
System Context: Concept Predictability	<ul style="list-style-type: none"> • What is the top-level concept of the program and how will it impact the mission? • What other new operational concepts will be enabled by these systems? How transformative are these (over current capabilities)? • How will current operational concepts be improved by these systems?
Implementation Context: Novelty/ Innovation	<ul style="list-style-type: none"> • What capabilities are new/must be developed and what capabilities exist today? • What is the current level of knowledge for each of these new capabilities? • Can you easily divide the technical risks into individual modular sub-projects? • What low technology readiness levels currently worry you the most?
Implementation Context: Cross-Domain Complexity	<ul style="list-style-type: none"> • Are there developmental dependencies on other programs? • Are there mission dependencies on other systems that provide capabilities? • How are the relationships between the program and external dependencies modeled?
Stakeholder Context: Strength of Relationships	<ul style="list-style-type: none"> • How is information on the current state of project assumptions and uncertainties disseminated across the government and suppliers? • How is knowledge shared across government/ contractor teams? Can you describe a knowledge sharing activity? • How are senior leadership trained to manage megaprojects? Is there unique training and to what level? What leadership characteristics are emphasized? • How was the evaluation of knowledge and experience used to form the team? Who (or what?) are the primary “hubs” of knowledge on the program?
Stakeholder Context: Alignment and Trust	<ul style="list-style-type: none"> • How often are senior leadership changes made? Government & contractor? • Is there a shared project “vision”? How is this communicated? Who promotes it? • How does program leadership arbitrate conflicts across the contractor teams? • Is there a common system to disseminate and access program data and information? Who has access to it? • What data/metrics are most valuable in evaluating stakeholder alignment across the supplier base?

The details of the answers to these questions are not included in this report. Instead, the results were used to feed into a set of megaproject lessons learned and the associated playbook described in a later section.

DATA, AI, AND VISUALIZATION

CHARACTERISTICS OF DATA, INFORMATION, AND KNOWLEDGE IN PROJECT VISUALIZATION

In project management, visualization tools allow the mapping of large amounts of data to visual attributes that aid human information processing. Project management applications are concerned with visualization of data, information, and knowledge, all used to improve the decision making of project leadership. We found very little literature that addresses the role of AI and visualization in project management. One exception is “Applying Artificial Intelligence to Project Management” by Paul Boudreau (independently published, 2019) which notes some of the technological outcomes he predicts include:

- Searching through project documents and reports to find incomplete or misleading or otherwise hidden data
- Predicting multiple courses of action for project success
- Analyzing project implementation strategies for disconnects areas of conflict
- Continuously guiding management decision-making strategies
- Optimizing resources and supply chains and tracking resource risks
- Constantly reevaluating uncertainties, assumptions, and risks as they evolve
- Monitoring project communications for areas of stakeholder misalignment
- Generating targeted messaging for critical stakeholders

There are thousands of project management tools and associated visualization forms that support decision making in project management. Current project managers have access to and must manage large quantities of project data and associated visualization forms for project reporting, project collaboration, and facilitation of team decision making. Examples include work breakdown structures, organization charts, Gantt schedule charts, PERT charts for integration planning, team collaboration calendars, staffing curves, tables of key data, progress histograms and aggregate trend charts, pictorial diagrams of key system components, wiring diagrams of interfaces, conceptual diagrams of process flows, value stream maps, risk categorization and prioritization, and accompanying narrative explanations. As standalone artifacts these represent data and information. Project views used to manage the effort must consider the project as a boundary, but also the larger enterprise as a boundary, in a combined project/enterprise decision space. 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. These might be categorized as knowledge-driven versus information-driven decisions. In complex projects, exchange of knowledge and creation of appropriate social networks for exchange is often more critical than information. How the network of decision-makers use data, information, and shared knowledge is paramount (McDermott & Freeman, 2015).

A paper “book” or graphics in a “war-room” has been the norm in megaprojects, but today and in the future digital visualization tools and shared digital “truth” data should be the standard. Modern data collection, data warehousing, data analysis, and visualization tools are integrating traditionally standalone project management processes into tools that allow interactive visualization and data management. These tools include dashboards that support people, team, project, and enterprise level views of the project. They place the data in a model-based framework for sensemaking that relates performance data to decision or process models which are more conceptual and in line with management heuristics. Computer visualization will improve traditional book-form or PowerPoint-based project complexity management.

In uncertain situations, leadership must “zoom out” as the decision process moves from established data-driven methods to higher levels of abstraction, then “zoom in” to select new data-driven methods and measures that have more relevance to the situation at hand. (Collins & Hansen, 2011) provided the “zoom out, then in” framing in their book, *Great by Choice*, describing such skills as the ability to sense and analyze change in the larger system, combined with the ability to focus in on plans and objectives for change. This mindset is essential to understanding the measurement constructs of a complex project and the process to build a data-driven visualization framework for decision making. The visualization approaches must first help leadership sense change in one of the myriads of project variables, then allow them to “zoom in” to analyze change details. AI, particularly LLMs, should be quite helpful in both sensing and selecting data for analysis (McDermott & Freeman, 2015).

Concepts of visual project management argue that managing the complexity of the data produced requires visualization of patterns that can be evaluated with speed and by multiple stakeholders (McDermott & Freeman, 2015). 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. AI creates the opportunity to see patterns with speed.

In complex situations one must choose patterns that maximize communication of insights and avoid propagation of entrained thinking. (Croll and Yoskovitz, 2013) advise when in domains of uncertainty to keep the following contextual data analysis patterns in mind. These form a top-level set of requirements for AIVis in the megaproject context:

- Qualitative/quantitative: qualitative data is unstructured, anecdotal, and hard to aggregate; quantitative data provides hard numbers but less insight. Correctly representing the type of data based on current context is important for meaningful communication. **The AIVis should be able to assess and evaluate predicted project performance based on both qualitative and quantitative information.**
- Prescribed/actionable: existing prescribed metrics might make you feel good or bad, but they don’t change how you act. Actionable metrics change your behavior by helping you pick a course of action. Make sure the data collected supports development of actionable strategies. **The AIVis should represent current and future courses of action (CoA) in easily explorable views.**
- Exploring/reporting: exploratory metrics are speculative and try to find unknown insights, while reporting metrics keep you abreast of normal, managerial, day-to-day operations. Most traditional project management tools focus on reporting metrics. Exploratory metrics are identified through “questions of interest” that attempt to define project issues and uncertainties and data is collected to help answer those questions. **The AIVis should allow for querying of both qualitative and quantitative data.** (LLMs are ideal for this.)
- Leading/lagging: leading metrics give you a predictive understanding of the future; lagging metrics explain the past. Data that reflects and can be tracked to confirm predictions of change must be used to inform change strategies. Contextual models that project historical data trends into the future must be developed for the project situation. **The AIVis should project both the current planning and future CoAs into future performance estimates.**
- Correlated/causal: project measures that change together are correlated, a measure that causes another measure to change is causal. Effective change strategies for dealing with situations in complex project management must be careful to find causal bases for change. **The AIVis should be able to explain the basis for its aggregated project measurement and status reporting.**

What separates the megaproject leader from a traditional project manager is the ability to recognize change patterns and facilitate team social interactions that result in knowledge exchange and selection of new project planning and execution CoAs (McDermott & Freeman, 2015). The Megaproject Uncertainty Framework categorizes these patterns at a high level.

In this research, we investigated two prototype display methods that take advantage of AIVis to offer significantly new approaches to meet the top-level requirements noted above. The Train Metaphor Megaproject Management Display introduces a metaphoric display, the train metaphor, illustrating project progression amidst challenges and milestones, allowing exploration of current and future CoAs. The Mega-Project Uncertainty Framework Dashboard visualization transforms the Project Uncertainty Framework into an information-rich interactive dashboard integrating qualitative and quantitative information.

THE TRAIN METAPHOR DISPLAY

The first visualization concept 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 29 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.

A metaphor display is a user interface that represents a very complex topic, challenging to visualize directly, by mapping attributes of the topic to attributes to something generally familiar to most users. For example, the security of a computer network with respect to cyber domain threats could be mapped to the physical security of an apartment complex.

Visualization of the complex phenomena of interest in mega-project management is a challenge. A number of potential metaphors were explored 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. The text below describes the implementation of the metaphor as related to typical megaproject components of interest.



Figure 29. Train Viewport

There are various components of this view to explain further, in order to illustrate the metaphor. To start, the right-side panel hosts critical information about the train itself. Information such as the active milestone the train is undertaking, the current weather, the amount of fuel (funding) left, and a list of the cars themselves. The fuel level is based on the number of coal cars currently on the train, with each one giving an arbitrary funding allocation of \$10 billion. Moreover, at the bottom of the screen there is a sliding bar with a “Stop” button which represents the speed control of the train. In the center is the viewport containing the model of the train, its cars, and its route. The different cars and components (such as the weather) will be discussed in later sections.

INFRASTRUCTURE

The train metaphor infrastructure visualization uses tracks to show planned project paths, with color and texture indicating status. Key elements include the rail yard for component origins, the main terminal as the final destination, depots for potential outcomes, switches for milestone decisions, bridges for external approvals, and tunnels for periods with limited visibility into progress. This is illustrated in Figure 30.

- Tracks show the planned paths of different parts of the project. Once underway, track color and texture represent status (e.g., yellow = behind schedule).
- Rail yard shows the origin of project components.
- Main terminal is the ultimate destination.
- Other depots represent possible other destinations (like Cancellation Depot and Half a Loaf Depot).
- Switches represent major milestone decision points.
- Bridges represent required passages through external wickets (need a better word) such as regulatory or legislative approval.
- Tunnels represent periods in project performance in which there is limited visibility to progress.

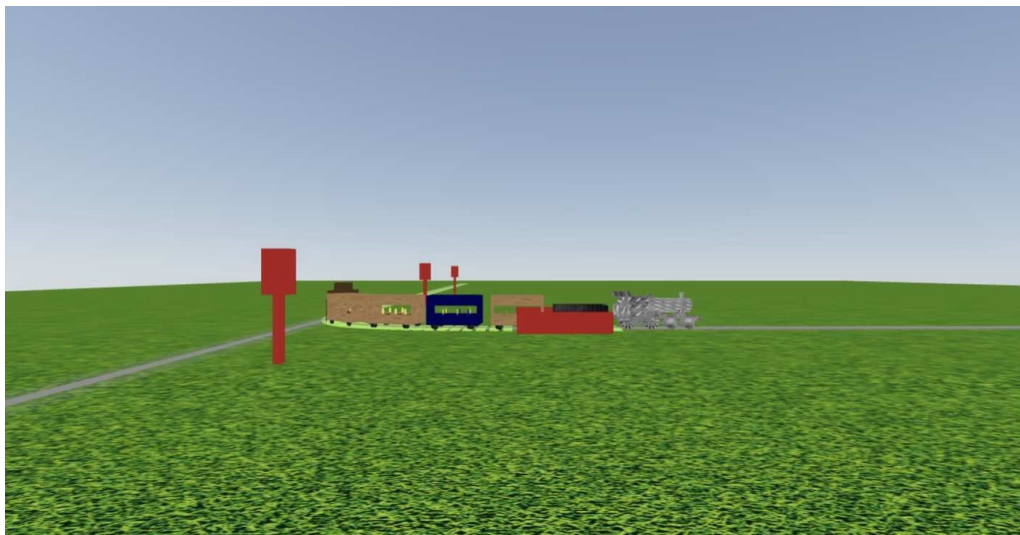


Figure 30. A train at a train station

TRAIN

An individual train represents a project with some mega-projects having multiple trains. Key components include the engine for engineering leadership, coal cars for funding, freight cars for development efforts with visual cues for progress, passenger cars for stakeholders, and the caboose for project management and support functions. Any train can have any number of any car, but a train must have at least one engine car to run. Engine cars have the ability to modulate the speed of the train with a slider below the viewport.

- Engine (locomotive) is the engineering/technical leadership and performance.
- Coal car (Figure 31) is behind the engine and represents funding.
 - » Each coal car symbolizes \$10 billion in funding for the project and adding/removing cars will increase/decrease the current amount of funding the project has.
 - » If the project has no funding (i.e., no coal car), the train will not run and halt. The coal level gradually decreases as the train moves. If the coal level reaches 0, then the project has run out of funding and the train (project) halts.

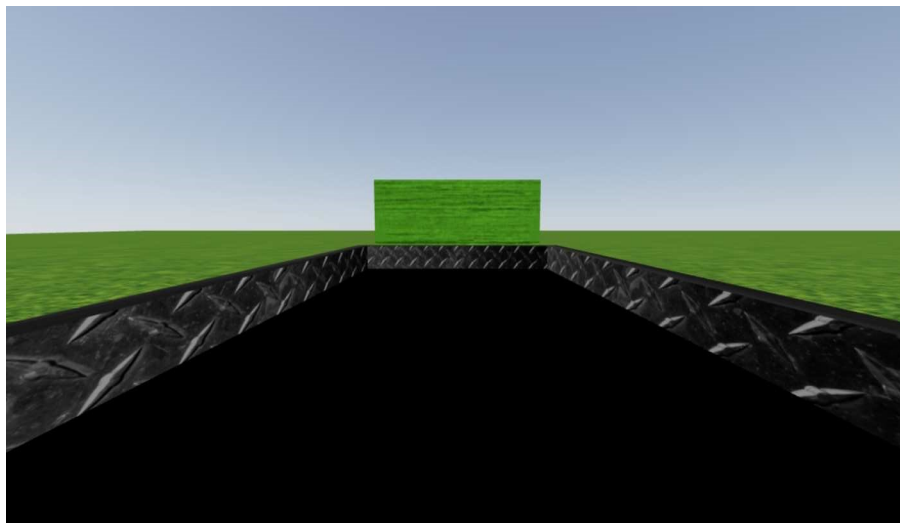


Figure 31. Drill-down of a Coal Car

- Freight cars (Figure 32) are different development efforts part of this train.
 - » Flat bed cars show a caricature of the object being developed, wire frame for undeveloped and filled-in for developed. A given caricature could be partially filled and partially wireframe.
 - » Box cars show other development efforts that don't lend themselves to a caricature, but words printed on the side of the box car could convey the gist. It could show filled and unfilled aspects.
 - » As the train progresses through its route, each crate will advance through development until being completed. When it is completed, and a new milestone is reached, it is replaced with a new task.

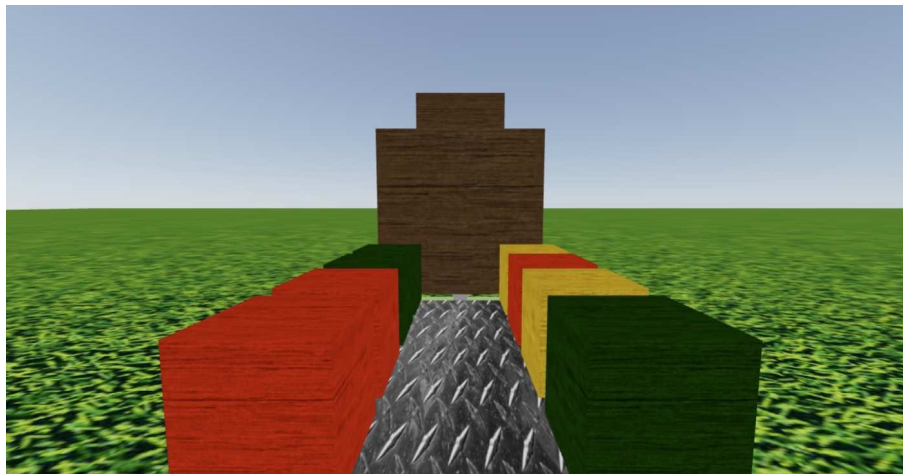


Figure 32. Drill-dwon of a Freight Car

- Passenger cars (Figure 33) represent stakeholders that are along for the ride on this train.
 - » Stakeholder sentiment is gathered from meeting documents and interpreted as facial expressions by the passengers of the car. Each head in the car corresponds with a stakeholder of the project, and by clicking on a head, you can see the stakeholder’s name and their current satisfaction level of the project.
 - » First class passenger car contains the primary stakeholders, and Coach passenger cars contain any additional stakeholders.
 - » The color of the passenger car is dictated by the average satisfaction level of the passengers within it. A green car indicates high satisfaction, red shows low, and yellow shows neutral.

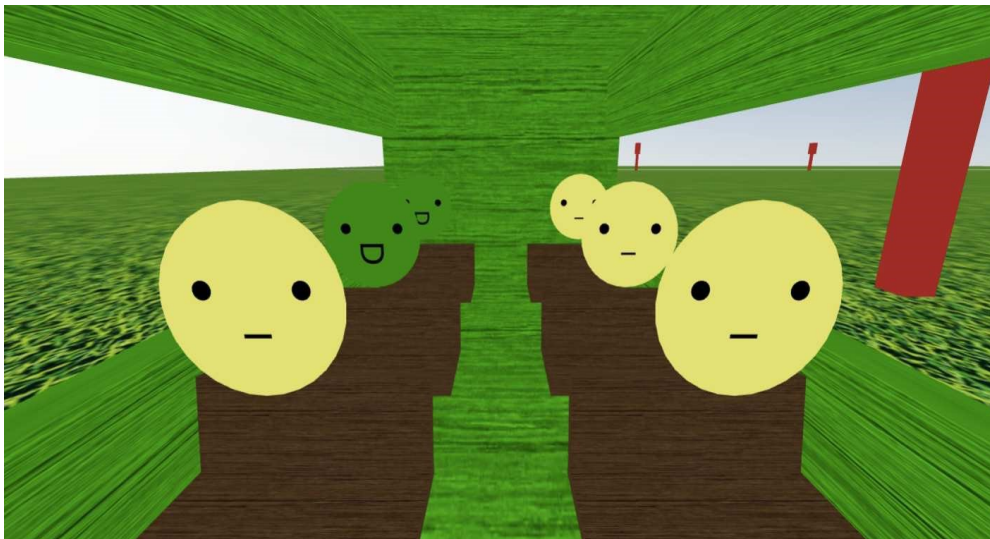


Figure 33. Drill-Down of a Passenger Car

- Caboose – last car in the train, represents project management and support functions for this train.

ENVIRONMENT

Meteorological conditions represent external factors impacting actual or predicted project performance, from sunny skies (no impact) to blizzards (severe halt), as seen in Figure 34.

- Sunny skies — no external conditions that impact performance. This is the default status of the weather and illustrates that everything (weather-wise) is doing good.
- Dark cloudy skies — growing threat but no impact yet. Like sunny skies, cloudiness does not impact the train. However, if unmitigated it can lead to the more serious weather conditions as described below.
- Heavy thunderstorms — current threat that slows progress. In thunderstorms, the train is impacted in its movement. Its speed is reduced by 25%, effectively making the project progress that much slower.
- Blizzard — current threat that largely halts progress. The blizzard is the most serious weather event, it halves the train's speed, reducing the project's development even more.

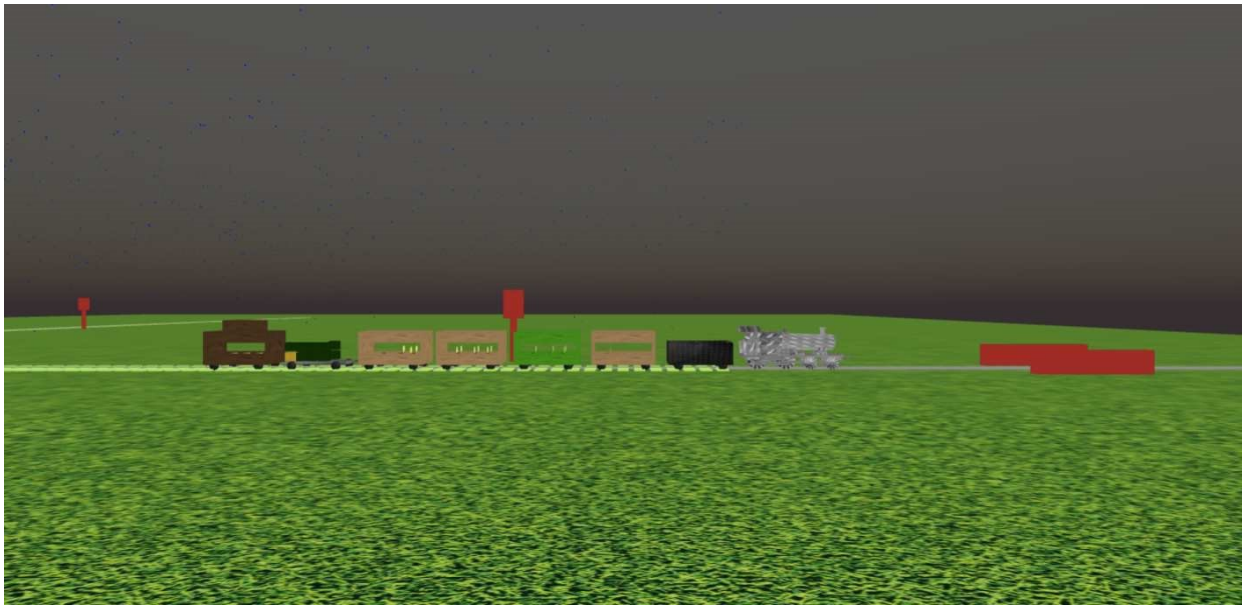


Figure 34. Train traveling through bad weather

STATIC REPRESENTATION OF THE TRAIN METAPHOR

The current project status is shown with a train moving along a track from the origin (rail yard) to the destination (terminal). The train is positioned at a specific point along the track, reflecting the project's achievements to date. Multiple trains can represent independent parts of a mega-project, each following its own route, with common infrastructure points showing interactions or dependencies, and trains may start at different times, merge, or follow distinct paths to the terminal.

- Track behind the train represents actual performance, with crossties colored solid green if no significant technical, schedule, or budget problems; solid yellow or solid red if there were (or still are) technical, schedule, or budget problems.
- Track in front of the train represents planned performance, colored a transparent light blue or gray if there are no predicted problems, hashed yellow or hashed red if there are predicted problems for technical, schedule, or budget performance.
- Depots between the origin and destination represent major reviews and decision points.
 - » Stakeholders may come and go from the passenger cars at a depot.
 - » Individual cars may be added or dropped at a depot.
- Coal bins along the way represent the funding profile for the project.
 - » Coal bins may be collocated with, or directly following, a depot or may appear at any point between depots if incremental funding is planned.
 - » Different funding sources can be depicted as different appearances of the coal bin (e.g. with different organizational symbols or other attributes).
 - » Coal bins behind the train represent funding that was received at that point; those in front of the train represent planned funding.
- Mile markers along the way represent project milestones (see Figure 35).
 - » Relative importance can be represented by larger vs smaller markers, perhaps further coded by color or other attribute.
 - » Those behind the train represent actual accomplishments. If missed or deferred, a hollow depiction of the mile marker can be shown behind the train with some sort of connector to a future mile marker if relevant.
 - » Those in front of the train represent planned achievements. When a train passes a marker, the milestone appears in the right panel and the freight cars take on any additional tasks associated with the new milestone.
- Switches along the way represent planned decision points regarding alternate routes to the terminal, or route to an alternate destination.

- Multiple trains can be used to represent portions of a mega-project that are basically independent, each following their own planned route to the destination.
 - » As appropriate, common infrastructure points such as depots or bridges can show points of interaction or interdependency.
 - » Trains could start at different times and have completely different routes to get to the terminal, or to a common depot before the terminal, at which point they might merge to become one train.



Figure 35. Train approaching a milestone marker

DYNAMIC REPRESENTATION OF THE TRAIN METAPHOR

The dynamic representation of the train metaphor enhances the static view by animating the train's movement along the track, with crossties changing color, mile markers evolving, and coal bins filling as funding is received. It shows progress with freight car contents updating and passengers boarding or disembarking, while weather conditions adjust accordingly. This dynamic view can also project future performance and explore scenarios like funding conflicts or alternate routes.

- Default would be a repeating loop showing the last epoch of project performance.
 - » An epoch could be a fixed calendar period, such as the past 12 months;
 - » Or it could be linked to major milestones, such as since leaving the last depot;
 - » Or if the project has just left a depot, the epoch of interest could extend back to the previous depot.
- The train moves along the track, and the crossties change color as the train passes over them.
 - » Speed of the train could vary to some degree to represent spending or some other aspect of performance.
 - » Mile markers change appearance as they are accomplished.
- Coal bins empty into the coal car as the train passes by, i.e., funding is received.
- Contents of the freight cars change as progress is made.
 - » Caricatures of flatbed components progress from wireframe to filled-in depiction.
 - » Contents of the boxcar containers reflect color-coded level of completion.
- Passengers come and go from the passenger cars, at depots if appropriate. If necessary, passengers can teleport into or out of the passenger cars.
- Weather conditions change as the train progresses as appropriate.
- The dynamic depiction can be set to show future predicted performance as well, for use in gaining insight into what is planned.
 - » Periods in which there is a potential conflict between the planned funding profile versus technical performance may be of particular interest.
 - » Taking alternate routes at an upcoming switch may also be of great interest for a "what if" scenario, seen in Figure 36.

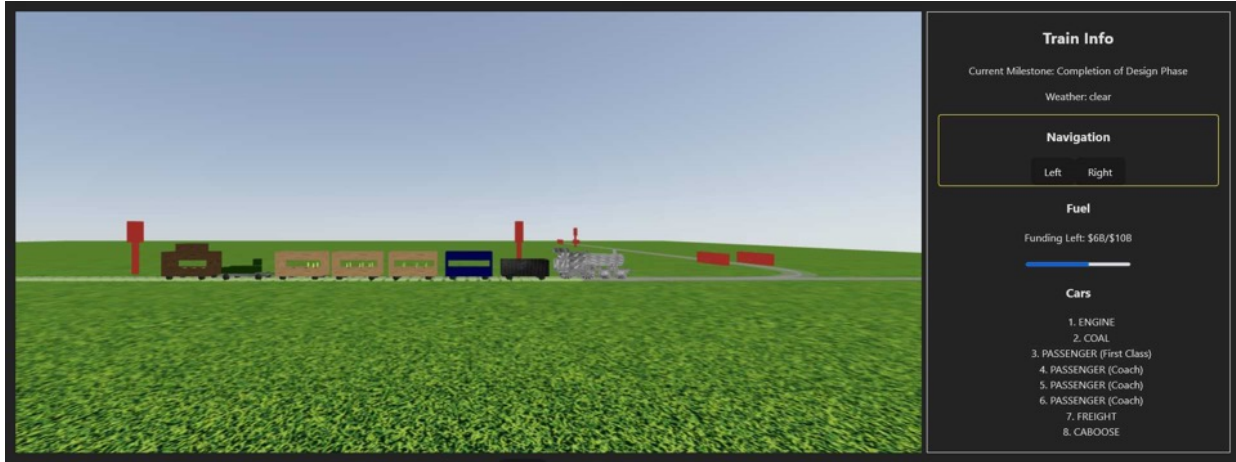


Figure 36. Train at a Fork

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.

THE MEGA-PROJECT UNCERTAINTY FRAMEWORK DASHBOARD

In this research, we introduce a prototype software dashboard directly using the Project Uncertainty Framework. This is an expansion of the use of the framework as an assessment tool, in a way that provides a top-level megaproject uncertainty 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. This research explored uniquely the use of LLMs to assess both qualitative and quantitative information into an AI-based visualization tool. The next sections discuss the design of the prototype tool.

PRIMARY VIEW

The primary functionality of the Uncertainty framework is the framework itself, which is divided into eight labeled sections, each representing a different category of uncertainty the framework measures.

1. External Environment Factor (Chaotic environment; Changing/Unknowable; Stable/Known)
2. Span of Control (Complex sources of supply; Known dependencies; Internal control)
3. Alignment & Trust (Conflicting equities; Known incentives; Trusted)
4. Strength of Relationships (Potentially resistant to goals; Inherent goal alignment; Stable team)
5. Number of Layers (Many interconnected; Narrow usage; Single)
6. Novelty/Innovation (Significant new knowledge; High modularity; Known design)
7. Predictability (High emergence, many new concepts; Limited new concepts; Known concepts)
8. Outcome (Fundamentally New capability; Similar capability; Improvement)

Each section includes three distinct categories, ranging from stable/known to complex/new, and can display one of three colors to reflect its overall status: red for a negative status, yellow for a neutral status, and green for a positive status. Additionally, blue dots may appear over sections to highlight relevant events. Hovering over these dots will show a brief summary of the event as shown in Figure 37.

These events can be retrieved from user-uploaded documents or automatically retrieved via a news API through the server and interpreted by the AI system. For more information, please see the News Gathering and Interpretation subsection.

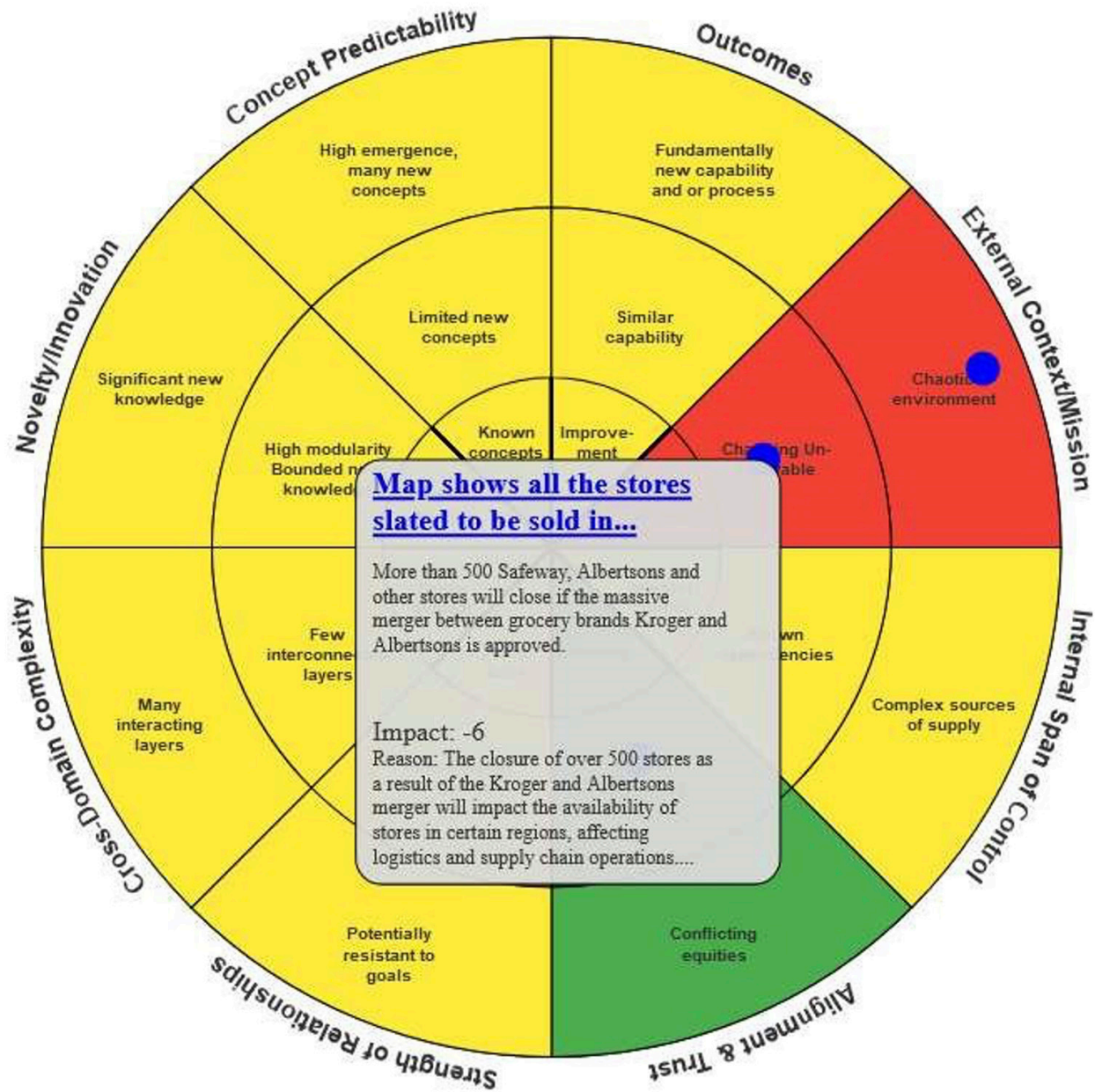


Figure 37. The Megaproject Uncertainty Framework Dashboard with Hover Interaction

SECTION VIEW

In addition to the main framework view, clicking on each of the 8 sections provides a more detailed view of that section. This detailed view includes the section’s name, a description, its various components, and its score (Figure 38). The score determines the section’s color and reflects its status, with a higher score indicating a more positive status. This score is augmented by documents uploaded (See Document Upload and Interpretation) or by news articles automatically gathered and interpreted.

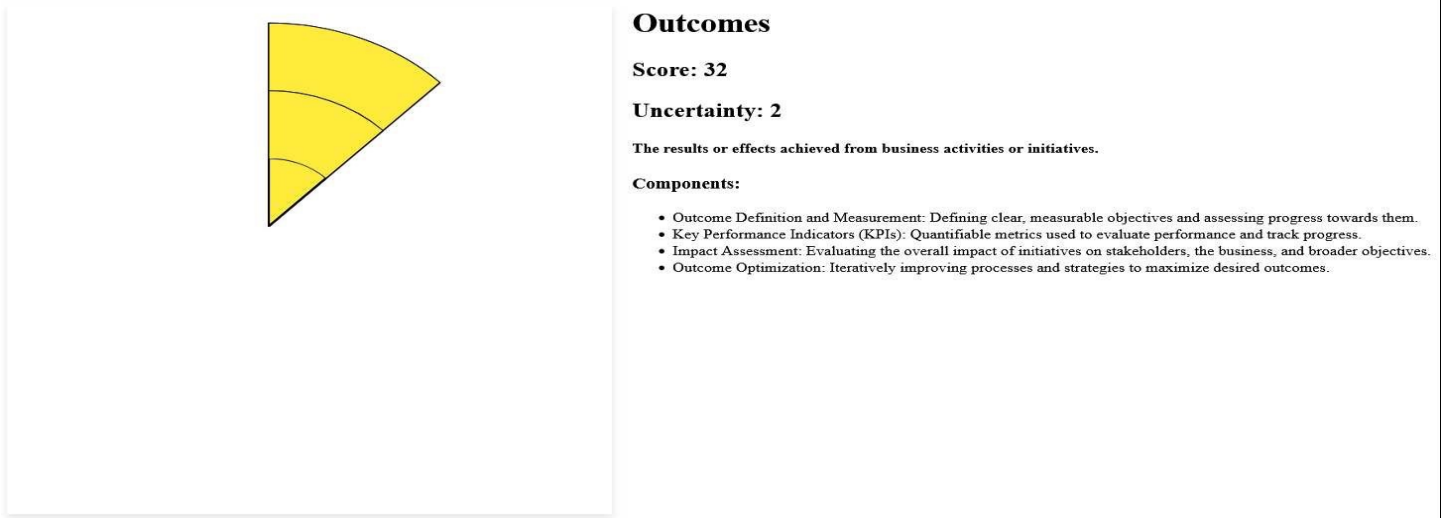


Figure 38. Example of a focused view of the “Outcomes” section in the mega-project Uncertainty Framework Dashboard

For each section, when an event is detected, it is added to a table that provides more detail than the blue dots in the main view. This table includes the event’s title (which links to the online article if retrieved via APIs), its retrieval date, a brief description of its content, its assigned impact score, an explanation of its relevance to the section, and any recommended mitigation or encouragement steps. The table is extracted in Figure 39.

Relevant News

Title	Date	Description	Impact	Reason	Next Steps
US producer prices slightly elevated in June - Reuters	Fri Jul 12 2024	U.S. producer prices increased slightly more than expected in June amid a rise in the cost of services, but that did not change expectations that the Federal Reserve could start cutting interest rates in September.	-7	The introduction of new federal cybersecurity policies requires AIRC to align its research with these new standards and build trust with governmental bodies that these regulations are met.	Monitor inflation rates, interest rate decisions by the Federal Reserve, and adjust budget and financial strategies accordingly.
The Law Firm Hitting Businesses With Thousands of Disability Suits - The Wall Street Journal	Sun Jul 14 2024	Entrepreneurs face allegations that their websites aren’t accessible to visually impaired people	-7	The article discusses entrepreneurs facing allegations that their websites aren’t accessible to visually impaired people due to disability lawsuits. This chaotic situation in the external context requires a proactive approach to address accessibility issues to comply with regulations and avoid further legal actions.	Enhance stakeholder engagement and communication to address accessibility concerns

Figure 39. Example of “Relevant Events” Table in the Subsection View

Using generative AI, the interpretation system analyzes incoming documents or news articles to assess their impact on the mega project, assigning an impact score. A higher score indicates a more positive impact, while a lower score signifies a negative one. The AI also provides reasoning for its assigned score and includes a “Next Steps” field, offering recommendations for mitigation in the case of a negative impact or possibility of expansion for a positive impact.

SELECTED SECTION VIEW: STAKEHOLDER STATUS

For the “Alignment and Trust” section, an additional table appears in the section-focused view, highlighting current stakeholder satisfaction. This table is populated from a database updated by parsing meeting recordings, minutes, or project progress reports, focusing on stakeholders who have strong opinions about the project’s status. The table lists each stakeholder’s name, satisfaction level, and their reasoning, which may be presented as direct quotes or interpreted by an AI system (Figure 40). A tracing functionality allows users to reference the original document. This data helps generate patterns of stakeholder concerns and disagreements, identifying who raised concerns, when, and who agreed or disagreed. Using LLM, we assess the impact of these concerns on the project, assigning an impact score to determine the urgency and significance of actions such as replacing a supplier or managing budget overruns. We also analyze recurring disagreements among stakeholder groups (e.g., individuals A and B favor conservative technology choices, while C, D, and E prefer more aggressive approaches) and track changes in stakeholder opinions over time regarding project decisions and votes.

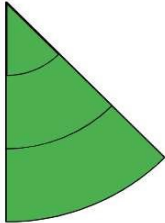
Notable Stakeholders

Stakeholder	Satisfaction	Feedback
Emily	Satisfied	Successful completion of initial groundwork and structural planning.
James	Satisfied	Successful completion of initial groundwork and structural planning.
Sarah	Satisfied	Successful completion of initial groundwork and structural planning.

Figure 40. Example of “Stakeholder” Table in the Subsection View

The satisfaction level of stakeholders influences the overall score of the “Alignment and Trust” section. Higher satisfaction among stakeholders results in a more positive impact. It’s important to note that this table includes only stakeholders with strong opinions at each time, those with a neutral stance will not be represented in the table.

Figure 41 showcases the full view of the “Alignment and Trust” section, including all standard components of the section view (See Section View for more details). This includes the overall score, fundamental components, uncertainty score, and relevant event table. Additionally, it includes the “Stakeholders” table, which is unique to this section.



Alignment & Trust

Score: 38

Uncertainty: 4

The degree of coherence and mutual confidence among stakeholders within and outside the organization.

Components:

- Stakeholder Alignment: Ensuring that the goals and interests of stakeholders are aligned with organizational objectives.
- Communication and Transparency: Fostering open and clear communication to build trust and alignment.
- Conflict Resolution: Addressing conflicts and disagreements constructively to maintain trust and collaboration.
- Collaborative Decision-Making: Involving stakeholders in decision-making processes to enhance buy-in and alignment.

Notable Stakeholders

Stakeholder	Satisfaction	Feedback
Emily	Satisfied	Successful completion of initial groundwork and structural planning.
James	Satisfied	Successful completion of initial groundwork and structural planning.
Sarah	Satisfied	Successful completion of initial groundwork and structural planning.

Relevant News

Title	Date	Description	Impact	Reason	Next Steps
Delta changes uniform policy following flap over flight attendants with Palestinian pins - USA TODAY	Sat Jul 13 2024	Starting Monday, Delta employees can no longer wear pins that represent any other countries or nationalities other than the United States.	-4	Delta's uniform policy change restricting employees from wearing pins representing other countries may impact the relationship and trust between employees of different nationalities, potentially affecting alignment within the workforce.	Implement diversity and inclusion training to foster cultural understanding and alignment among employees.
Biden admin proposes free family seating mandate for airlines - The Hill	Thu Aug 01 2024	The Biden administration proposed a new rule Thursday that would require airlines to seat parents next to their young children for free. The proposal would bar airlines from charging fees for parents to sit next to their children younger than 13. If adjacent ...	-5	The proposed rule would impact the alignment and trust category as it involves ensuring that airlines comply with the mandate without exploiting loopholes or finding alternative ways to charge for seating arrangements.	Monitor compliance closely and establish clear consequences for violations to ensure airlines adhere to the rule.

Figure 41. Full View of the “Alignment and Trust” Section

INPUT SOURCE VIEW

News Gathering and Interpretation News articles are automatically gathered through external News APIs. Currently, we use the free [News API](#) which enables the dashboard to quickly and efficiently retrieve important news. The response is then filtered to include only those articles relevant to the mega project. We can further specific thresholds such as business, logistics, infrastructure, and transportation related. These articles are further analyzed by the AI system, which identifies those with the most impact on the mega project, assigns an impact score, and provides a reason and next steps. (For more information see Relevant News Table). To avoid duplicate interpretations and prevent skewing the overall impact score, the AI system compares article metadata with previously analyzed articles to ensure each one is uniquely assessed.

Although you can view news specific to a particular section in its section focused view, you also have the option to see all relevant news for all sections in one place. Simply navigate to (Input Sources News Monitoring), via the navbar to access all news articles pertinent to the mega project, as shown in Figure 42.

Each news card contains almost the same information found in the "Relevant News" table (with the sole addition of the author). The only true difference is that now the relevant news for every section is in one place. This page will change and update as more news articles are found to be relevant and stored in the database.

The screenshot shows a sidebar on the left with the following menu items: Megaproject Uncertainty Framework, Wheel Tool, Stakeholder Status, and Input Sources. The main content area displays a grid of news cards. Each card contains the following information:

- Title:** US producer prices slightly elevated in June - Reuters
- Author:** Lucia Matkani
- Text:** U.S. producer prices increased slightly more than expected in June amid a rise in the cost of services, but that did not change expectations that the Federal Reserve could start cutting interest rates in September.
- Impact:** -7
- Reason:** The introduction of new federal cybersecurity policies requires AIRC to align its research with these new standards and build trust with governmental bodies that these regulations are met.
- Next Steps:** Monitor inflation rates, interest rate decisions by the Federal Reserve, and adjust budget and financial strategies accordingly.
- View Article:** [View Article](#)

Other visible news cards include:

- Title:** Map shows all the stores slated to be sold in Kroger-Albertsons merger - USA TODAY
- Author:** Mary Wainath-Holdridge, James Powell
- Text:** More than 500 Safeway, Albertsons and other stores will close if the massive merger between grocery brands Kroger and Albertsons is approved.
- Impact:** -6
- Reason:** The closure of over 500 stores as a result of the Kroger and Albertsons merger will impact the availability of stores in certain regions, affecting logistics and supply chain operations.
- Next Steps:** Develop contingency plans for alternative store locations and supply chain routes.
- View Article:** [View Article](#)

- Title:** Delta changes uniform policy following flap over flight attendants with Palestinian pins - USA TODAY
- Author:** Amanda Escinas
- Text:** Starting Monday, Delta employees can no longer wear pins that represent any other countries or nationalities other than the United States.
- Impact:** -4
- Reason:** Delta's uniform policy change restricting employees from wearing pins representing other countries may impact the relationship and trust between employees of different nationalities, potentially affecting alignment within the workforce.
- Next Steps:** Implement diversity and inclusion training to foster cultural understanding and alignment among employees.
- View Article:** [View Article](#)

- Title:** The Law Firm Hitting Businesses With Thousands of Disability Suits - The Wall Street Journal
- Author:** Ruth Simon, Coriella James
- Text:** Entrepreneurs face allegations that their websites aren't accessible to visually impaired people
- Impact:** -7
- Reason:** The article discusses entrepreneurs facing allegations that their websites aren't accessible to visually impaired people due to disability lawsuits. This chaotic situation in the external context requires a proactive approach to address accessibility issues to comply with regulations and avoid further legal actions.
- Next Steps:** Enhance stakeholder engagement and communication to address accessibility concerns
- View Article:** [View Article](#)

- Title:** What's worse than thieves hacking into your bank account? When they steal your phone number, too - The Associated Press
- Author:** FATIMA HUSSEIN
- Text:** What's worse than thieves hacking into your bank account? When they steal your phone number, too. Associated Press writer Fatima Hussein recently fell victim to a type of fraud known as post-out hijacking, also called SIM-swapping. It's a less-common form of ...
- Impact:** -6
- Reason:** The article on phone number theft through post-out hijacking impacting wireless providers highlights the External Context/Mission category the most. The fraud incident underscores a chaotic, unknowable external environment where evolving fraud techniques pose security threats to telecom companies. This event has a negative impact on AIRC as it emphasizes the importance of implementing robust security measures to safeguard against fraudulent activities and protect sensitive data.
- Next Steps:** Enhance security measures such as two-factor authentication to protect against SIM-swapping attacks.
- View Article:** [View Article](#)

- Title:** Biden admin proposes free family seating mandate for airlines - The Hill
- Author:** Julia Skapero
- Text:** The Biden administration proposed a new rule Thursday that would require airlines to seat parents next to their young children for free. The proposal would bar airlines from charging fees for parents to sit next to their children younger than 13. If adjacent ...
- Impact:** -5
- Reason:** The proposed rule would impact the alignment and trust category as it involves ensuring that airlines comply with the mandate without exploiting loopholes or finding alternative ways to charge for seating arrangements.
- Next Steps:** Monitor compliance closely and establish clear consequences for violations to ensure airlines adhere to the rule.
- View Article:** [View Article](#)

- Title:** Simone Biles wins 10th Olympic medal with gold in vault - NBC News

Figure 42. "News and Monitoring" Page

DOCUMENT UPLOAD AND INTERPRETATION

In addition to automatic news monitoring, you can manually upload PDF documents to the dashboard (Figure 43). The dashboard parses these documents, and the AI system interprets the data to assess its impact on the project. Both the interpretations and the files are stored in the database with security ensured. Documents can be uploaded by using the navbar to navigate to (Input Sources > Upload PDFs). You can then select “Browse...” or drag a PDF into the box at the top and click “Upload” to start the parsing and interpretation process. Below the upload bar, a table displays previously interpreted documents. You can view and download raw documents by clicking their names, and see the full AI interpretation by clicking the “Show” button. To delete files and their interpretations, click the “Delete” button. By organizing these uploads, you can decide whether to use each document for customized LLM processing or not.

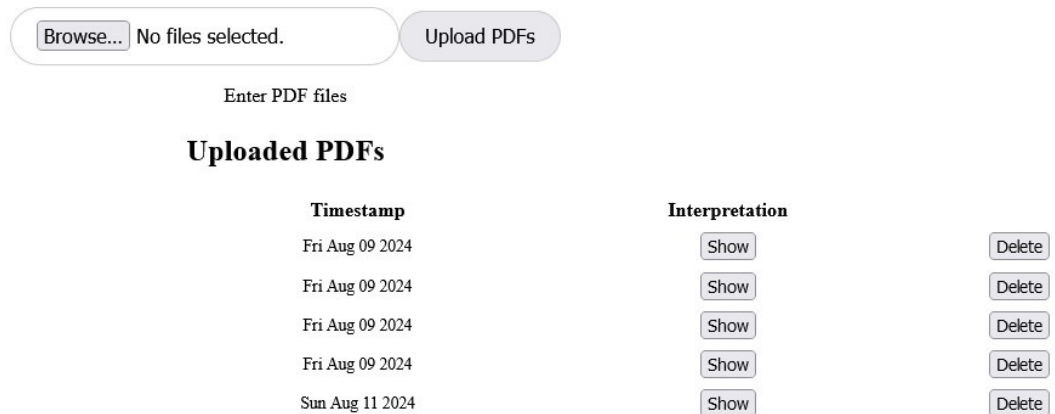


Figure 43. “Upoad PDFs” Page

The Uncertainty framework dashboard also includes functionality for tracking financial movements of existing and potential suppliers and partners over time. By navigating to (Input Sources > Financial Data Monitoring), via the navbar, you can enter a stock ticker symbol to view its price history, hover over the graph to see specific prices, and switch between various time series detection algorithms and their thresholds. Currently, data is automatically gathered through the [FMP API](#), a free service used for obtaining stock data.

WEBSITE SCRAPING

Additionally, the dashboard can scrape external websites for information. This feature is currently in its early stages of development and is designed to collect and store all available data in the database. To use the web scraping tool, navigate to (Input Sources > Website Links). The page you’ll access includes a box for submitting URLs, with one URL per line. Each URL represents a website from which the scraping tool will collect data. Note that scraping times can vary significantly based on the size of the website—small websites may take a few seconds, while larger ones might take several minutes.

AI SYSTEM

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.

Many of the functionalities of this dashboard reference the underlying AI system, so it is important to also highlight its intricacies. The Uncertainty framework has the capability of changing the underlying AI system to better suit the needs/budget of the project. If preferred, you can select to use OpenAI's [ChatGPT](#) to handle interpretation and other tasks. This comes with the drawback of it being both a paid service and restricted to only allow use of approved topics. For military applications, this may not be a viable route. The positive route is that you do not need the machines capable of running a LLM yourself.

Conversely, you can select to use an Open-source LLM model to manage interpretation. By default, the model is Meta's [LLama-3](#). The positive and negatives of this option are essentially the opposite to that of using ChatGPT. You are unhindered by potential censoring of topics and it is free to use (minus the cost of electricity). However, you are required to possess (or have access to) machines that are capable of running a LLM. An insufficiently fast machine will lead to slow response times for interpretation and filtering.

We developed a custom generative AI framework for the project employing a Retrieval-Augmented Generation (RAG) approach to effectively harness and utilize context, which is essential for the functionality of generative AI systems. This framework consists of three key modules:

- Data Ingestion
 - » Documents and other sources are converted to text, using Optical Character Recognition (OCR) if necessary.
 - » The text is split into manageable pieces.
 - » Embeddings—vectors that capture the syntactic meaning of the text—are computed using specialized language models.
 - » These embeddings, along with the text and metadata, are stored in a vector database.
- Retrieval and Inference
 - » When a generation request is initiated:
 - ◇ The AI searches the vector database for relevant pieces of context.
 - ◇ A history of previous requests and their outcomes is included.
 - ◇ Any stakeholder adjustments from past inputs are added.
 - ◇ A carefully designed prompt is attached to elicit the desired generation.
 - » All gathered information is passed to a locally-hosted, open-source LLM to generate the desired output.

- Final Steps

- » The generated content is used to update the relevant report, dashboard, or simulation.
- » Provisions are made for corrections based on stakeholder feedback.

The process is shown in Figure 44 below.

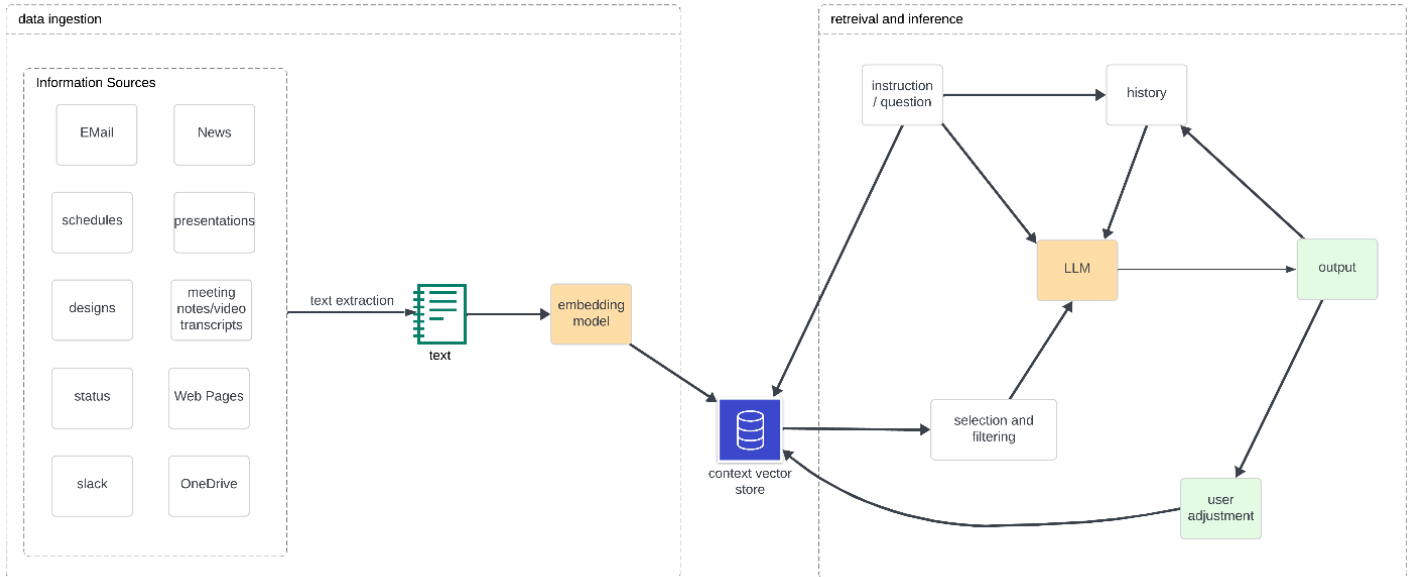


Figure 44. RAG-Based Generative AI Process Flow

Additionally, the project explored the ability of LLM tools combined with sentiment analysis to search for project team misalignment in meeting minutes, a key measurement aspect of the Stakeholder Context > Alignment and Trust dimension of the Megaproject Uncertainty Framework. An example output is shown in Figure 45. These tools could be used on meeting transcripts either post-meeting or collected in real time. The team demonstrated the use of these tools in our internal meetings as a potential feed into the dashboard, but did not score these inputs. We also did not address the ethics and privacy issues with the use of these tools in real environments. As noted in the figure, all the outputs were anonymous.

Speech Emotion Analysis with Speaker Diarization (GPU-accelerated)

Transcribe speech, identify speakers, and analyze emotion for each speaker's segments using AI, accelerated with CUDA.

The interface is divided into two main sections. On the left is an audio player with a waveform, a progress bar from 0:00 to 38:43, and playback controls. Below the player are 'Clear' and 'Submit' buttons. On the right is a 'Transcript with Sentiment Analysis' panel containing the following text:

- Speaker SPEAKER_05: And we might have other things at the top level of system, all be to like our software, you know, the software that we develop to do the automated conversion. Sentiment: neutral 😊 (Score: 0.93)
- Speaker SPEAKER_00: But we should get together and talk about it. I don't think we need to change it for this minute. Yeah, yeah, we don't need to change right this minute. Sentiment: neutral 😊 (Score: 0.49)
- Speaker SPEAKER_05: Do you agree on that kind of. Sentiment: curiosity 😊 (Score: 0.41)
- Speaker SPEAKER_03: Do you agree on that kind of. Sentiment: curiosity 😊 (Score: 0.41)
- Speaker SPEAKER_05: And it's got to work well with the clips, get integration. Sentiment: approval 👍 (Score: 0.44)
- Speaker SPEAKER_03: And it's got to work well with the clips, get integration. Sentiment: approval 👍 (Score: 0.44)
- Speaker SPEAKER_05: And it's got to work well with the clips, get integration. Sentiment: approval 👍 (Score: 0.44)

At the bottom of the transcript panel is a 'Flag' button.

Figure 45. Example sentiment analysis of a meeting transcript.

CRITICAL SKILLS FOR MEGAPROJECT LEADERSHIP

INTRODUCTION

According to the Oxford Handbook of Megaproject Management, megaprojects are characterized as “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). These projects often function as mega-systems (Stevens, 2011) and are marked by operational uncertainty, behavioral complexity, pluralistic decision-making, and external environmental volatility (McDermott et al., 2024).

Megaprojects, as with many large, complex systems, traditionally have a lower-than-desired success rate. In fact, research by Flyvbjerg, a leading scholar in megaproject management, 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, 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.

Merrow, an authority in megaproject leaders, highlights that “the fate of difficult projects seems to hinge more on the project leaders than the results of simpler projects” (Merrow, 2011). In another study, co-authored with Nandurkdikar, 100 megaprojects and their leaders were examined to help determine the factors that differentiate between successful and less-successful leaders of specifically large-scale, transboundary, complex projects.

This research focused on megaproject leaders – the individuals who must steer the complex temporary enterprises that create megaprojects – and the skills that best enable their success. It provides a framework that details 24 competencies that are required for successful megaproject leadership, how these competencies can be distributed amongst a team, and how organizations seeking to initiate mega projects should think about the selection of the leadership team.

The world is full of large ambitious projects aimed at solving major infrastructure challenges. Dozens of important megaprojects that hold the potential to change the way people interact with their infrastructure and their surroundings are either in planning or development.

-KPMG 2015

One cannot help but be awestruck by megaprojects. When huge budgets, massive footprints, unanticipated transformative benefits and all the thrills and spills of a theme park ride come together in one exhilarating project, it's hard not to be enthralled.

-KPMG 2015

LITERATURE REVIEW

The literature review was broken into a few major categories of information:

- Overview literature/background on megaprojects themselves with historical examples (case studies). This included information on mega-systems and is not reflected in the literature review below but is instead in the broader literature review (see the previous literature review section).
- Existing frameworks with relevant skills and competencies.
- Literature on the qualities and skillsets of megaprojects leaders, both successful and unsuccessful.
- In-depth literature on specific skills or characteristics. These items are referenced individually within the framework.

The literature reviews for the first two categories are outlined below. The third category, which provides clarification or additional detail on specific skills for megaproject leaders, is folded into the discussion of the framework itself.

EXISTING FRAMEWORKS WITH RELEVANT SKILLS AND COMPETENCIES

There are several existing frameworks that have relevance for the creation of megaproject leadership. If megaprojects are also mega-systems, systems engineering frameworks have relevancy, as do frameworks that deal with complexity and project and technical leadership. The competency frameworks examined as part of this work include:

- Helix^{SE} – this is research from the SERC that examines what makes systems engineers effective. As megaprojects are also mega systems, systems engineering skills are important inputs to megaproject leaders (Hutchison et al., 2019). This framework includes critical skills in systems engineering, systems mindset, interpersonal skills, and technical leadership, many of which align with the literature on effective megaproject leaders.
- Helix^{EMP} – this is research from SERC researchers Hutchison and McDermott, taking the foundational framework of Helix^{SE} and expanding it to cover employability skills more generally (McDermott et al., 2021). There are three main themes that are folded into the results as appropriate: self-leadership and learning, team leadership and collaboration, and complex problem-solving.
- DAU Innovation Competencies & Skills Model – this framework supports the DAU “Innovate to Win” initiative. It focuses on cultivating key competencies necessary for fostering innovation within defense acquisition. These competencies are:

- | | |
|----------------------------|-------------------------|
| » Creative Thinking | » Negotiation |
| » Critical Thinking | » Decision Making |
| » Strategic Thinking | » Analytical Thinking |
| » Change Management | » Technical Proficiency |
| » Problem Solving | » Project Management |
| » Risk Management | » Adaptability |
| » Collaborative Leadership | » Networking |
| » Communication | |

The model encourages continuous learning and adaptability to achieve innovative outcomes in defense acquisition processes (Martinelli, 2023).

- Complex Project Leadership Competency Standards – generated by a collaborative effort of 169 individuals from 24 nations to identify the critical skills of complex project leadership. It is divided into five main competency areas:
 - » Drive systemic thinking and action,
 - » Focus strategically on delivering project outcomes,
 - » Engage collaboratively with stakeholders,
 - » Exercise contextual leadership awareness, and
 - » Apply system governance and delivery assurance (International Centre for Complex Project Management, 2023).
- Framework for Analysis of Transformational Leaders - a framework based on the principles of transformational leadership, including:
 - » Management by exception – these are more transactional skills (deal with low-performing employees, avoid technical mistakes and blunders, deal with performance lapses, stabilize organization if needed).
 - » Contingent reward (pay, work-life balance).
 - » Individualized consideration – coaching, delegation, training opportunities).
 - » Idealized influence (model exemplary behavior, avoid personal scandal, use charismatic communication).
 - » Inspirational commitment (gain commitment to the work and the profession, teamwork).
 - » Intellectual stimulation (ensure the need for change, provide a plan, build internal support, ensure top management support, ensure external support, provide resources, institutionalize changes, pursue comprehensive change) (Van Wart, 2015).
- Technical Leadership – researchers from the SERC worked with leaders in the DAU to develop a framework for explaining the skills required for effective technical leadership (Pennotti et al., 2015). This utilizes three lenses, which build in complexity: systems, business, and enterprise. Figure 46 is an illustration of the key skills required in each lens.

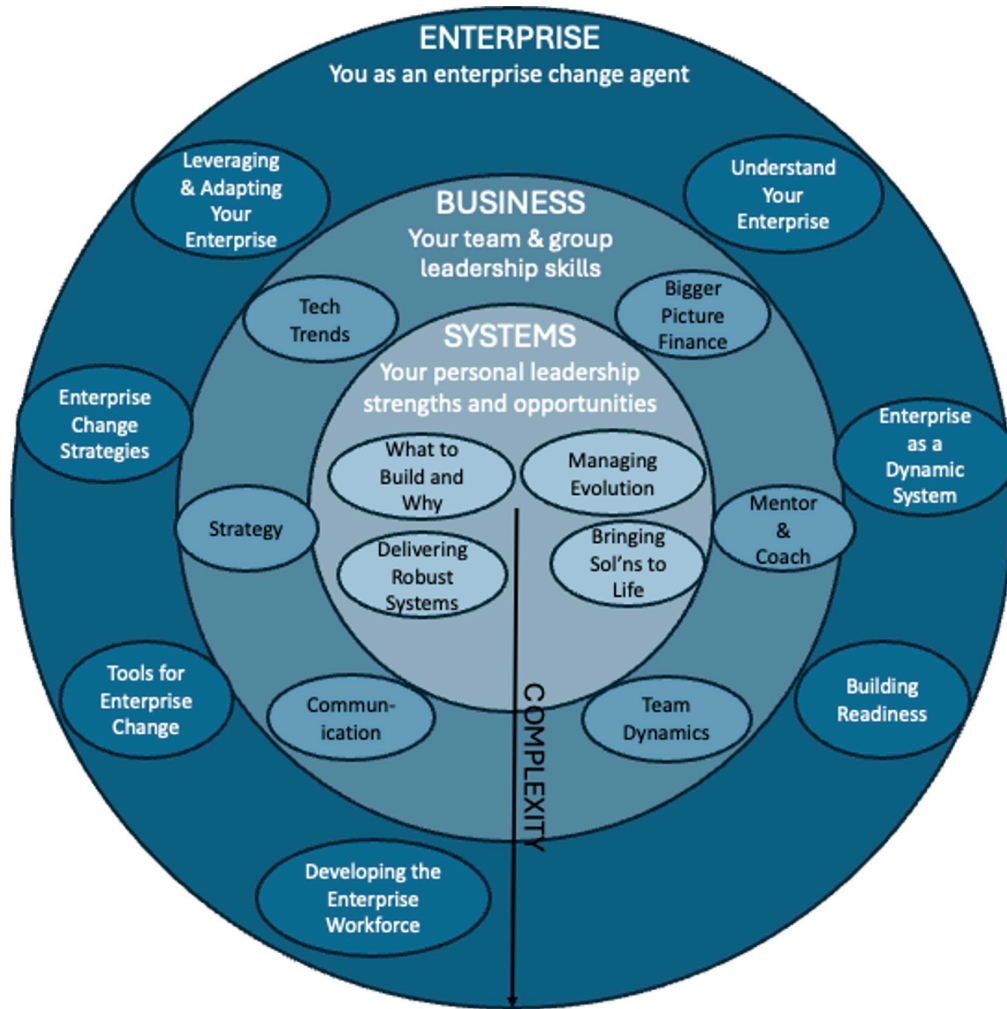


Figure 46. Overview of the Skills Outlined in (Pennotti et al., 2015), Building in Complexity through the Systems, Business, and Enterprise Lenses

LITERATURE ON QUALITIES & SKILLSETS OF MEGAPROJECT LEADERS

Any review of literature on megaproject leaders must start with Merrow and Nandurdikar's book, *Leading Complex Projects*. (2018) This book provides insights into managing large-scale, complex projects. The book discusses the unique challenges of such projects, emphasizing the need for strong leadership, effective communication, and rigorous planning. Key themes include managing uncertainty, stakeholder engagement, decision-making under pressure, and balancing short-term objectives with long-term goals. The authors offer practical strategies based on research findings to help project leaders improve performance, mitigate risks, and navigate the complexities inherent in large, high-stakes projects.

- Historically, excellent program managers have been selected as megaproject leaders. Success in a first complex project is a good indicator for success in a second. "It is not even clear that a long career progression in smaller, less-complex is of any substantial value to the complex project leader at all."
- Skillsets for PMs overlap with megaproject leadership – but there are very different emphases.
- Most effective megaproject leaders have had:
 - » Broad and varied jobs - most successful megaproject leaders have depth in the domain of the project but have worked more broadly and become generalists.
 - » Making timely decisions under conditions of uncertainty.
 - » Opportunity to watch others lead complex projects.
 - » Experience sorting out difficult interpersonal situations.
 - » Many come from engineering (most megaprojects are engineered systems).

Critical skills for megaproject leaders include:

- They are highly open to new experience, self-disciplined, engaging, stable, and test high in emotional intelligence (the five-factor model).
- Project management remains important but in the context of cooperation and not in transactional methods (as it is usually employed).
- They prefer to manage people, create alignment, and focus on communications over on work processes.
- They are highly aware of their own abilities for learning.

This is the most comprehensive resource in the literature. In addition, over 70 articles on megaproject leadership skills were reviewed. The full details of each of these articles can be found in the Annotated Bibliography. Overall, several key themes appeared consistently across the literature. In particular, there were five major 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, and
- Manage Risk.

FRAMEWORK FOR MEGAPROJECT LEADERSHIP SKILLS

The critical skills and abilities (competencies) for megaproject leaders were identified based on the literature but also with this lens in mind. Each of the competencies outlined in the framework are necessary to successfully perform these five activities. Stated differently, it takes a number of individual competencies to deliver these capabilities effectively.

There are six major competency areas required for megaproject leaders:

- Domain/Discipline Skills Foundations
- Personal Characteristics
- Mindset
- Thinking Skills
- Interpersonal Skills
- Enterprise Technical Leadership

Note that “mindset” and “thinking skills” are related. In general, mindset is about the attitudes and beliefs that influence how someone approaches situations, while thinking skills are the cognitive tools and processes used to analyze and solve problems. These areas are related and these skills go together, with mindset often shaping how effectively thinking skills are applied.

Each of these six areas is defined and explained at the high level below. Appendix A provides detailed information on the framework, including providing specifics on which frameworks and articles support individual competencies in the literature.

DOMAIN/DISCIPLINE FOUNDATIONS

Historically, technical leaders have been more effective when they have had deep experience in the primary domain and at least some experience with the most critical disciplines for the system. This is true at smaller scales of complex projects (Helix) as well as at the megaproject leaders. Merrow and Nandurdikar’s analysis of 100 megaproject leaders highlighted that most of the successful leaders had a technical background, often in engineering (2018). This does *not* mean that megaproject leaders should *do* engineering work, but that they should have enough technical depth to be able to make major technical decisions, have effective dialogs on technical/engineering concerns, and know when to consult experts in a given discipline.

One important note in Merrow and Nandurdikar’s work is that leaders who have experience in more than one domain – but include experience in the primary domain for a megaproject – are more likely to be successful (2018). In the example of Dzulkarniain Azaman, Merrow and Nandurdikar (2018) highlight:

... This early experience ... is similar to what we have seen in the early careers of other leaders: A solid grounding in the fundamentals of their domain with exposure to the world of project management is followed by managing smaller-scale mini-projects and, more importantly, seeing projects from end-to-end, which provides the learning of seeing one’s design, engineering, and project management decisions play out in the field.

The specific domain(s) and discipline(s) needed are dependent upon the individual megaproject.

PERSONAL CHARACTERISTICS

Though personal characteristics are not always included in competency frameworks, in the case of megaproject leadership, these characteristics emerged so strongly that it is critical to include them. In as much as these characteristics are more intrinsic/difficult to change, they become critically important for the selection of the right individuals for megaproject leadership.

There are six critical characteristics for megaproject leaders:

- Self-Aware – the ability to understand and recognize one’s own thoughts, emotions, and behaviors, and how they affect oneself and others.
- Self-Motivated – the internal state that helps us initiate, continue, or terminate a behavior (Davis, 2024).
- Trustworthy – the quality of being deserving of trust or confidence, often demonstrated through dependability or reliability.
- Humble – having a modest view of one’s own importance; a lack of pride and arrogance. In the context of megaproject leadership, a humble leader is one who sees their role as serving others.
- Open-Minded - able to consider something without prejudice or application of pre-conceived notions.
- Courageous - able to do something difficult or risky, even in the face of fear or danger. Is essential for leaders to confront the inherent risks, uncertainties, and complexities of megaprojects.

Additional details about characteristics, including detailed examples and citations from the literature, can be found in Appendix A.

MINDSET

Mindset is about the attitudes and beliefs that influence how someone approaches situations. These are closely related to the Thinking Skills that are discussed in the following section. The critical characteristics of the mindset of successful megaproject leaders are:

- Paradox Mindset - the ability to hold and balance seemingly opposed views and being able to easily move from one perspective to another (Hutchison et al., 2020).
- Strategic Thinking - essential for leaders of megaprojects due to the scale, complexity, and long-term implications of these endeavors. It involves the ability to envision the future, anticipate challenges, align resources, and make decisions that drive the project toward its objectives despite uncertainties.
- Vision/Goal Setting - vision is a broad idea of what the megaprojects is trying to achieve in the future. Goals are specific aims or steps that will help reach that vision. The ability to create the vision and then identify key steps to attaining it is critical for megaproject leadership.
- Comfort with Uncertainty - the ability to function in an environment of unpredictability and lack of sufficient information.

Additional details about characteristics, including detailed examples and citations from the literature, can be found in Appendix A.

THINKING SKILLS

Thinking skills are the cognitive tools and processes used to analyze and solve problems. These are related to Mindset (previous section), with mindset often shaping how effectively thinking skills are applied. The critical thinking skills of successful megaproject leaders are:

- **Political Savvy** - the ability to exhibit confidence and professional diplomacy, while effectively relating to people at all levels internally and externally (NIH, nd). Note that the literature reflects that an effective megaproject leader has the ability to navigate political landscapes, but they also need to be able to insulate their teams from political situations that could cause disruption as much as possible.
- **Recognize Patterns** - abstraction is the quality of dealing with ideas rather than specific events. This is part of the ability to recognize patterns across different disciplines, domains, or contexts.
- **Solve Complex Problems** - finding solutions to difficult or complex issues. Megaprojects are complex, involve a wide variety of stakeholders, and require the integration of multiple disciplines. By their nature, they will generate many problems which need rapid solutions.
- **Innovate** - coming up with new ways to do things; making changes to methods, processes, and approaches. In the Shenhar and Dvir model (2007), megaprojects are often highly novel, trying to put capabilities together in a way that has not been done before. That novelty necessarily requires innovation in the enterprise as well as the project itself.
- **Anticipate Future Situations** - the ability to predict what will happen or be needed in the future; foresight. This is closely related to the Mindset capability of Vision/Goal Setting, which requires the ability to forecast what is within the realm of possibility for future states.

Additional details about characteristics, including detailed examples and citations from the literature, can be found in Appendix A.

INTERPERSONAL SKILLS

By their nature, megaprojects involve a diverse set of stakeholders, both internally to the team and externally. Every reference in the literature review cited the importance of successfully managing stakeholders for the success of large, complex projects. These are closely tied to the competencies necessary for Enterprise Technical Leadership (following section). Success depends on proactive communication, trust building, and frequent engagement (Schoemaker et al., 2013).

A wide variety of interpersonal skills are required for megaproject leaders, though they can generally be grouped into the three main competencies:

- **Communication** - fundamentally, communication is the ability to convey and receive information effectively. There is a wide array of communication skills, deadline with how you express yourself, understand others, and adapt your communication style based on the audience. Successful megaproject leaders must master all aspects of effective communication. Communication is a focused task of successful complex project leaders (Merrow and Nandurdikar, 2018).
- **Relationship Building** - the process of creating and maintaining connections with people to create a sense of team or to achieve a purpose.
- **Negotiation/Persuasion** - megaprojects by nature have a diverse community of stakeholders. There will be conflicts between stakeholders and conflicts of priority within the team (e.g. trade-offs between budget, schedule, and performance).

Additional details about characteristics, including detailed examples and citations from the literature, can be found in Appendix A.

ENTERPRISE TECHNICAL LEADERSHIP

By their nature, megaprojects are large, complex temporary enterprises. They require enterprise leadership skills in addition to the technical leadership skills required to oversee successful innovation. Enterprise Technical Leadership skills are:

- Promote Learning Culture - create an environment that encourages and prioritizes gaining new knowledge and skills. Learning is rewarded. The megaproject leader provides an example of continuous learning. Creating a learning culture in the context of megaprojects is critical to adapt to complexity, improve performance, and foster innovation.
- Foster Openness - encourage a culture of openness and communication, and be open to new ideas and perspectives. This is closely linked with the individual leader's open-mindedness.
- Collaborate - the ability to work with others to produce or create something is a critical aspect of megaprojects. Building a collaborative team is critical to megaproject success.
- Demonstrate Trust - effective megaproject leaders create an environment that actively shows that they believe their team acts in good faith and will do their best to help the project achieve its goals.
- Resolve Conflict - the ability to peacefully settle disagreements between multiple parties.
- Coach and Mentor - coaching¹ and mentoring² help to develop leadership skills, foster collaboration, and enhance trust and performance. Coaching is a critical skill for megaproject leadership (Van Wart, 2015).

Additional details about characteristics, including detailed examples and citations from the literature, can be found in Appendix A.

¹ Coaching focuses on specific skills and performance improvement in a shorter time frame. (Clutterbuck, 2008)

² Mentoring is a longer-term relationship centered on holistic development and guidance. (Clutterbuck, 2008)

SELECTING MEGAPROJECT LEADERS

Merrow and Nandurdikar (2018) highlight the current problems with selecting megaproject leaders. Most specifically, success on smaller-scale simpler projects is not a good predictor for success on large-scale complex projects. However, most organizations select megaproject leaders based on their performance on considerably smaller projects. How can we improve the selection of individuals for these critical roles?

First, it is critical that megaproject leaders have experience in the primary domain(s) and discipline(s) for the megaproject. Merrow and Nandurdikar (2018) highlight that the majority of effective megaproject leaders in their study had an engineering background. Even those who had been program managers for several years often had at least an undergraduate education in a more technical area. Selecting individuals who have depth in an area and breadth across others (a “T-shaped” professional) again will improve the probability that the individual will have the necessary skillset to successfully navigate megaprojects.

The “Big 5” Personality traits of neuroticism, extraversion, openness, agreeableness, and conscientiousness can be a useful indicator of whether an individual has a personality appropriate to megaproject leadership. In general, successful megaproject leaders score high in extraversion, openness, agreeableness, and conscientiousness and low in neuroticism. Utilizing an existing and widely used tool like the Five Factor method to understand the personal characteristics of potential leaders, candidates who are less likely to be effective can be weeded out more rapidly.

Megaproject leaders should also be individuals who have demonstrated their capabilities in the context of the five critical activities outlined in the framework. While it is unlikely that individuals will have done so on such a large scale, looking for examples where individuals have successfully handled uncertainty, worked with very diverse teams, and managed risk effectively are good indicators that they will have the skillset to successfully handle megaprojects.

TRAINING MEGAPROJECT LEADERS

We created a megaproject leadership skills framework (Figure 47) and mapped the critical skills to the current DAU Advanced Leadership Development (ALD) program training.

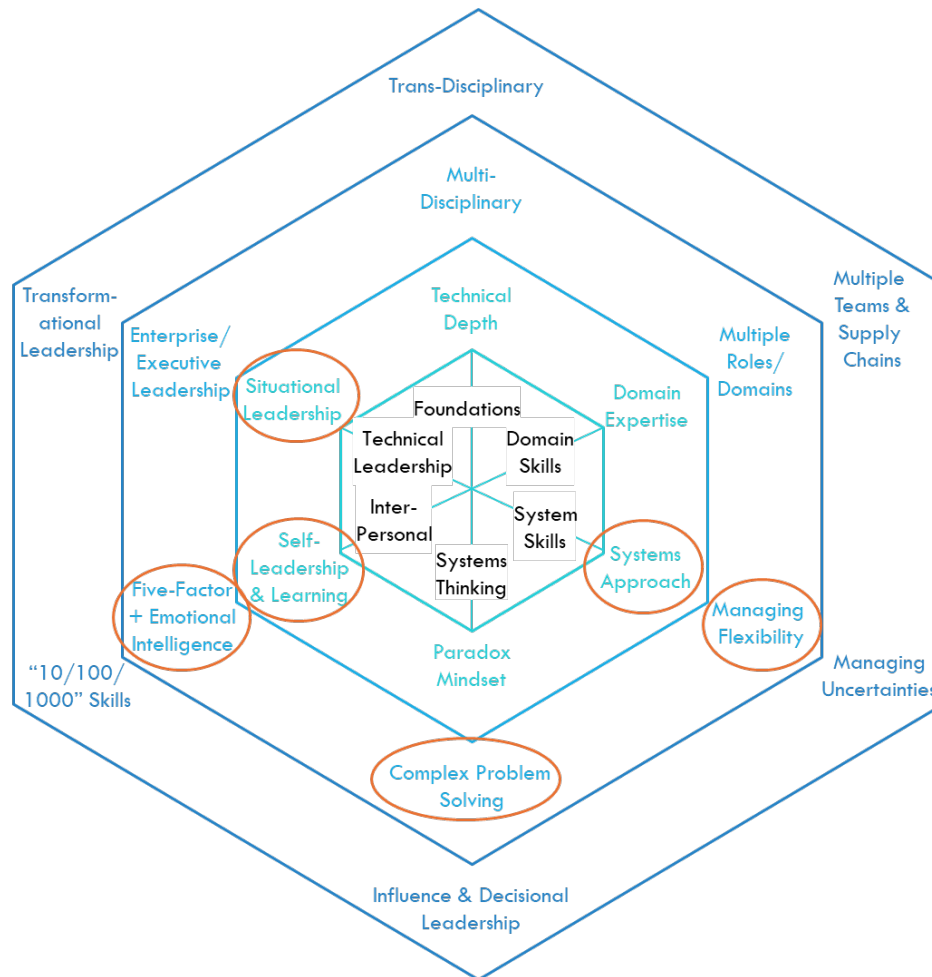


Figure 47. Megaproject Leadership Skills Mapped to DAU Training.

This includes courses ALD1100 “Growing as an Acquisition Leader” and ALD 2100 “Leading Through Others”, as well as several shorter self-paced video-based courses. We found good coverage of the topics (circled items) in layer 1 of the framework, indicating these courses are a good foundation to megaproject leadership. We also found good coverage of the topics in layer 2, however Enterprise/Executive Leadership was lacking coverage (although these topics are taught outside of DAU for military and civilian leadership). The six topics in the outer layer, which are more specific to megaprojects, are not taught. Because most DoD acquisition professionals will experience some aspects of a megaproject in their careers due to the number of DoD MDAPs, we would recommend that introductory megaproject leadership training be offered by DAU. This would include leading transdisciplinary development (highly related to innovation), leading complex supply chains, leading with influence, scaling great teams (the 10/100/1000 skills), and transformational leadership. Each of these topic areas is learnable and has related academic curriculum.

CONCLUSIONS

Effective leadership is the cornerstone of successful megaproject management, distinguishing projects that deliver on their promises from those that fail to meet cost, schedule, or outcome expectations. This paper has identified a comprehensive framework of six key competency areas—ranging from domain expertise and personal characteristics to advanced interpersonal and enterprise technical leadership skills—that are crucial for megaproject leaders. The findings underscore that while technical proficiency and experience in managing complex systems are essential, they must be complemented by strong interpersonal skills, a strategic mindset, and the ability to navigate uncertainty and risk.

Moreover, the analysis reveals that successful megaproject leaders are characterized not only by their expertise but also by their capacity for self-awareness, openness, and a paradox mindset. Organizations should focus on these competencies when selecting and developing megaproject leaders, moving beyond conventional criteria that emphasize experience in smaller projects. Ultimately, by cultivating leaders with the right mix of skills and attributes, organizations can significantly increase the likelihood of megaproject success, achieving transformational impacts on infrastructure and society at large. This research offers a critical roadmap for understanding the complexities of megaproject leadership and suggests pathways for improving project outcomes through more effective leadership selection and development strategies.

A great deal more is riding on the success of the megaproject than just the individual project itself. ... The public's trust and confidence in public leadership and institutions may stand in the balance. Earning and retaining that trust and confidence is the responsibility of all of us in the public sector.

Bearfield & Dubnick (2009)

THREE PROGRAM DESIGN STRATEGIES TO MANAGE UNCERTAINTY IN MEGAPROJECTS

Three emerging strategies in the DoD should have consequential impacts on the successful performance of megaprojects, as indicated by the literature. These are Digital Engineering (DE), Modular Open Systems Approach (MOSA), and Agile Development. These concepts are essential to manage knowledge in megaprojects. DE, or a “single modeling environment” as noted in the T5 project, greatly increases knowledge visibility and transfer between disciplines, teams, and suppliers. MOSA, particularly modularity, encapsulates knowledge in terms of reuse of already developed technologies and components. Both strategies were noted in the Findings and Recommendations section of the Executive Summary Report. Agile development strategies support the “Least Responsible Moment (LRM)” concept discussed in the Playbook Report. The team did not conduct extensive research on these strategies because they have been studied extensively in other SERC/AIRC reports.

Play 5. Decide at the last responsible moment (LRM)

The LRM was developed from the theory of constraints and popularized by the agile software movement. It is a strategy of delaying a decision until the moment when the cost of not making the decision is greater than the cost of making it. Rather than doing everything you need to do all at once, you do something either at the point at which you need it, or at the point at which it would be irresponsible not to do it. This can be carried out by any discipline and at any phase of a project (Ingenu, 2018).

1. Develop requirements iteratively, do not freeze requirements prior to the “last responsible moment” but rapidly execute afterward.
2. Develop the design iteratively, do not freeze design prior to the “last responsible moment” but rapidly execute afterward.

Play 7. Invest in flexibility to manage risk & uncertainty

Deploy modularity:

1. Create modularity in design, modularity isolates necessary knowledge
2. Enforce modularity in build, this simplifies integration and test

Play 8. Invest in digital models and environments for design and project execution

1. Invest in single modeling environments to allow all design teams to share all data, models, drawings and written design information.
2. Identify key performance drivers and invest in high fidelity models to evaluate/validate performance early.
3. Use multidimensional trades and value engineering to look at what could be simplified or reduced in scope without impacting customer experience.
4. Build predictive models of key parameters in the System Context.
5. Create guidelines and training that set out the principles of the design for all the team. This item is critical as it creates alignment between disciplines and suppliers on the goals of the design.

QUALITATIVE & QUANTITATIVE MODELING TO CAPTURE KNOWLEDGE IN MEGAPROJECTS

The research team conducted a literature review and analysis of different types of qualitative and quantitative analysis tools that would aid in the discovery and management of knowledge transfer in megaprojects. This section covers those investigations. Three modeling approaches were assessed:

- Hetero-Functional Graph Theory (HFGT)
- Concept-Knowledge Theory (C-K)
- System Theoretic Process Assessment (STPA)

TOWARDS A HETERO-FUNCTIONAL GRAPH THEORY APPROACH TO MEGAPROJECT MANAGEMENT (AMIRREZZA HOSSEINI, AMRO M. FARID)

This research proposes the use of Model Based System Engineering (MBSE) and Hetero-Functional Graph Theory (HFGT) to model the complexity of megaprojects and support analyses that can bring their costs and schedule back under control. As the megaproject management literature is rapidly evolving with a significant amount of divergence between authors, this report builds upon the recent and extensive megaproject management review provided by (Denicol et al., 2020). More specifically, Denicol et al. concludes with four self-reinforcing research directions: 1) design the megaproject management system architecture, 2) bridge the theoretical gap between megaproject management and manufacturing, 3) evaluate the potential for collaborative decision-making, and 4) address the significant supply chain challenges associated with megaproject management. Consequently, this report aligns its argument with these four research directions as a proxy for megaproject management literature as a whole. Our research focuses on advancing the application of MBSE and HFGT to megaproject management, particularly in response to the challenges highlighted by Denicol et al. Furthermore, to facilitate the argument, the management of a megaproject is classified as a convergent system-of-systems where the mega-project requires multiple unlike systems to be integrated into a single system; and done so in a manner that utilizes a common (i.e., convergent) language.

The remainder of this section proceeds as follows. Section II provides a background to (formal) graph theory, multilayer networks, and their limitations. It also exposites the HFGT meta-architecture as a means of overcoming these limitations. Section III then relates the HFGT meta-architecture to the complexities found in megaproject management. Section IV then elaborates HFGT's potential to address six key themes found in the megaproject management literature. Finally, section V concludes the work.

II. BACKGROUND: MODEL-BASED SYSTEMS ENGINEERING (MBSE) & HETERO-FUNCTIONAL GRAPH THEORY (HFGT)

This paper's proposed use of MBSE and HFGT is based upon the recognition that many project management techniques are ultimately rooted in graph theory and multi-layer networks. Consequently, this section introduces graph theory in Sec. II-A and multi-layer networks in Sec. II-B and some of the limitations that may impede their utilization in the context of mega-project management. Sec. II-C then discusses the HFGT meta-architecture as a means of overcoming some of these limitations.

A. Graph Theory and its Limitations

Graph theory has presented a useful abstraction across many applications because it is predicated on the construction of a graph.

Definition 1 – Graph : $G = \{V, E\}$, consists of a collection of nodes V and a collection of edges E . Each edge $e \in E$ is said to join two nodes which are called its endpoints. If e joins v_1, v_2 in V , we write $e = (v_1, v_2)$. Nodes v_1 and v_2 , in this case, are said to be adjacent. Edge e is said to be incident with nodes v_1 and v_2 respectively (van Steen, 2010).

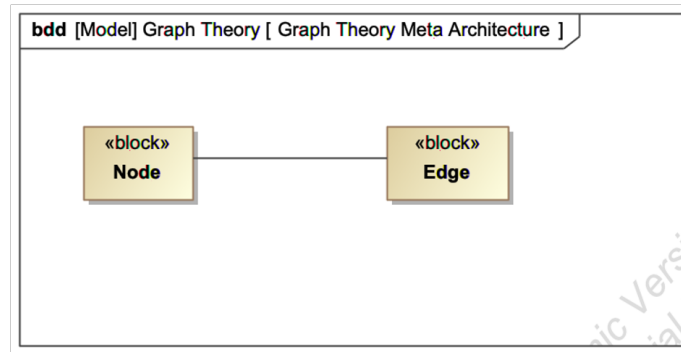


Figure 48. Block Definition Diagram of the Graph Theory Meta Architecture.

While the above definition recognizes that all systems are composed of interconnected constituent elements, it has limitations in the systems engineering of convergent systems-of-systems. From a MBSE perspective, Defn. 1 implies a graph theory “meta-architecture” as depicted in the block definition diagram in Figure 48. A block definition diagram of the graph theory meta-architecture is presented in Figure 48. Here, a meta-architecture is an architecture that describes multiple systems in a domain-agnostic language/ontology without reference to the multiplicity caused by instantiation. Consequently, a transportation system might have many intersections and roads, but the intersections are still nodes, and roads are still edges. Note that graph theory, as it is traditionally and most commonly applied, focuses primarily on an abstracted model of a system’s form; neglecting an explicit description of the system’s function. The system function, what a system does, in terms of verbal phrases, has been entirely omitted from the explicit statement of the formal graph and any understanding of the system’s function is implicit. For example, the same transportation system may be used to allow vehicles to move along roads from one intersection to another, but this transportation function is implied by the graph rather than explicitly stated. Consequently, the graph theory meta-architecture is quite limiting and it is less than clear how formal graph theory may be applied to convergent systems-of-systems that are fundamentally transformative with multiple operands. As convergent systems-of-systems are *hetero-functional*, formal graph theory may impede rigorous approaches where multiple and unlike megaproject management functions and operands can be modeled.

B. Limitations of Multi-Layer Networks

To overcome many of the analytical limitations of (formal) graph theory, the network science literature has advanced the concept of “multi-layer networks” where two or more network “layers” interact with each other.

Definition 2 – Multi-Layer Networks : Much like a conventional graph, a multi-layer network $G_m = \{V_m, E_m\}$ is formally defined as a tuple of nodes V_m and edges E_m . Such a multi-layer network is organized into an integer n number of layers $L_1 \dots L_n$. Here, a given layer $L_\alpha = \{V_\alpha, E_\alpha\}$ is understood as a graph where the nodes V_α and edges E_α have at least one semantic aspect, feature, or operand in common (e.g. electricity, water, people, etc.) (Kivela, et al., 2014)

From an MBSE perspective, Defn. 2 multi-layer network implies the meta-architecture depicted in Figure 49. The node block is retained, and the edge block becomes an intra-layer edge block. Both of these become part of a layer as a new block. Finally, an inter-layer edge is added with associations to two nodes and two layers. Alternatively, a multi-layer network can be conceptualized using the meta-architecture in Figure 49. In this case, a multi-layer network retains the node and edge blocks from the graph theory meta-architecture in Figure 48 but makes sure to label each node with its associated layer (attribute) and each edge with its origin and destination node and layer.

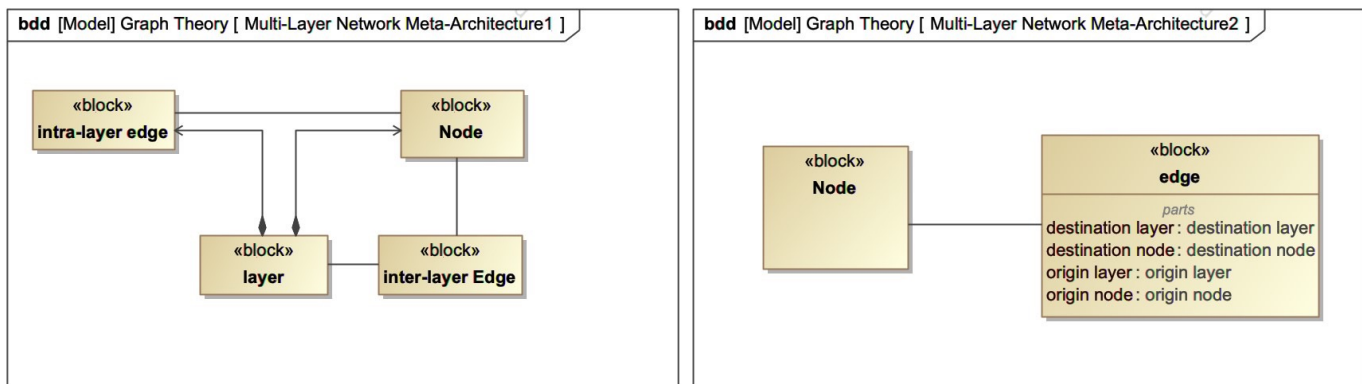


Figure 49. (left) Block Definition Diagram of a Multi-Layer Network Meta Architecture. (right) An Alternative Block Definition Diagram of a Multi-Layer Network Meta Architecture.

Despite the expanded meta-architecture of multi-layer networks, Kivela et al, in their comprehensive review, showed that *all* multi-layer network models have from at least one of the following limitations (Kivela et al., 2014):

1. Alignment of Nodes between layers
2. Disjointment between layers
3. Equal number of nodes for all layers
4. Exclusively vertical couplings between layers
5. Equal couplings between layers
6. Node counterparts are coupled between all layers
7. Limited number of modeled layers
8. Limited number of aspects for each layer

To demonstrate the consequences of these modeling limitations, the HFGT textbook conceived the hypothetical system shown in Figure 50 as an example that cannot, at present, be modeled with multi-layer networks. In contrast, a complete HFGT analysis of this hypothetical test case was demonstrated in the aforementioned text (Schoonenberg et al., 2019). To follow up this result, the tensor formulation of hetero-functional graph theory proved that multi-layer networks are neither ontologically lucid nor complete (Farid, Thompson, & Schoonenberg, 2022). As the management of mega-projects is likely to exhibit at least one of the characteristics described above, multi-layer networks are likely to present modeling limitations that result in analytical impasses.

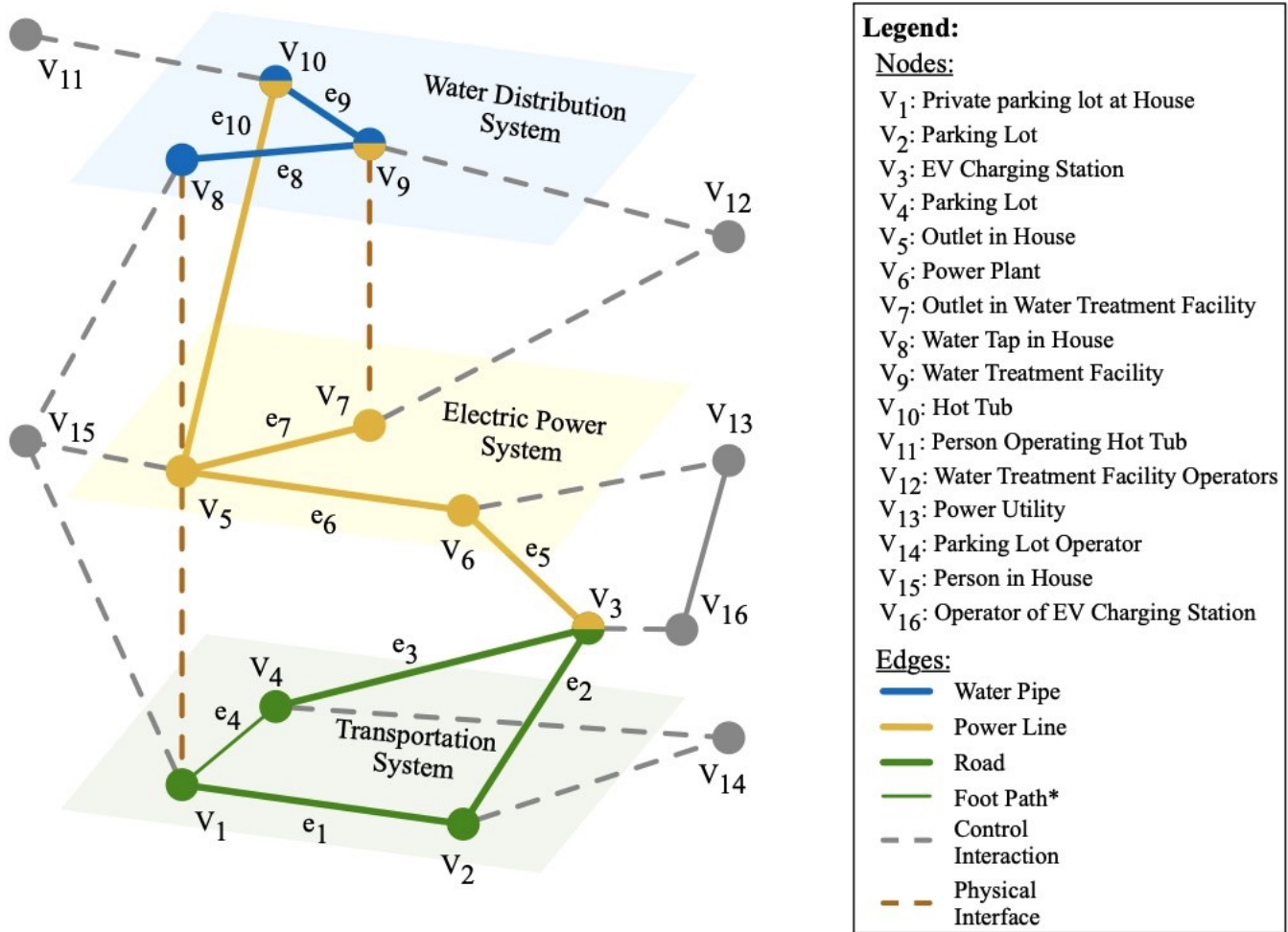


Figure 50. A Hypothetical Four-Layer Network including transportation, electric power, water distribution, and decision-making elements that exhibit all eight of the modeling constraints found in multi-layer networks. [Schoonenberg, et al., 2019]

C. The HFGT Meta-Architecture

Sections II-A and II-B revealed that (formal) graph theory and multi-layer networks exhibit ontological limitations that impose analytical limitations in the context of mega-project management. Ultimately, one of the main sources of complexity in mega-projects is not just their size but also their heterogeneity in structure and function. In contrast, HFGT has a rich meta-architecture that has the potential to address this heterogeneity. While a complete treatment of HFGT is not feasible here, a brief exposition elucidates its value to megaproject management.

Rather than using nodes and edges as its starting point, hetero-functional graph theory recognizes that humans' ability to describe (engineering) systems is rooted in natural language and more specifically subject + verb + object sentences. Consequently, the HFGT meta-architecture shown in Figure 51 states that engineering systems (e.g. mega-project management enterprises) are composed of (cyber and physical) operands as objects and (physical and decision-maker) resources as subjects. Naturally, these physical and decision-maker resources also carry out processes as verb + operand predicates. Ultimately, the combination of a resource and a process creates a capability that serves as a node in a hetero-functional graph and the logical sequence of two sentence-capabilities becomes an edge.

Building upon the central theme of subject-verb-object sentences, the HFGT meta-architecture in Figure 51 recognizes that there are fundamental differences between the types of operands, resources, and processes. These differences – when recognized within the ontology of HFGT – directly support analyses of complex engineering systems like mega-projects. Physical operands are classified into matter, energy, and living beings because they exhibit distinguishing features that are lost if the categories are merged. Consequently, HFGT treats a megaproject as an aggregated physical operand (composed of matter, energy, and living beings) that a mega-project management enterprise (as an engineering system) must deliver. This mega-project (as a physical operand) has a state that is initialized at its start, evolves through transitions connected by arcs as it proceeds, and ultimately concludes. The mega-project management enterprise is also composed of transformation resources, independent buffers, and transportation resources (as physical resources) that realize transformation, holding, and transportation processes on the mega-project and its constituent matter, energy, and living being operands. The distinction between transformation and transportation stems from the preference toward value-adding (vs non-value-adding) activities in manufacturing. In the meantime, the spatial distribution of complex engineering systems (like megaproject management enterprises) necessitates transportation processes. The mega-project management enterprise is also composed of cyber-operands that represent information and money. These underscore the digital and financial considerations inherent to complex engineering systems. Finally, a mega-project management enterprise is composed of a plethora of decision-making resources including clients/sponsors, prime contractors, suppliers, operators, and other stakeholders. These decision-making resources have explicit roles that include measurement processes (that pull information from physical resources and operands), decision processes (that send information to physical resources and operands, cyber-transformation processes (that create/destroy cyber-operands e.g. creation of money/information), and cyber-transportation processes (e.g. money transfer and information communication). In all, HFGT recognizes the fundamental differences between types of operands, resources, and processes while still retaining the underlying simplicity of subject + verb + object sentences.

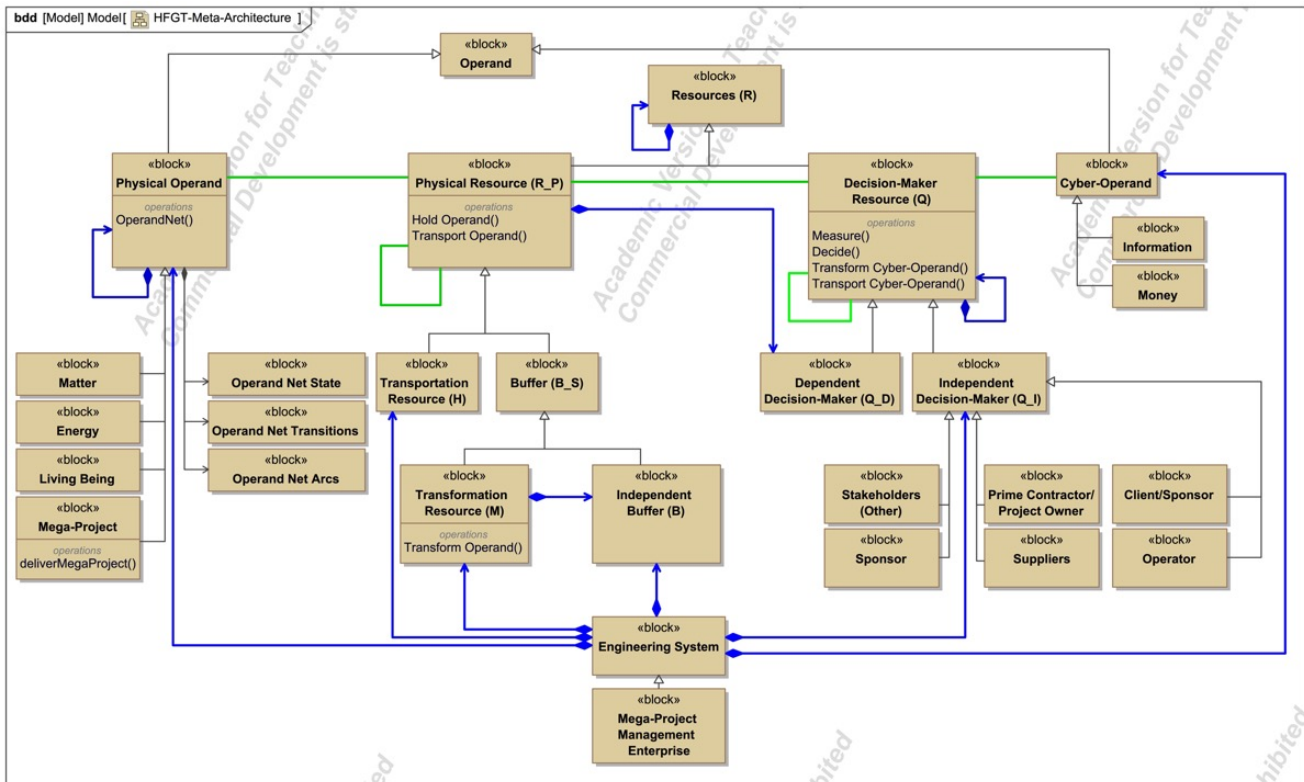


Figure 51. Block Definition Diagram of the HFGT Meta Architecture.

In addition, HFGT has demonstrated its versatility and broad applicability across many scientific and engineering disciplines; underscoring its potential in convergence science. HFGT’s ability to model heterogeneous networks of arbitrary topology and connect them in flexible ways surpasses the capabilities of traditional multi-layer networks. This adaptability makes HFGT valuable to a wide range of professionals. For natural and engineering scientists, HFGT provides a framework to reconstitute conservation laws within complex systems. Decision and control scientists can use HFGT to support diverse decision-making structures, whether centralized, decentralized, or distributed. Systems engineers find a natural translation from SysML into quantitative models with HFGT, while operations researchers benefit from its generalization of minimum cost flow principles. Furthermore, social scientists can bridge the gap between qualitative insights and quantitative models using HFGT, and applied mathematicians can extend their work with the theory’s solid foundation in graph theory and tensor analysis. Collectively, these attributes demonstrate HFGT’s significant potential to unify disparate fields within convergence science, fostering interdisciplinary collaboration and innovation.

Finally, HFGT has made foundational contributions to the structural analysis of complex systems. HFGT’s versatility allows it to be applied to complex systems of systems with arbitrary topologies, making it highly adaptable to various urban and engineering contexts. The theory’s extensibility enables it to incorporate numerous physical elements and functions, ensuring comprehensive coverage of the system under analysis. HFGT is inherently designed to manage directed graphs, which are crucial for representing the directional flow of resources and information in complex systems. Moreover, HFGT is fundamentally cyber-physical, integrating both physical and digital aspects of system architecture. Ultimately, HFGT posits that beneath the specific applications lies an underlying meta-architecture that can be applied generically across different domains, offering a unified and convergent framework for understanding and optimizing a wide range of complex engineering systems.

III. APPLYING THE HFGT META-ARCHITECTURE TO MEGAPROJECT MANAGEMENT

In light of the HFGT meta-architecture introduced in Sec. II-C, this section now seeks to relate it to the complexities of megaproject management that Denicol et al. articulate in the introduction of their literature review. The HFGT meta-architecture provides a systematic and structured framework for bridging the gap between theoretical/quantitative models and the practical challenges in managing large-scale projects. The following discussion explores how HFGT can address key aspects of megaproject management including the coordination of diverse stakeholders, the decomposition of complex projects into manageable components, and the integration of decision-making processes across various levels of project execution.

- Megaprojects are inherently established as temporary organizations, led by various entities such as client teams, prime contractors, or coalitions of multiple parties, which may include owners, sponsors, and other stakeholders. These entities collaborate on a shared activity within an uncertain environment. HFGT offers a systematic approach to modeling these complex, temporary structures by decomposing them into key components. First, HFGT conceptualizes the megaproject itself as an operand that may have an uncertain state and evolution. Furthermore, the megaproject management enterprise creates the organizational structures for the conduct of the megaproject itself. Its decision-making resources include stakeholders, prime contractors, temporary alliances, joint ventures, and coalitions of multiple parties. Such a model transparently identifies the complex interrelationships between all components of the megaproject and their inherent uncertainties.
- Megaprojects are often decomposed into smaller, interrelated projects, which are then organized as part of a larger program. HFGT addresses this complexity by treating the megaproject as an operand that may be decomposed into additional operands that represent projects in and of themselves. Because operands can be systematically decomposed into smaller parts, it is possible to implement a structured approach to managing the detailed relationships and dependencies between smaller projects and the larger megaproject. In addition to a mathematical description, the visualization of the mega-project architecture facilitates the seamless integration of the component projects and augments the potential for effective coordination and management.
- Megaprojects also require robust organizational structures to coordinate the efforts of multiple entities, such as the client, prime contractor, and suppliers. HFGT effectively models these complex organizational structures within a mega-project management enterprise composed of decision-making resources that include these entities. In HFGT, these decision-making resources have agency over their respective physical resources (i.e., technical assets and human resources). This creates a mega-project management enterprise architecture where decision making resources and their processes are integrated with physical resources and their processes and these are in turn applied to the execution of the megaproject itself. This architectural description can enhance transparent oversight over and alignment between all aspects of the project including the coordination between subgroups and the management of physical, financial, and informatic interfaces. Furthermore, HFGT's ability to quantitatively model these interactions is vital to optimizing time, cost, and quality goals for all stakeholders involved.

- Mega-project management suffers from distinct theoretical foundations and analytical frameworks that collectively lead to piecemeal approaches and solutions. In contrast, HFGT converges all aspects of the mega-project management enterprise within its meta-architecture as a unifying ontological and architectural framework. More specifically, decision-making resources and their processes can provide a cohesive understanding of decision-making, leadership, teamwork, and team integration within a unified system. Returning to the meta-architecture in Figure 51, the decomposition arrows (in blue) and association links (in green) identify these relationships explicitly. While traditional leadership, in a socio-psychological sense, is not directly modeled, HFGT captures the hierarchical structure and peer-to-peer interactions between decision-makers. Therefore, it can offer a comprehensive framework for analyzing the multifaceted nature of megaproject management enterprises. Furthermore, HFGT asserts that such a meta-architecture can serve as a unifying theoretical foundation for the complex, integrated, and quantitative analyses required in megaproject management. Such an integrated approach can serve to reconcile disparate and partial theoretical approaches and ultimately offer a cohesive strategy for understanding and managing large-scale, multifaceted projects.

In all, Denicol et al. emphasize the need for new theory-building research that adopts a systemic view founded in production systems and integrates the various aspects of megaproject management performance. HFGT aligns with this recommendation by offering a unifying theoretical foundation and quantitative framework for the analysis of megaprojects. Furthermore, it is important to recognize that the earliest works on HFGT address mass-customized production systems that bear many of the same features found in mega-projects. Denicol further observes that the terminology within the field of megaproject management lacks convergence. Different authors use different conceptualizations and different terms to describe the same phenomena. In contrast, HFGT imposes a consistent and convergent terminology throughout its meta-architecture. Operand, resource, and process definitions are clearly stated and their classifications are transparently made. This meta-architecture has already proven to be effective across a range of domains, including mass-customized production systems, transportation systems, energy systems, water systems, and healthcare systems. Most recently, HFGT's potential for convergence has been recognized with a \$3.6M National Science Foundation (NSF) Growing Convergence Research project (NSF, 2024). This extensive evidence across a wide variety of disparate application domains suggests that HFGT's approach to imposing a unified terminology and framework is well-suited to the domain of megaprojects.

IV. ADDRESSING MEGAPROJECT MANAGEMENT THEMES

In addition to their introductory exposition on megaproject management, Denicol et al. analyzed 86 articles to identify six key themes that impact megaproject performance: 1) decision-making behavior, 2) strategy and governance, 3) risk and uncertainty, 4) leadership and capable teams, 5) stakeholder engagement, and 6) supply chain integration. This section elaborates HFGT's potential to address these six key themes.

A. Decision-Making Behavior

In general, HFGT addresses decision-making through its decision-making resources, the decision-making processes allocated to them, and the serial and parallel arrangement of these processes. Denicol et al. further elaborate three critical issues under the decision-making behavior theme: 1) optimism bias, 2) strategic misrepresentation, and 3) escalating commitment. To mitigate optimism bias, HFGT has produced stochastic discrete-event simulation models that offer a more realistic depiction of system execution, potentially reducing overly optimistic expectations, and allowing for a more accurate assessment of potential risks (Kayal & Farid, 2021). Additionally, such stochastic discrete-event simulation models can quantify the negative impacts of optimism bias on megaproject management lead times, delivery, and resilience. Strategic misrepresentation is a more complex socio-cultural issue where decision-makers may mislead or be incentivized to mislead stakeholders. An HFGT model is unlikely to resolve such a problem because all models are only as good as the data they are built upon. Nevertheless, the development of a consistent and unified framework is much more likely to transparently reveal inconsistent modeling assumptions and data; thereby creating a moderate deterrent against strategic misrepresentation. Finally, HFGT addresses escalating commitments where decision-makers persist in a failing direction of project execution and ignore alternative pathways to project completion. Because HFGT is ultimately a type of graph theory, it identifies lower-risk options and execution pathways as alternative paths through a hetero-functional graph (Farid, 2015) and thereby facilitates their selection. By applying these analyses, HFGT enhances the rationality of decision-making processes, mitigates common behavioral pitfalls in megaproject management, and supports more effective and informed decision-making throughout the project.

B. Strategy, Governance, and Procurement

HFGT also addresses strategy, governance, and procurement within the structure and function of its decision-making architecture. In this context, Denicol et al. identify three key concepts: 1) the roles and responsibilities of stakeholders, 2) governance structures, and 3) delivery model strategies. Perhaps one of the most confounding aspects of megaprojects is that the processes of physical execution and decision-making pertaining to the megaproject are distributed amongst a plethora of stakeholders. There is no single entity that has the authority to compel the execution of all parts of the megaproject. Consequently, the only hope for successful execution of the megaproject is when all stakeholders understand their respective roles and responsibilities. Fortunately, and as mentioned previously, HFGT explicitly identifies all physical and decision-making processes in the megaproject management enterprise and allocates them to their associated physical and decision-making resources. This allocation provides clarity to all stakeholders as to their respective roles and responsibilities. Furthermore, the HFGT meta-architecture admits aggregations of decision-making resources and processes; thus enabling the construction of complex governance structures such as teams, committees, organizations, and consortia. Finally, the HFGT literature provides many examples of modeling peer-to-peer relationships in supply chains in production, service, and infrastructure systems that span multiple organizations (Farid, 2015; Thompson & Farid, 2024; Thompson & Faird, 2012; Schoonenberg & Farid, 2022).

C. Risk and Uncertainty

HFGT also provides a structured approach to addressing risk and uncertainty. In this context, Denicol et al. highlight three key challenges: 1) technological novelty, 2) flexibility, and 3) complexity. These challenges are critical as they influence the successful management and execution of large-scale projects. Technological novelty introduces risks associated with first-of-their-kind technologies, where balancing between the reuse of established technologies and innovative designs is essential. Flexibility refers to the system's ability to adapt to changing circumstances. Complexity involves managing the numerous parts and interrelationships within a megaproject and its external interactions. HFGT offers a structured approach to modeling and managing these challenges. Generally speaking, risk and uncertainty are represented as stochastic quantities within the system, supported by HFGT's ability to simulate discrete events. More specifically, and for technological novelty, HFGT distinguishes between "known-unknowns" and "unknown-unknowns". For "known-unknowns", a system's parametric model allows for detailed analysis. Yet "unknown-unknowns" are harder to manage as they represent design challenges that cannot be easily modeled before they exist. In terms of flexibility, HFGT addresses design, construction, and supply chain flexibility. More specifically, it distinguishes between the existence and availability of megaproject capabilities; recognizing that while some capabilities may not be currently utilized, it may take relatively straightforward to make them available. This distinction allows the megaproject management enterprise to respond to foreseen and unforeseen risks and systematically develop resilience as a life cycle property. Finally, HFGT provides tools to quantify and manage complexity. It specifically models modularity, decomposes the system into manageable modules, and controls the cascading risks across the mega-project management enterprise. By integrating these strategies, HFGT offers a comprehensive framework that addresses the risks and uncertainties inherent in megaprojects.

D. Leadership and Capable Teams

In exploring the theme of leadership and capable teams within megaprojects, Denicol et al. identify three key concepts: 1) project leadership, 2) competencies, and 3) capabilities. Project leadership puts emphasis on the need for dedicated champions and leaders who are committed to the project's success. Competencies refer to the essential skills and abilities that individuals within project teams must possess. Capabilities, on the other hand, represent the collective organizational knowledge and ability to produce specific products or services, relying on effective team collaboration. HFGT addresses these areas by offering a structured approach to model the roles, competencies, and capabilities within an organization. Generally speaking, leadership is captured by modeling decision-makers and capable teams as physical resources within the project. Stakeholders are also treated as decision-makers with process-level influence. More specifically, with respect to project leadership, it models their formal roles and clarifies how leadership functions within the megaproject enterprise management structure and goals. Additionally, HFGT includes individual competencies as processes and these competencies functionally aggregate to form the organization's overall capabilities. By integrating competencies within a broader MBSE framework, HFGT enhances human resource management; ensuring that the necessary skills and knowledge are utilized effectively throughout the megaproject management enterprise. Furthermore, HFGT models the relationships between different competencies which is necessary for building team-based organizational capabilities. Finally, HFGT has yet to address the subtle socio-cultural differences of leadership and conflict management. To that effect, recent works on the propagation of socio-cultural and socio-psychological factors in social networks present an interesting direction for further investigation. In all, through its structured approach, HFGT supports the alignment of leadership and team structure with overall project objectives; contributing to the successful execution of megaprojects.

E. Stakeholder Engagement and Management

In the context of stakeholder engagement and management within megaprojects, Denicol et al. identify three critical concepts: 1) institutional context, 2) stakeholder fragmentation, and 3) community engagement. The institutional context encompasses the formal organizational structures, rules, and norms that govern the megaproject. Stakeholder fragmentation refers to the challenges posed by the involvement of multiple parties; often leading to complex and sometimes conflicting interactions among stakeholders. Community engagement ensures that local populations are considered and integrated into the megaproject's execution. As mentioned previously, HFGT models these complexities through its decision-making architecture. For institutional context, HFGT models formal organizational structures and rules, to clearly represent the project's institutional framework. However, the formality of HFGT is less able to describe informal norms and other "unwritten rules" of an organization. To manage stakeholder fragmentation, HFGT directly model and thus identify the stakeholder fragmentation. In this respect, it is particularly important to recognize when multiple stakeholders have conflicting agency over another stakeholder. Once identified, new decision-making processes and governance mechanisms should be designed, modeled, and implemented to resolve the potential for conflicting agency and manage the the diverse interests of stakeholders. In terms of community engagement, it is important to recognize MBSE's long tradition of participatory modeling. From there, MBSE models (i.e., in SysML) can be algorithmically converted into the HFGT counterparts. Through its structured approach and integration with MBSE, HFGT enhances the project's ability to navigate complex stakeholder environments, and provides a means for incorporating local community interests into the decision-making processes of the megaproject management enterprise.

F. Supply Chain Integration and Coordination

Finally, HFGT supports a wide range of continuous and discretized supply chain models; offering a comprehensive framework that integrates these critical aspects of megaproject management into a unified system for analysis and optimization. According to Denicol et. al, the supply chain integration and coordination theme focusing on: 1) program management, 2) commercial relationships, and 3) systems integration. Program management involves establishing the systems, procedures, and tools necessary to monitor, control, and optimize benefits across multiple interrelated projects. Commercial relationships refer to the formal interactions between organizations delivering projects and sub-projects. Systems integration is concerned with the technical and managerial capabilities required to combine various components produced by different parties into a cohesive operational asset. HFGT provides a structured and comprehensive framework to model these critical components within a megaproject context. HFGT allows for the straightforward representation of a megaproject as an aggregation of multiple smaller projects; each managed by physical resources and decision-maker resources. Thus, it facilitates the clear depiction of complex interdependencies within the supply chain. By formalizing contractual relationships and supporting change order processes, HFGT enhances program management; facilitating the potential for a live digital twin representation of the megaproject's management. Additionally, HFGT can use contract nets to model complex commercial interactions such as games or auctions and subsequently calculate performance metrics. Systems integration is inherently supported by HFGT, as it models the physical and cyber operands passed between physical and decision-making resources. This comprehensive approach ensures that all aspects of the supply chain – from the planning and execution of individual projects to the integration of their outputs into the final deliverable – are effectively coordinated and controlled.

V. CONCLUSION

This paper proposes the use of MBSE and HFGT to address the complexities found in megaproject management. One of the primary challenges in megaprojects is the lack of a convergent understanding of these projects as complete production systems; encompassing planning, design, manufacturing, construction, and integration into operations. HFGT addresses this gap by providing a systematic approach that models megaprojects as a convergent systems-of-systems. This method considers the interdependencies between different phases of a megaproject; enabling a more complete study of how value is created, evolved, and transferred across the megaproject management enterprise. MBSE provides a graphical means of describing these interdependencies, and HFGT translates these graphical models into their mathematical counterparts. Furthermore, HFGT can simulate megaprojects as stochastic discrete-event systems which provide a clear, quantitative, and unbiased foundation for decision-making. Such an analytical capability enhances quantitative objectivity in risk and uncertainty management. Furthermore, HFGT can model the structural relationships within megaproject management to help identify single points of failure and other structural vulnerabilities. Finally, the HFGT's attention to a system's decision-making architecture provides a basis for identifying, engaging, and managing stakeholders and their often conflicting interests.

In all, MBSE and HFGT provide a means for addressing for many of the concluding recommendations provided by Denicol et. al.

- MBSE and HFGT not only model the megaproject management enterprise, they provide a systematic means for its quantitative analysis.
- HFGT's origins in mass-customized, reconfigurable manufacturing systems facilitates the placement of megaproject management on a firm manufacturing system foundation.
- HFGT specifically addresses a diversity of collaboration/decision-making architectures including centralized, distributed, decentralization, hierarchical, coordinated/uncoordinated and thereby well-equipped to managing and assessing multi-stakeholder collaborations.
- An MBSE-HFGT workflow can engage communities and institutions in participatory (graphical) modeling and support collaboration through mathematical analysis (as evidenced by the recently funded NSF GCR project).
- HFGT supports a wide range of continuous and discretized supply chain models; offering a comprehensive framework that integrates these critical aspects of megaproject management into a unified system for analysis and optimization.

By addressing Denicol et al.'s concluding recommendation, MBSE and HFGT not only align with current megaproject management research needs but also push the boundaries of how megaprojects can be managed and optimized within a unified theoretical foundation.

CONCEPT-KNOWLEDGE THEORY AS METHOD TO QUANTIFY OBTAINED KNOWLEDGE

Traditional project integration methods, such as program evaluation and review technique (PERT), are extremely useful to manage and track plans and risks, but are not useful in managing and tracking uncertainties. Uncertainties fundamentally rely on integration of knowledge, not just resources and assets. (Lenfle, Le Masson, & Weil, 2016) introduce the use of Concept-Knowledge (C-K) design theory (Hatchuel & Weil, 2009) as a tool to manage highly complex and uncertain design processes in situations with transformational outcomes. We investigated the use of C-K theory as a qualitative approach to address uncertainties in the System and Implementation Contexts.

The name “C-K theory” reflects the assumption that design can be modelled as the interplay between two interdependent spaces with different structures and logics: the space of concepts (C) and the space of knowledge (K). Both pragmatic views of design and existing design theories define design as a dynamic mapping process between required functions and selected structures. However, dynamic mapping is not sufficient to describe the generation of new objects and new knowledge which are distinctive features of design. C-K theory intends to capture this generation and offers a rigorous definition of design.

C-K theory is both a design theory and a theory of reasoning in design. It defines design reasoning as a logic of expansion processes, for example a logic that organizes the generation of unknown objects. C-K theory also explains cognitive and collective aspects of design activities by specific mode of reasoning. It helps industries and companies be more creative, helps decision-makers, students or researchers develop more breakthrough technologies, solutions and innovation.

CK THEORY FRAMEWORK

The core idea of this framework is to separate concept and knowledge in two different spaces, and to keep in mind that the object of study **never** has invariant definitions and properties. For instance, the person practicing the theory should not take for granted that a chair has legs or a surface to sit on. The definition of a chair may evolve to a more abstract thing like: “something that maintains the user in a vertical position effortlessly”.

A concept is defined as a proposition that is neither true nor false. It generally will emerge from market needs (or mission needs in military contexts), that is when a technical or market requirement is not satisfied by existing solutions/technologies. Concepts are gathered on the C-space.

Knowledge is defined as the group of propositions with known logical status (we know if they are true or false): all that we (or the designer) know belongs to this. Knowledge is contained in the K-space.

C-K theory forces exploration of uncertainties into the real world of developmental projects: “it brings the innovation from the imaginary space, the conceptual space where new things are appearing, to the K-space or Knowledge space, and provide it with attributes. The new attributes for designed things extend our knowledge that will feed back the conceptual space” (Hatchuel & Weil, 2009).

C-K Theory has four main steps:

- 1. C-space (Concept Space):** where new ideas and possibilities are created and explored.
- 2. K-space (Knowledge Space):** where established knowledge and facts are stored and used to evaluate and develop concepts.
- 3. C → K:** transforming concepts into knowledge by validating or rejecting them.
- 4. K → C:** using existing knowledge to inspire new concepts.

We conducted an analysis of two concepts in the T5 Case Study and the corresponding knowledge space. This analysis was done from the historical literature on the T5 project, conducted in hindsight. It was done to assess the effectiveness and ease of use of the concept and should not be interpreted as relevant to T5 project outcomes.

C-K THEORY FOR HEATHROW TERMINAL 5 BAGGAGE CLAIM

Applying **C-K Theory** to the baggage handling system for Heathrow T5 involves breaking down the design and development process into the **Concept Space (C-Space)** and the **Knowledge Space (K-Space)**. In the case of T5, baggage handling was a critical system meant to ensure efficiency, reduce delays, and manage the high volume of luggage passing through the terminal. However, as widely known, the baggage system faced significant challenges when T5 was launched in 2008, leading to delays and operational problems. Let's apply the C-K Theory framework to the phases leading up to the launch to analyze the process:

The Initial Concept Development Phase (C-Space) has the conceptual goal for the baggage handling system to be fully automated, capable of handling 70,000 bags per day with high speed, accuracy, and reliability. The initial concepts, or high-level goals, include efficiency, automation, scalability, reliability, and security. In these goals, the concept expansion has the following:

- **Radio Frequency Identification (RFID) Tagging:** the idea of using RFID technology to track baggage in real-time.
- **High-Speed Conveyors:** the concept of fast-moving conveyors to transport luggage efficiently across the terminal.
- **Buffer Zones:** temporary storage for bags, allowing the system to manage early arrivals or bags for connecting flights.
- **Automated Sorting:** developing systems that automatically route bags to the correct flight or transfer point without human input.
- **Redundancy Mechanisms:** designing backup systems to maintain operations in case of system failure.

The Knowledge Exploration Phase (K-Space) grounds the expanded concepts in knowledge, both from past baggage systems and cutting-edge technologies that were new to the aviation industry at the time.

Existing Knowledge

- **Past Experience with Baggage Systems:** previous baggage handling systems at Heathrow and other large international airports provided a baseline for knowledge, including problems with delays, mechanical failures, and security concerns.
- **Industry Best Practices:** research into other major airports, like Denver International Airport's failed baggage system, offered valuable lessons about the risks of over-reliance on unproven technologies.
- **Technological Knowledge:** by the early 2000s, there was extensive knowledge about RFID tagging, x-ray screening, and the use of conveyors, but no airport had fully integrated these technologies into a single, automated system of the scale T5 envisioned.
- **Safety and Regulatory Requirements:** compliance with aviation security regulations, such as the need for thorough screening of each bag, placed constraints on system design.

Acquisition of New Knowledge

- **Prototype Testing:** before implementation, prototypes of baggage handling technologies were tested in labs and simulated environments to assess feasibility.
- **Consultations with Technology Providers:** experts in automation, RFID technology, and baggage system software were consulted to bring cutting-edge ideas into the design.
- **Feasibility Studies and Simulations:** detailed simulations of the baggage handling system were conducted to predict the flow of bags during peak operational hours. However, these simulations may not have fully accounted for real-world variability.
- **Case Studies on Automation:** analysis of previous airports that used some level of automation, such as Frankfurt and Amsterdam, provided insights into the benefits and risks of fully automating such a critical system.

Challenges Identified (Limits of Knowledge)

- **Complexity of Integration:** integrating multiple layers of technology (RFID, conveyors, screening systems) was a significant challenge. These systems needed to communicate seamlessly, but the knowledge required for such integration was still developing.
- **Unforeseen Human Behavior:** many early tests did not sufficiently account for how airport staff or passengers might inadvertently disrupt the system's operation (e.g., late baggage drop-offs or missed transfers).
- **Time Constraints:** tight deadlines to complete the project before T5's grand opening created pressure to finalize designs before all potential issues were fully explored.

Development and Implementation Phase (Interaction between C-Space and K-Space)

Below is the overarching aspect of the C-K space; however, there were nine different aspects of the baggage handling system (BHS) that were analyzed. Each analyzation resulted in further understanding, exploration, and solution spaces.

Iterative Concept Refinement

As the concepts were tested against the knowledge base, refinements were made:

- **Automated Sorting Systems:** initial concepts of a fully automated sorting system were modified to include buffer zones where luggage could be temporarily stored to accommodate flight delays or early arrivals.
- **Redundancy and Backup Systems:** recognizing the potential for mechanical failure, the concept of redundant systems was expanded. However, these redundancy mechanisms were not robust enough to handle the scale of the terminal on launch day.
- **Real-Time Monitoring:** the system was designed to include real-time monitoring, with feedback loops allowing operators to manage the flow of luggage dynamically. However, operational knowledge about how to manage such a complex system was still developing.

Knowledge Application in Implementation

- **Modular System:** based on knowledge from similar airports, a modular approach to baggage handling was adopted, where different components of the system could be serviced independently.
- **Training and Adaptation:** training programs were put in place for staff to operate the new system, although these were insufficient to prepare staff for the scale of the challenges that arose during the launch.
- **System Integration and Testing / Stress Testing:** the baggage system was tested extensively before launch. However, limitations in real-world testing—particularly stress testing the system under full operational loads—meant that some issues were not fully identified before the terminal became operational.

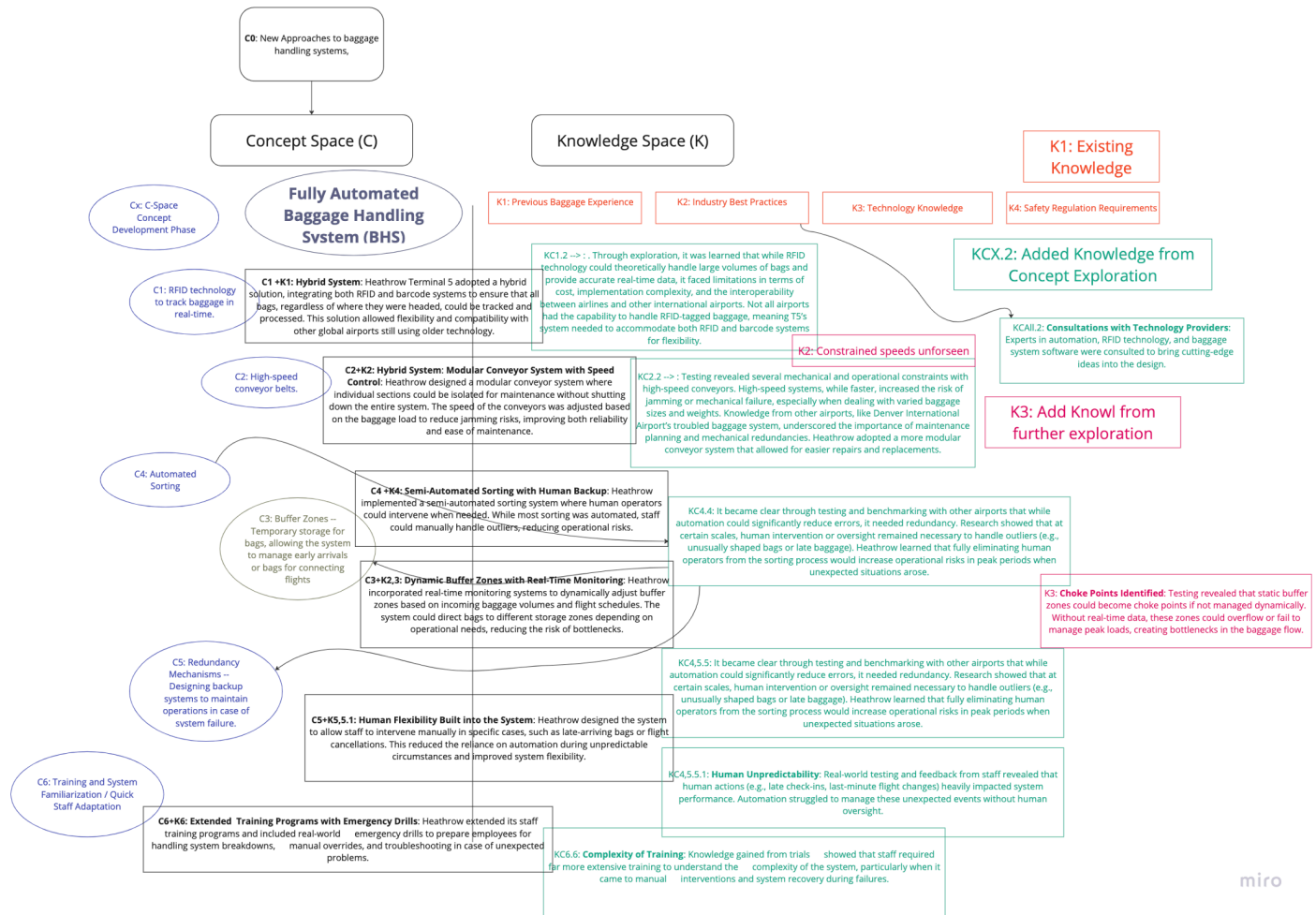


Figure 52. Snapshot of C-K Theory for T5 BHS.

Challenges on Launch Day (2008) – Knowledge Gaps and Concept Failures

Despite the extensive conceptual and knowledge development, the launch of Terminal 5 in 2008 was marred by significant failures in the baggage handling system:

- **Conceptual Failures**

- » The idea of a fully automated, smooth-running baggage system did not materialize on launch day. The system failed to cope with the sheer volume of luggage and real-world variability in passenger behavior and timing.
- » Redundancy mechanisms were not sufficient to manage the cascading failures that occurred when the system became overloaded. The idea that automation could fully replace human intervention was flawed, and the backup systems proved insufficient to handle the resulting operational failures.

- **Knowledge Gaps**

- » One of the main issues was the underestimation of the human factor: late baggage check-ins, last-minute flight changes, and staff unfamiliarity with the new system caused significant delays.
- » Real-time feedback loops between different components of the system were not functioning as expected, exacerbating the issue. There was limited knowledge about how to manage and troubleshoot such a complex and integrated system in a live environment, especially when multiple systems failed simultaneously. The real-time feedback mechanisms between different components of the system did not function as expected, revealing a gap in the understanding of how integrated systems would work under full operational loads.

Post-Launch Learning and Refinement

- **Feedback Loop:** the operational failures on launch day generated critical new knowledge, which led to adjustments in both the concept and the implementation of the baggage system.
- **Real-World Testing:** the concept of thorough stress testing was reinforced, and post-launch, more comprehensive real-world testing was incorporated into the system development process.
- **Human Factor Consideration:** future iterations of the system included adjustments to accommodate the unpredictability of human actions, such as late baggage drop-offs and missed flights.
- **Modular Adaptation:** knowledge gained from post-launch issues prompted further modularization of the system, allowing for more flexible manual interventions when the automated systems failed.

In the wake of the issues that surfaced during the launch of T5, further iterations between the Concept Space and Knowledge Space were necessary. New knowledge, drawn from the system's operational failures, allowed Heathrow to refine the baggage handling process over time, ultimately leading to a more stable and functional system. Lessons learned included:

- **Better Real-World Testing:** more comprehensive stress testing before the launch of new systems.
- **Human Factor Consideration:** accounting for unpredictability in human behavior and ensuring that the system was flexible enough to handle these disruptions.
- **Ongoing System Adjustments:** adopting a more modular and adaptable system that allowed for real-time intervention by staff when automated systems failed.

In the end, Heathrow Terminal 5's baggage handling system became a cautionary tale in the risks of pushing technology to its limits without fully accounting for the human, operational, and technical complexities involved. The C-K theory helps illuminate where conceptual ambition outpaced knowledge and where iterative refinement, based on real-world feedback, was necessary for success.

C-K THEORY FOR CONTRACTING INNOVATIVENESS AT HEATHROW T5

Applying C-K Theory to the **innovative contracting solutions** used in the Heathrow T5 megaproject offers insight into how novel contractual frameworks were developed and refined. The T5 Agreement, which was a unique contract management approach used in the project, aimed to reduce disputes, foster collaboration, and manage risks more effectively. This contracting model was especially innovative for a project of T5's scale, where multiple contractors and stakeholders were involved.

C-K Theory can help analyze how the T5 Agreement emerged as a concept (C-space), how it was grounded in existing legal and project management knowledge (K-space), and how this approach evolved over time through iterative learning and innovation. This analysis will also show how the T5 Agreement influenced future contracting models for other megaprojects.

- Step 1: Concept Space (C-Space) for Innovative Contracting at T5

The **C-space** refers to the novel ideas and concepts proposed for the project's contracting model. Heathrow T5's megaproject was faced with several contracting challenges due to the large number of stakeholders, the scale of the project, and the need to minimize delays and disputes.

- *Concepts in the C-Space for Contracting at T5:*

1. Risk-Sharing Contract (The T5 Agreement):

- » Traditional contracts for megaprojects tend to place most of the risk on contractors, leading to disputes, delays, and cost overruns. The **concept** of the T5 Agreement was to create a collaborative contract where risks were shared between BAA (the airport authority) and contractors. This approach was designed to align the interests of all parties and reduce adversarial relationships.

2. Dispute-Free Collaboration:

- » Another innovative idea was to ensure a **dispute-free environment** by focusing on resolving problems collaboratively rather than through litigation. This concept involved building mechanisms into the contract that encouraged early identification and resolution of issues before they escalated.

3. Flexibility in Design and Delivery:

- » The T5 Agreement included the **concept of flexibility**, allowing contractors to adapt designs and construction methods during the project's delivery. This was a departure from traditional rigid contracts where any design change could trigger costly variations and disputes.

4. Incentive-Based Performance:

- » The concept of **incentive-based contracting** was also introduced, whereby contractors were rewarded based on performance milestones, particularly for meeting time, cost, and quality targets. The goal was to create motivation for contractors to optimize their performance rather than simply adhere to minimum contractual obligations.

These concepts represented new approaches to managing megaprojects, as the traditional adversarial contracting methods were often seen as obstacles to delivering large-scale infrastructure projects on time and within budget.

- Step 2: Knowledge Space (K-Space) for Contracting at T5

The **K-space** consists of the existing knowledge and practices that informed the development of the T5 Agreement. Heathrow Terminal 5's management team, led by BAA, had to draw on both established and emerging knowledge in project management, legal frameworks, and risk management to transform the concepts in the C-space into viable solutions.

- *Existing Knowledge Relevant to Contracting at T5:*

1. Traditional Adversarial Contracts (Knowledge):

- » Traditional contracting models for large infrastructure projects typically placed a heavy burden of risk on contractors. These contracts were often rigid, leading to disputes, claims, and litigation when things went wrong. This knowledge informed the T5 team that traditional contracts could hinder collaboration and delay project delivery.

2. Risk Allocation and Management (Knowledge):

- » Megaprojects frequently experience cost overruns, delays, and unforeseen challenges, which are typically dealt with by assigning risk to contractors. However, **knowledge of risk management** highlighted that unfair risk allocation often led to increased project costs due to claims and defensive contractor behavior. BAA used this knowledge to explore how better risk-sharing could improve project outcomes.

3. Collaborative Contract Models (Emerging Knowledge):

- » There was growing interest in **collaborative contracting models** at the time, especially in the construction industry, where early examples of partnering agreements had been introduced. These models showed that collaboration, rather than adversarial relationships, could lead to more effective problem-solving and project delivery.

4. Incentive-Based Contracting (Knowledge):

- » The idea of **incentive-based performance contracts** had been explored in other industries, with success in aligning contractor goals with project outcomes. Knowledge from these fields suggested that giving contractors financial incentives based on meeting specific performance criteria could reduce the risk of delays and improve overall project quality.

In the case of T5, the knowledge space included both the limitations of traditional contracting and the emerging potential of more collaborative models. The challenge was to apply this knowledge in the specific context of a megaproject with numerous stakeholders and an unprecedented scale.

- Step 3: Transforming Concepts into Knowledge (C → K) Through the T5 Agreement

Transforming the concepts in the C-space into operational realities involved testing the innovative contracting ideas through real-world implementation. This transformation process for T5's contracting solutions was iterative, involving the development of contractual frameworks, performance metrics, and risk-sharing mechanisms.

- *Key Transformations of Concepts into Knowledge:*

1. Risk-Sharing in Practice:

- » The concept of risk-sharing through the T5 Agreement was transformed into an operational model where BAA and contractors shared risks more equitably. This resulted in a more collaborative working environment, where risks such as delays, design changes, and unforeseen challenges were managed jointly rather than blamed on any single party.
- » **Outcome:** The risk-sharing model helped reduce disputes during the project, and contractors were more willing to focus on solving problems instead of shifting blame.

2. Implementing a Dispute-Free Environment:

- » The concept of a dispute-free environment was supported by contractual mechanisms such as joint risk registers, regular problem-solving workshops, and open communication channels between stakeholders. Instead of relying on legal action to resolve issues, the focus was on early identification and collaborative resolution.
- » **Outcome:** While no project is entirely free from disputes, T5 experienced fewer formal disputes than comparable projects, and problems were generally addressed at a working level before escalating.

3. Flexibility in Contract Delivery:

- » The T5 Agreement's flexibility concept was tested by allowing contractors to adapt designs and methods in real-time. This flexibility meant that contractors could adjust to changing conditions, such as unforeseen site conditions or technological developments, without triggering expensive contract variations.
- » **Outcome:** Flexibility in the contract allowed for greater adaptability, although managing this required constant communication and collaboration between BAA and contractors. The project did experience some delays, but the flexibility helped mitigate more significant disruptions.

4. Incentive-Based Performance:

- » The concept of incentives was turned into contractual terms where contractors were rewarded for meeting time, cost, and quality milestones. Performance reviews were conducted at regular intervals, and financial incentives were tied to specific project outcomes.
- » **Outcome:** Contractors had a clear motivation to achieve milestones, and the performance-based incentives helped align their objectives with BAA's goals. This system reduced the likelihood of contractors cutting corners or delaying the project unnecessarily.

- Step 4: Using Knowledge to Inspire New Contracting Concepts (K → C)

As knowledge was gained from the implementation of the T5 Agreement, new ideas and improvements to contracting solutions emerged. The lessons learned from this innovative approach to contracting inspired new concepts for managing future megaprojects.

- *New Contracting Concepts Inspired by the T5 Project:*

1. Refinement of Collaborative Risk-Sharing Models:

- » Knowledge gained from the success of the T5 risk-sharing model led to the concept of refining collaborative contracts for future megaprojects. The idea was to develop more detailed frameworks for managing specific types of risks (e.g., design risk, environmental risk) based on the project's phase.
- » **New Concept:** Creating modular risk-sharing frameworks that could be adapted based on the project's progression or changes in scope.

2. Enhanced Dispute Resolution Mechanisms:

- » While the T5 Agreement reduced formal disputes, there was still room for improvement in resolving complex issues. The knowledge gained from T5 led to the idea of enhancing the dispute resolution mechanisms through real-time, AI-driven issue-tracking systems that could flag problems before they escalated.
- » **New Concept:** Introducing advanced technology to track, predict, and resolve disputes in real time through AI-driven risk management platforms.

3. Standardization of Collaborative Contracts for Industry-Wide Use:

- » T5's success inspired the idea of creating standardized collaborative contract models that could be used across multiple sectors for megaprojects. This concept aimed to reduce the time and effort required to develop unique contracts for each project.
- » **New Concept:** Developing industry-standard collaborative contracting templates that incorporate best practices from T5 and other projects.

- Step 5: Iterative Learning and Refinement of the T5 Contracting Model

The iterative learning process in C-K Theory is evident in how the contracting solutions at T5 evolved over time. The project team continually refined their approach as they gained more knowledge about how the risk-sharing, collaboration, and performance incentives affected project delivery. This iterative process also laid the foundation for new contracting models that would be used in future projects at Heathrow and other major infrastructure developments.

- Conclusion: C-K Theory Applied to Contracting Solutions at Heathrow Terminal 5

Applying C-K Theory to the innovative contracting solutions used at Heathrow Terminal 5 illustrates how novel concepts can be developed, tested, and refined through the interaction between concept space and knowledge space. The T5 Agreement, which introduced collaborative risk-sharing, dispute-free environments, flexibility, and performance-based incentives, represented a significant departure from traditional contracting models. By continuously iterating between the concept space (novel ideas) and the knowledge space (practical experience), the project team was able to transform innovative contracting concepts into operational knowledge.

The lessons learned from T5 not only improved the project's outcomes but also inspired new concepts for managing contracts in future megaprojects. By embracing the principles of C-K Theory, Heathrow Terminal 5's management demonstrated how innovative contracting models could be leveraged to enhance collaboration, reduce disputes, and ultimately deliver large-scale projects more efficiently and effectively.

Table 2. C-K Theory Chart for Contracting Innovations at Heathrow T5, in Table-Form

C-Space (Concepts)	K-Space (Knowledge)	C+K Interaction (Solution)
<p>Single-Point Accountability: Create a contract where one party is responsible for all elements of the construction and operations.</p>	<p>Traditional Contracting Models: Knowledge of traditional contracts with multiple parties holding individual responsibility for various aspects of large projects. This method often leads to fragmented accountability and disputes.</p>	<p>Single Integrated Contract (SIC): Heathrow introduced a new contractual model with BAA (British Airports Authority) as the sole accountable entity overseeing contractors and suppliers. This reduced conflict and streamlined decision-making processes.</p>
<p>Collaboration Instead of Competition: Promote a collaborative environment among contractors to work together toward a common project goal, avoiding the traditional adversarial approach.</p>	<p>Historical Contractor Behavior: Knowledge of conventional procurement models that encourage competition, often resulting in misalignment of goals and disputes between stakeholders.</p>	<p>Integrated Project Team (IPT): Heathrow implemented a collaborative model where key contractors and suppliers formed an Integrated Project Team (IPT). Contractors were encouraged to collaborate rather than compete, aligning incentives with overall project success.</p>

C-Space (Concepts)	K-Space (Knowledge)	C+K Interaction (Solution)
<p>Risk Sharing: Design contracts that share risks and rewards between the client (BAA) and the contractors, so that all parties are motivated to mitigate risks.</p>	<p>Traditional Risk Allocation: Existing contracts in megaprojects often place the majority of risks on contractors, leading to increased costs due to contractors inflating their bids to cover potential risks.</p>	<p>Pain/Gain Share Mechanism: Heathrow's T5 adopted a pain/gain sharing system. This innovative contract ensured that contractors would share in both the financial risks and rewards of the project, encouraging them to deliver on time and within budget.</p>
<p>No-Litigation Clause: Incorporate a clause that prevents contractors from resorting to litigation during the project, encouraging disputes to be resolved internally.</p>	<p>Frequent Litigation in Megaprojects: Previous knowledge shows that litigation often stalls progress in megaprojects and can lead to costly delays. This adversarial behavior undermines collaboration and trust.</p>	<p>No-Blame Culture: Heathrow introduced a no-blame, no-litigation clause in their contracts. This innovative approach required contractors to resolve disputes internally rather than through litigation, fostering a culture of trust and cooperation.</p>
<p>Performance-Based Incentives: Contracts should include bonuses for achieving milestones and high performance rather than just fulfilling minimal contractual obligations.</p>	<p>Performance Measurement Issues: Knowledge from past projects where performance-based contracts were not well defined, leading to unclear criteria for bonuses or penalties, and misalignment of project goals.</p>	<p>Clear Performance Metrics: Heathrow developed clear, measurable performance criteria that were linked to milestone achievements. Contractors received bonuses for exceeding performance targets, ensuring alignment with Heathrow's quality and time goals.</p>
<p>Supplier Involvement in Design Phase: Engage suppliers and contractors early in the design phase to ensure that designs are practical and can be built within the cost and time constraints.</p>	<p>Late Contractor Involvement: In conventional contracts, suppliers and contractors are typically brought in after designs are finalized, leading to potential delays and redesigns during the construction phase.</p>	<p>Early Contractor Involvement (ECI): Heathrow involved suppliers and contractors in the design phase to incorporate practical insights into the construction plans early. This reduced costly redesigns and improved overall project efficiency.</p>

C-Space (Concepts)	K-Space (Knowledge)	C+K Interaction (Solution)
<p>Fixed-Price Incentive Contracts: Consider a contracting model where the price is fixed, but incentives are provided for finishing ahead of schedule or under budget.</p>	<p>Cost Overruns in Large Projects: Knowledge shows that megaprojects often experience cost overruns due to scope creep and unforeseen challenges. Fixed-price contracts can mitigate this, but they can also create disincentives for quality.</p>	<p>Fixed-Price with Flexibility: Heathrow used a hybrid model where the base price was fixed, but incentives were provided for completing tasks early or saving on costs without sacrificing quality. This ensured cost control while motivating contractors to perform better.</p>
<p>Continuous Improvement and Feedback Loops: Incorporate contractual mechanisms for continuous feedback and process improvement throughout the project lifecycle.</p>	<p>Iterative Process in Construction: Knowledge from previous projects shows that feedback loops and continuous improvements are rarely formalized, often leading to repeated mistakes and inefficient practices.</p>	<p>Continuous Improvement Mechanisms: Heathrow introduced formal feedback loops, requiring contractors to regularly assess and improve their processes throughout the project. This created a culture of continuous improvement, reducing inefficiencies over time.</p>

SUMMARY

- **Single Integrated Contract:** Reduced conflicts by making BAA responsible for overseeing all aspects of the project.
- **Integrated Project Team (IPT):** Encouraged a collaborative environment, reducing adversarial competition.
- **Pain/Gain Share Mechanism:** Aligned the interests of all parties, sharing both risks and rewards to promote timely and cost-effective completion.
- **No-Litigation Clause:** Promoted internal dispute resolution, reducing costly legal delays.
- **Clear Performance Metrics:** Introduced performance-based incentives with well-defined goals, aligning contractor motivation with project success.
- **Early Contractor Involvement (ECI):** Involved contractors early in the design phase, leading to more practical and cost-effective project execution.
- **Fixed-Price with Incentives:** Ensured cost control while motivating contractors to perform above the baseline requirements.
- **Continuous Improvement Mechanisms:** Built a feedback loop into the project, ensuring continuous learning and adaptation throughout the lifecycle of the project.

SYSTEM THEORETIC PROCESS ANALYSIS (STPA) AND STPA-SEC (SECURITY) FOR MEGAPROJECT MANAGEMENT

INTRODUCTION TO STPA AND STPA-SEC FOR MEGAPROJECT MANAGEMENT

Traditional methods of risk management often struggle to cope with the scale and complexity inherent in these massive endeavors. STPA, originally designed to enhance safety in complex systems, and its security-oriented counterpart, STPA-Sec, provide a systematic approach that can offer significant advantages in megaproject management.

STPA works by addressing safety risks at the system level, focusing on unsafe control actions and interactions within a project's control structure (Leveson, 2018). This method is particularly well-suited for megaprojects like large-scale infrastructure developments, as it helps to identify potential risks that arise from the interdependencies between technical systems, human operators, and organizational procedures. By mapping out control loops and feedback mechanisms, STPA allows project managers to visualize how decisions are made, how they affect various components, and how to prevent failures before they occur. This forward-looking, systemic approach can dramatically improve the reliability of project outcomes, ensuring that both operational efficiency and safety are maintained throughout the project lifecycle.

STPA-Sec builds on this framework by extending its principles to address security concerns, making it invaluable for megaprojects where cyber and physical security risks are ever-present. In today's world, megaprojects increasingly rely on interconnected digital systems, which heightens their vulnerability to cyberattacks and other malicious threats. STPA-Sec helps project managers identify unsafe control actions that could be exploited by adversaries or cause unintended vulnerabilities. By integrating both safety and security considerations into the early design and planning stages, STPA-Sec ensures that risk management is not just reactive but proactive, anticipating threats before they arise. This dual focus on safety and security makes STPA-Sec an indispensable tool for managing the complexities of modern megaprojects, from airports to smart cities, where a holistic approach to risk is critical to long-term success (Yu, Wagner, & Luo, 2021).

Applying STPA and STPA-Sec in megaproject management provides a powerful toolkit for identifying and mitigating risks that could derail these massive, high-stakes projects. The structured nature of these methodologies ensures that safety and security are prioritized in every phase of the project, from conceptual design to final implementation, enabling smoother execution, fewer disruptions, and a greater likelihood of project success. The research effort suggests that if STPA and STPA-Sec are initiated from the beginning, systemically mapping out the complexities can improve operational efficiency.

STPA, STPA-SEC FOR TERMINAL 5

Heathrow T5 represents one of the most ambitious infrastructure projects in the history of the United Kingdom. The terminal was designed to handle 30 million passengers annually and featured state-of-the-art facilities, including an advanced baggage handling system. However, the initial opening of T5 in March 2008 was plagued by significant operational failures, particularly within the baggage handling system, leading to widespread disruption and reputational damage for both British Airways and Heathrow Airport (Doherty, 2008). These issues highlighted the inherent complexities and risks associated with managing such a megaproject. Applying STPA-Sec to the management of T5 provides a systematic approach to understanding and mitigating security risks in complex systems. This analysis explores how STPA-Sec could have been applied to T5, emphasizing its potential to improve the management and security of megaprojects.

In the application of STPA-Sec to Heathrow's Terminal 5 management, the construction of a critical infrastructure system, applying STPA-Sec involves:

- 1. Defining the System:** identifying components like construction firms, IT systems for operations, supply chains, and regulatory bodies.
- 2. Modeling the Control Structure:** mapping how these entities interact and make decisions.
- 3. Identifying Unsafe Control Actions (UCAs):** considering risks like poor coordination leading to unauthorized access to critical systems.
- 4. Deriving Security Requirements:** implementing strict access controls and continuous monitoring of contractor activities.
- 5. Continuous Monitoring:** regular security reviews and adapting strategies as the project progresses.

Defining the System and Its Boundaries

The first step in applying STPA-Sec to a megaproject like Heathrow T5 is to clearly define the system and its boundaries. This involves understanding the key components of the project, identifying the stakeholders, and mapping out the physical, technological, and organizational elements that make up the entire operational ecosystem. By defining the system and its boundaries, the project management team can better understand where potential security vulnerabilities may exist and how different parts of the project interact. This comprehensive understanding forms the foundation for analyzing risks and implementing controls.

The T5 project was a massive undertaking, involving multiple stakeholders, including British Airways (BA), the British Airports Authority (BAA), various contractors, and technology providers. The key systems within T5 included the baggage handling system, security screening processes, passenger flow management, and IT infrastructure.

Complex Interdependencies: The success of T5 relied heavily on the seamless integration of these systems. The baggage handling system, for example, was interconnected with IT systems that managed flight schedules, passenger data, and security protocols.

It is important to review the key components and physical, technological, and organizational boundaries with its stakeholders. In addition, the system interactions and dependencies, and defining boundaries for security considerations is consequential as well.

Key Components of the T5 System:

Defining the physical boundaries of the T5 system involves determining the physical infrastructure and geographical layout of the terminal. T5 is a massive structure, consisting of several levels of passenger areas, baggage handling zones, secure areas, runways, and administrative offices. Each area is subject to different security protocols and is integrated into the broader operational ecosystem of Heathrow Airport (Gil, Miozzo, & Massini, 2012).

- **Baggage Handling System (BHS):** a fully automated, large-scale baggage sorting and transportation system designed to handle millions of pieces of luggage annually. The system is dependent on IT infrastructure and mechanical components such as conveyor belts and scanning systems.
- **Passenger Flow Management:** this includes the processes for checking in passengers, managing security screenings, boarding, and overall crowd control within the terminal. Passenger flow is tightly linked to security operations.
- **Security Systems:** involves physical security checkpoints, advanced scanning technology, surveillance systems, and the coordination of security personnel responsible for maintaining the safety of passengers and staff.
- **IT Infrastructure:** the backbone of all digital operations, responsible for managing flight schedules, passenger information, and the automated baggage system. It includes hardware, software, and network communications.
- **Airline Operations (British Airways):** BA is the primary operator of T5, meaning that the airline's operations, flight scheduling, and customer services must be deeply integrated into the terminal's processes.
- **Contractors and Vendors:** various third-party contractors are responsible for the construction, maintenance, and operation of critical systems such as the BHS, IT infrastructure, and security equipment.

Key Physical Boundaries

Defining the physical boundaries of the T5 system involves determining the physical infrastructure and geographical layout of the terminal. T5 is a massive structure, consisting of several levels of passenger areas, baggage handling zones, secure areas, runways, and administrative offices. Each area is subject to different security protocols and is integrated into the broader operational ecosystem of Heathrow Airport.

- **Passenger Areas:** includes check-in areas, lounges, retail spaces, and boarding gates. These areas are primarily focused on passenger services and must adhere to security screening protocols.
- **Baggage Handling Zones:** located behind the scenes, these are restricted areas where luggage is processed, sorted, and transported to aircraft. Access is limited to authorized personnel, and automated systems dominate this space.
- **Secure Areas:** these are high-security areas accessible only to authorized personnel, such as airside operational zones, the air traffic control tower, and secure storage facilities.
- **Runways and Aircraft Parking Zones:** although physically connected to the terminal, these areas have a different set of security requirements and boundaries, as they involve direct interaction with aircraft and ground control operations.

Key Technological Boundaries of the System

The technological boundaries of T5's system extend to all IT, communication, and digital infrastructure that supports the terminal's operations. This includes both hardware and software components, as well as internal and external networks. The IT infrastructure for T5 is crucial to the functioning of both the baggage handling system and passenger management, as well as ensuring that British Airways' operations are integrated into terminal systems.

- **Internal IT Systems:** includes the software platforms that manage flight schedules, baggage tracking, and passenger information. These systems are critical for ensuring smooth operations, and any failure here could have widespread consequences.
- **External Communication Links:** T5's IT systems are interconnected with Heathrow's central operations, as well as external systems such as British Airways' headquarters, customs and immigration databases, and other airlines operating at Heathrow.
- **Security Systems:** includes surveillance systems, physical access control systems, and automated threat detection software (e.g., facial recognition and anomaly detection).
- **Backup Systems and Redundancy:** these are critical for ensuring that if the primary systems fail, operations can continue without significant disruptions. This includes redundant servers, backup communication systems, and secondary data centers.

Key Stakeholders

Defining the organizational boundaries involves identifying the key stakeholders involved in the project, each of whom plays a role in the terminal's operation and security. In megaprojects like T5, numerous entities must collaborate effectively to ensure that the project is successful and secure.

- **British Airports Authority (BAA):** the organization responsible for the overall management and operation of Heathrow Airport, including T5. BAA is responsible for ensuring that T5 adheres to airport-wide security and operational protocols.
- **British Airways (BA):** as the primary airline operating out of T5, BA's operations must be fully integrated into the terminal's systems, especially in relation to flight scheduling, baggage handling, and passenger flow. BA has its own set of security protocols, which must align with T5's overall security measures.
- **Contractors and Vendors:** many third-party contractors were involved in the construction and operation of T5's systems, from the design and implementation of the BHS to the maintenance of IT infrastructure. Their contractual obligations and adherence to security protocols are critical for the project's success.
- **Security Agencies:** government security agencies such as UK Border Force and aviation security teams work closely with Heathrow's internal security teams to ensure that all security risks are mitigated and that screening processes are robust.
- **Passengers and Staff:** both the public (passengers) and internal stakeholders (airport staff) interact with the terminal's operations, which means their safety and compliance with security measures are essential.

Key System Interactions and Dependencies

One of the most critical aspects of defining the system is understanding the interactions and dependencies between different components and stakeholders. T5 is a complex ecosystem where technological systems, human operators, and organizational entities must work seamlessly together to ensure efficient operations and security.

- **Baggage Handling and IT Systems:** the BHS is directly dependent on the IT infrastructure to operate efficiently. Any failure in the IT system could cause the BHS to malfunction, leading to operational chaos.
- **Passenger Flow and Security Systems:** passenger management is heavily reliant on security screening systems to ensure safety. This includes interactions between human security personnel, automated screening technologies, and communication systems.
- **Airline Operations and Baggage Handling:** British Airways' operations are tightly integrated with the BHS and other terminal systems. Any delays or malfunctions in the BHS or security systems directly affect the airline's ability to maintain schedules.
- **Contractor and Maintenance Interactions:** contractors responsible for the maintenance of critical systems must coordinate with the project management and security teams to ensure that any system updates or repairs do not introduce security vulnerabilities or operational disruptions.

Key Security Boundaries

Security is a critical boundary within the T5 system, cutting across physical, technological, and organizational domains. The T5 system must be designed with a clear understanding of security perimeters, including restricted access areas, secure zones, and potential cybersecurity threats. Defining these security boundaries helps in identifying where controls need to be applied to prevent unauthorized access, system tampering, or other forms of security breaches.

- **Physical Security Perimeters:** these define which areas are accessible only to authorized personnel (e.g., baggage handling zones, airside operations, and runways).
- **Digital Security Boundaries:** these include firewalls, access controls, and encryption measures to protect sensitive data and IT systems from unauthorized access or cyberattacks.
- **Operational Security:** ensures that all procedures and protocols, such as the handling of baggage, security screening, and passenger flow, meet strict security requirements to prevent both physical and digital threats.

Defining the system and its boundaries is a foundational step in the application of STPA-Sec to Heathrow Terminal 5. By clearly identifying the physical, technological, and organizational components of the T5 system, along with understanding the interactions and dependencies between these elements, project managers can gain a comprehensive view of where potential security risks may arise. Establishing these boundaries allows for more effective risk identification, enabling the implementation of targeted security controls that address the unique vulnerabilities of T5. This holistic understanding of the system ensures that both operational efficiency and security are maintained in this complex megaproject, laying the groundwork for proactive risk mitigation and long-term project success.

MODELING THE CONTROL STRUCTURE FOR HEATHROW TERMINAL 5 MANAGEMENT

Modeling the control structure is the second critical step in applying STPA-Sec to the Heathrow T5 megaproject. In this phase, the focus is on identifying and mapping the various control actions, feedback loops, and decision-making processes that influence the operation and security of the terminal. By understanding how different components of the system interact and how control decisions are made, vulnerabilities can be pinpointed, and UCAs can be more easily identified and mitigated. For a complex infrastructure project like T5, with numerous technological systems, stakeholders, and operational activities, modeling the control structure ensures that both operational and security risks are systematically understood and managed.

To apply STPA-Sec, a detailed control structure model of T5 would have been necessary, illustrating how decisions were made and how information flowed between different components of the system. Key actors include BAA (as the airport operator), BA (as the primary airline), the baggage handling system operators, IT infrastructure providers, security personnel, and project management teams. While the control loops would depict how feedback and control actions were communicated, such as how baggage handling data was relayed to BA operations and how security alerts were managed.

Understanding Control Actions and Control Loops

A control structure consists of control actions—the decisions or actions taken by controllers (people or automated systems)—and feedback loops—the information or signals sent back to the controller that inform future actions. At T5, this involves identifying who or what is controlling different subsystems (e.g., baggage handling, security, IT) and how information flows between these controllers and the components they influence.

In the context of T5, several key controllers interact to manage different aspects of the terminal's operation. These controllers can be categorized as either **human** or **automated** controllers, each playing a vital role in decision-making and system monitoring.

Human Controllers:

- **Project Management Team (BAA):** responsible for overseeing the overall operation of T5, the project management team is the top-level human controller. Their decisions influence every aspect of the terminal's construction, operations, and security. They set policies, manage contracts with stakeholders (e.g., British Airways, contractors), and coordinate responses to incidents or disruptions.
- **Security Personnel:** security teams are responsible for managing the physical and digital security of the terminal. They control access points, monitor surveillance systems, and respond to security threats. Their actions are guided by policies established by the project management team but also rely on real-time data from various monitoring systems.
- **Operations Team (BA):** British Airways controls airline operations within T5, including flight schedules, gate assignments, and customer service. Their decisions heavily influence passenger flow and baggage handling.
- **Maintenance and IT Teams:** these teams are responsible for managing and maintaining the infrastructure, including the BHS, IT systems, and physical components of the terminal. They are crucial for preventing and responding to system failures.

Automated Controllers:

- **BHS Control Software:** The BHS is controlled primarily by automated systems that sort and direct luggage based on real-time flight information and passenger data. The BHS is a closed-loop control system that continuously monitors the status of baggage and conveyor operations, making adjustments as necessary.
- **Security Screening Systems (Automated Scanners):** Automated screening systems, such as body scanners, X-ray machines, and facial recognition software, are responsible for assessing passenger data and detecting anomalies or prohibited items. These systems generate real-time feedback, informing security personnel of any detected threats.
- **IT Infrastructure Control Systems:** The IT systems that manage flight scheduling, passenger information, and digital communications rely on automated processes to ensure data is processed and shared across relevant systems in real time.

To model the control structure for T5, we need to map out how the various controllers interact with the components they influence and the feedback loops that inform future actions. Each control structure has several layers of interactions, with feedback loops providing real-time information to help controllers adjust their actions as needed.

While a robust STPA, STPA-Sec analysis was completed from opensource material, the technical report will focus on only one aspect: the Baggage Handling System.

Control Loops in the BHS:

- **Controller:** the BHS control software.
- **Controlled Processes:** baggage sorting, tracking, and transportation.
- **Control Actions:** the BHS control software directs conveyor belts, activates baggage scanners, and routes luggage to the appropriate destinations based on flight schedules and check-in data.
- **Feedback Loops:** the system receives feedback on the status of conveyor belts, baggage location, and potential errors (e.g., bag misroutes, delays). If a problem is detected (e.g., a jammed conveyor), the system either resolves the issue autonomously or alerts the human maintenance team for manual intervention.

Key Dependencies and Interactions in the Control Structure

The control structure of T5 involves multiple interdependent systems that rely on one another to function correctly. Failures in one part of the system can cascade through the network of control loops, affecting the entire terminal's operations.

Dependency Between BHS and IT Systems:

- The BHS relies heavily on real-time data from the IT systems, such as flight schedules and check-in information, to route baggage correctly. Any failure in the IT infrastructure (e.g., a data corruption or system crash) can disrupt the BHS, leading to misrouted or lost baggage.

Potential Control Structure Failures

Understanding the potential failures in the control structure helps identify areas where security risks may arise. These failures typically occur when feedback is delayed, misinterpreted, or unavailable, or when control actions are not properly executed.

Delayed Feedback in the BHS Control System:

- If the BHS fails to provide real-time feedback on the status of baggage, errors (such as misrouted luggage) can go unnoticed until it is too late, leading to security risks and operational disruptions.
- 2.3 Identifying UCAs for T5 BHS

Identifying UCAs is a crucial step in applying STPA-Sec to the Heathrow T5 megaproject. UCAs are control actions that, when taken incorrectly or in certain contexts, lead to security vulnerabilities or system failures. In the case of T5, UCAs arise from the complex interactions between various subsystems, stakeholders, and technologies that make up the terminal's infrastructure. Given the scope and complexity of the project, potential UCAs are diverse and span across both operational and security domains.

The T5 megaproject faced numerous potential unsafe control actions, particularly in its baggage handling system, where many of the initial operational issues were concentrated.

UCAs in the BHS

The BHS at T5 was designed to be a fully automated system that handled the sorting, tracking, and transportation of luggage. Its failure at launch was one of the major issues that affected the terminal's operations. Potential UCAs in this system include:

- **Incorrect or Delayed Data Input (Operational Failure):** the BHS relies on accurate and timely data inputs from check-in desks, flight schedules, and baggage loading systems. A UCA could occur if incorrect or delayed data input into the BHS system results in misrouted baggage or missing luggage. For example:
 - » **Failure Scenario:** baggage is mistakenly routed to the wrong flight or terminal, resulting in operational delays and security risks if unaccounted-for baggage enters restricted areas.
- **Inadequate Fault Detection (Systemic Issue):** the BHS was expected to detect and resolve faults autonomously. A UCA would occur if the system fails to detect a hardware or software fault in a timely manner, causing a backlog of luggage.
 - » **Failure Scenario:** if a baggage conveyor belt malfunctions and the system does not issue an alert, luggage could pile up, leading to both security risks (unmonitored baggage) and operational chaos.
- **Failure in Human-Machine Interfaces (Coordination Failure):** a UCA could arise if human operators (ground staff or system engineers) fail to interpret system alerts correctly or are unable to intervene in the system's operation due to inadequate training or malfunctioning interfaces.
 - » **Failure Scenario:** operators might miss an alert indicating a system error, allowing the problem to escalate, leading to both security vulnerabilities (untracked luggage) and operational disruptions.
- **Improper Maintenance Scheduling (Operational Risk):** maintenance scheduling is crucial for ensuring the smooth operation of a complex system like the BHS. A UCA would occur if maintenance is scheduled without considering the system's operational state or load.
 - » **Failure Scenario:** if the BHS undergoes unscheduled maintenance during peak travel times, it could cause a cascade of failures, affecting the entire terminal's operations.

ANALYZING SECURITY RISKS FOR T5 BHS

Once UCAs are identified for a project like Heathrow T5, the next step in STPA-Sec is to analyze the security risks associated with these UCAs. This involves understanding the potential threats, vulnerabilities, and consequences that arise when control actions are either improperly executed or not executed at all. The goal is to trace how a failure or security gap could evolve into a larger issue and impact the system as a whole.

For T5, the security risks span across operational disruptions, cybersecurity threats, and mismanagement of critical systems. Below is a detailed analysis of the security risks associated with the UCAs identified in the previous section.

Using STPA-Sec, the identified UCAs could be analyzed to understand the potential security risks they pose to T5.

- **Operational Disruptions:** the BHS malfunction represented a significant operational risk, leading to thousands of passengers missing their flights and baggage piling up in the terminal. This not only caused financial losses but also posed a security risk as mishandled baggage could have been exploited to introduce prohibited items into the secure areas of the airport.
- **Cybersecurity Threats:** the reliance on interconnected IT systems made T5 vulnerable to cyberattacks. An attacker could potentially exploit a vulnerability in the IT infrastructure to disrupt operations or steal sensitive passenger data.

Security Risks in the BHS

The BHS at T5 was one of the most critical components, and its failure during the launch period posed significant security and operational risks. The following security risks arise from the identified UCAs within the BHS:

1. Misrouted or Lost Luggage (Operational and Security Risk):

- » **UCA:** incorrect or delayed data input into the BHS system leads to misrouting of baggage.
- » **Risk Analysis:** misrouted or lost luggage can lead to significant operational delays, but it also poses security risks if untracked baggage enters restricted or sensitive areas. This creates the possibility of unauthorized items being introduced into the terminal's secure zones. Additionally, lost luggage may contain personal or sensitive information, exposing passengers to identity theft or data breaches.
- » **Potential Impact:** compromised airport security, operational delays, and reputational damage to the airport and airline.

2. Unmonitored System Malfunctions (Operational Risk and Vulnerability to Sabotage):

- » **UCA:** inadequate fault detection within the BHS leads to unaddressed system failures.
- » **Risk Analysis:** when system malfunctions are not promptly detected, it can create opportunities for malicious actors to exploit the vulnerabilities in the system. For example, bags that remain unaccounted for due to a conveyor malfunction might become targets for tampering, smuggling, or theft. Additionally, unchecked system failures could disrupt the entire baggage handling process, leading to cascading failures in the broader airport operations.
- » **Potential Impact:** sabotage of baggage handling, extended airport delays, and compromised baggage security.

3. Human-Machine Interface Failures (Risk of Human Error):

- » **UCA:** failure in the human-machine interface (HMI) results in operators missing or misinterpreting system alerts.
- » **Risk Analysis:** human error becomes a significant risk when operators are unable to accurately interpret alerts from the automated system. This can lead to security risks if dangerous items are not flagged in time or if operators are unable to intervene when there is a system breach. The reliance on automated systems without proper human oversight can exacerbate vulnerabilities.
- » **Potential Impact:** increased likelihood of security breaches, unaddressed technical failures, and operational breakdowns.

4. Inadequate Maintenance Scheduling (Vulnerability to Breakdown):

- » **UCA:** poorly timed or neglected maintenance of the BHS causes system failures during peak operational periods.
- » **Risk Analysis:** maintenance failures can lead to system overloads or breakdowns, especially during peak periods of operation. This risk is magnified during times of high passenger volume, when any downtime in the baggage handling system can have significant knock-on effects on flight schedules and airport security. Unscheduled downtime or failure of critical components due to lack of maintenance could also expose the system to sabotage or unintentional security vulnerabilities.
- » **Potential Impact:** major service disruptions, increased vulnerability to security breaches, and damage to passenger trust in the system.

The security risk analysis of Heathrow T5 based on identified UCAs reveals the intricate vulnerabilities that can arise in a complex, interconnected system like a modern airport terminal. By breaking down risks across critical areas—such as the BHS, passenger flow, IT infrastructure, and overall project management—it is clear that the project was exposed to multiple layers of potential failures that could have resulted in security breaches or operational disruptions.

The BHS posed significant risks, not only due to technical failures like system malfunctions or improper data input, but also because of human errors in operating the interface and maintaining the system. Misrouted or unmonitored baggage created security vulnerabilities where unauthorized access to restricted zones or tampering could occur. The cascading effect of these failures highlights how critical it is for complex systems to have real-time monitoring, fail-safes, and redundancies to mitigate the risks of both operational breakdowns and security threats.

Deriving Security Requirements for T5 BHS

Once the UCAs and security risks for Heathrow T5 have been identified and analyzed, the next crucial step in the STPA-Sec methodology is to implement and monitor effective security controls. These controls are designed to mitigate the specific risks associated with T5's complex systems, ensuring the security and operational resilience of the terminal. In this section, we will explore the implementation of appropriate controls and the monitoring mechanisms that should have been put in place to manage T5's security risks in the context of the BHS, passenger flow, IT infrastructure, and project management.

From the analysis of UCAs and associated risks, specific security requirements could be derived to mitigate these risks.

- **Redundant Systems:** to prevent BHS failures, redundant systems and real-time monitoring should have been implemented. These measures would ensure that even if one component failed, others could take over without disrupting operations.
- **Enhanced Communication Protocols:** improving communication channels between the control room, security personnel, and airlines could have minimized response times to security alerts, reducing the likelihood of a security incident.
- **Cybersecurity Measures:** robust cybersecurity measures, such as intrusion detection systems, regular security audits, and strict access controls, would have been necessary to protect T5's IT infrastructure from potential cyber threats.

Implementing Controls for the BHS

Given the critical role the BHS played in T5's operations and the security risks posed by system failures, a range of technical and procedural controls should be implemented to ensure its reliable and secure operation.

1. Redundant Systems and Real-Time Monitoring

- **Control Implementation:** to address the risk of BHS malfunctions, redundant systems and backup infrastructure should be implemented to ensure continuous operation even in the event of a failure. This redundancy could involve backup conveyor belts, additional sorting systems, or parallel IT systems that automatically take over if the primary system fails.
- **Monitoring:** a real-time monitoring system for the BHS should be deployed, allowing operators to detect and respond to any malfunctions or anomalies immediately. This system would provide constant feedback on the status of all critical components, enabling early intervention before a failure escalates.

2. Automated Fault Detection and Alerts

- **Control Implementation:** automated fault detection algorithms should be incorporated into the BHS. These systems would be programmed to identify anomalies in the system's performance, such as delayed baggage or conveyor belt failures, and automatically issue alerts to operators.
- **Monitoring:** the monitoring process should include regular checks to ensure that the fault detection system is functioning as intended and that alerts are being properly communicated and acted upon. The system should also have built-in logging to track past faults and responses, allowing for analysis of recurring issues.

3. Operator Training and Human-Machine Interface (HMI) Improvements

- **Control Implementation:** ensuring that human operators are well-trained and equipped to interpret system alerts is critical. Training programs should be implemented to improve operator proficiency with the BHS and its alert systems, as well as their ability to intervene manually when necessary.
- **Monitoring:** regular operator evaluations and simulation exercises should be conducted to ensure that staff remain competent in responding to system failures. The effectiveness of the HMI should also be regularly assessed and updated to reduce the risk of human error.

Implementing and monitoring controls at Heathrow T5 is a crucial step in mitigating the identified security risks associated with its complex systems. Redundancy, real-time monitoring, and automated fault detection in the baggage handling system, combined with enhanced security screening and communication protocols, would ensure that operational and security risks are addressed.

DEPLOYMENT OF T5 BHS

The immediate result was a major reputational blow to both Heathrow Airport and British Airways when opened on March 27, 2008. The high-profile launch of the terminal had been intended as a showcase of modern airport design and efficiency, but the baggage system failure tarnished the terminal's image. It took several weeks to resolve the issues, and British Airways suffered significant operational and financial losses due to flight cancellations, lost baggage claims, and compensation payments to affected passengers. Heathrow T5's baggage failure became a case study in how technical systems, even when designed with the latest technology, can fail without sufficient operational preparation and human oversight. The incident highlighted the importance of thorough testing, staff training, and crisis management planning when launching large, complex systems.

Though the baggage system eventually stabilized and T5 became a success in later years, the initial opening was widely regarded as a public relations disaster for both Heathrow and British Airways. The baggage system, which was highly automated and designed to handle up to 12,000 bags per hour, was expected to be state-of-the-art, but several factors contributed to its failure.

The heart of the problem was the baggage handling system itself. The automated system, which relied on sophisticated software and a network of conveyor belts, scanners, and robotic arms, failed to operate as expected. Baggage was either misdirected, delayed, or lost within the system. The automated luggage loaders failed to function properly, leading to a backlog. However, ultimately, although the system was complex and advanced, staff members were inadequately trained to manage it effectively during the launch. There was confusion about how to handle the system manually when automated components failed. Many of the employees operating the system had only received limited training, which hindered their ability to manage and respond to the crisis quickly. In addition, while the baggage handling system had been tested prior to the terminal's opening, the tests were not sufficiently rigorous under real-world conditions. The system had not been fully stressed under peak operational loads, leading to unexpected breakdowns when thousands of bags were processed at once during the terminal's first days.

As a result of these issues, passengers faced long delays, with 34 flights being cancelled by the end of the first day (Brady & Davies, 2010). Tens of thousands of bags went missing, and over 28,000 passengers were affected within the first few days. British Airways, the sole operator of T5, was forced to cancel more than 500 flights in the first five days after opening (Milmo, 2008) (Chaos at the opening of Heathrow Terminal 5, 2008) (BBC News Channel, 2008). Further analysis can be found in the C-K Theory section.

LESSONS LEARNED AND RECOMMENDATIONS ON STPA FROM TERMINAL 5 USE CASE

The issues experienced during the opening of T5 underscore the importance of integrating methodologies and tools such as STPA and STPA-sec, aiding in providing security analyses into the management of megaprojects. The following recommendations are derived from the retrospective application of STPA-Sec to T5:

- **Early and Continuous Security Integration:** security considerations should be integrated from the earliest stages of the project and continuously revisited as the project evolves.
- **Cross-Functional Collaboration:** effective communication and collaboration between different stakeholders (e.g., airlines, airport authorities, contractors) are crucial to managing security in complex systems.
- **Comprehensive Testing and Simulation:** before going live, complex systems like T5's BHS should undergo extensive testing and simulation under various scenarios to identify and mitigate potential risks.

The application of STPA-Sec to the Heathrow T5 project provides valuable insights into how a systematic security analysis could have potentially mitigated the risks that led to the operational challenges during its launch. By focusing on the control structures, unsafe control actions, and security risks, STPA-Sec offers a powerful tool for managing the complexities of megaprojects, ensuring that both safety and security are prioritized throughout the project lifecycle. As infrastructure projects continue to grow in scale and complexity, the lessons learned from T5 highlight the critical importance of adopting comprehensive security analysis methodologies like STPA-Sec to safeguard against future operational failures and security breaches.

RECOMMENDATIONS FOR FUTURE RESEARCH

The research conducted on this project was intentionally very broad. In this section we identify several topics that we believe warrant future research.

- 1. Megaproject Leadership Framework Evaluation:** the leadership framework developed highlights the critical importance of the ability to navigate uncertainty, bring together diverse multi-disciplinary teams, and demonstrate systematic thinking. In follow-on research, the team would collect data based on this framework from existing megaprojects to build an assessment model that will help organizations select individuals most likely to be effective at leading megaprojects. This work would include insights into skills needed for future megaproject management (e.g., looking at the use of LLMs and AI to understand status of megaprojects, what additional skills are required of megaproject leaders?)
- 2. Megaproject Leadership Training:** we mapped the current DAU ALD program trainings to our initial megaproject leadership framework. The team would like to assist DAU in the design and development of courses that fill in the gaps toward megaproject leadership. A series of awareness courses that introduce the six unique leadership aspects of megaprojects is needed.
- 3. Demonstration of HFGT to DoD Megaprojects:** in our research, “A Hetero-functional Graph Theory Approach to Mega-Project Management”, we argued that MBSE and HFGT can provide an effective means for improving mega-project management performance. We qualitatively analyzed Denicol's recent review of mega-project management and elaborated on how HFGT can (1) help design the mega-project management system architecture, (2) bridge the theoretical gap between mega-project management and manufacturing, (3) evaluate the potential for collaborative decision-making, and (4) address the significant supply chain challenges associated with mega-project management. In a future project, we would seek to demonstrate this opportunity quantitatively. We would synthesize a case study that (1) exhibits the above characteristics in mega-project management and (2) demonstrates how MBSE and HFGT can quantitatively model these characteristics. Once the mega-project management case study has been modeled, we would conduct a structural resilience analysis that identifies structural weaknesses in the mega-project management's architecture and provides quantitative insights on how to reveal these weaknesses. We would also conduct a stochastic discrete-event simulation of the mega-project's management that identifies the source of cost and schedule overruns. Again, we expect that our model will provide quantitative insights on how to improve mega-project management cost and schedule performance.
- 4. Evolving and Improved LLMs for Megaproject Situational Awareness:** current LLM models face limitations as they remain fundamentally language models. While they can provide generally relevant information, they often lack the depth of detail, reasoning, and source references. For a megaproject tracking system to be truly effective, it must offer high accuracy, validity, and full traceability. Such a system should not only present pure language-based summary and suggestion but also provide clear, well-supported reasoning and thorough automation catering to different user groups, to ensure that all information can be tracked and verified throughout the project lifecycle.

For further research, we would extend the AI-assisted Megaproject monitoring system will focus on three key areas:

- Develop a customized (open-source) LLM model for megaprojects that incorporates all collected literature, lessons learned, and reports generated during this research project into the model to enhance the accuracy and effectiveness of model outputs.
- Improve the process of implementing LLM models for megaproject monitoring systems, particularly to add traceability of LLM models.
- Create use cases and develop ready-to-use software prototypes tailored for supply chain management in the mega project system.

Traceability: Our system would provide valid links and embedded references for majority of the AI-generated statements, ensuring a clear chain or network of references for key decisions. These links must be accurate, verifiable, and free from fabricated information, which is not commonly seen in existing LLM model outputs. For instance, a decision to replace a supplier or renegotiate a contract could be supported by (1) tracking fluctuations in world shipping container costs, (2) a customer complaint summary or quality report generated through GenAI analysis of recorded communications and feedback from the QA team, (3) a summary of frequent delivery delays extracted from the inventory database with ML support, (4) identification of overpriced contracts through competitor comparison reports from AI-assisted market research and others. All sources will be traceable through APIs and stored in the reference database, so decision-makers can always trace back to the online information, existing databases, and other relevant documents.

Besides the traceability, other features of the megaproject monitoring system include:

- **Role-Based Access:** the system will be tailored to address the needs of different stakeholders, such as developers, managers, and other roles, by providing customized access and functionality based on their specific requirements.
- **Version Control:** all exported documentation from the system will feature versioning to enable traceability to specific points in time and other artifacts, such as branch numbers in code development.
- **Detail Levels:** the system will accommodate (select and automate) various levels of detail. For example, a developer may need to view the full unified modeling language (UML) architecture of a model, while a development manager may only need a high-level overview of modules. The system will allow users to extract the necessary level of detail.
- **Interactive Dashboard:** the system is interactive, allowing users to engage fully with the mega project monitoring system. Features will include modifying information, leaving comments, sending alerts, confirming implementation plans, rearranging report flows and details, and others.

5. Megaproject Courses of Action Simulator: the research team will develop prototypes of visualization methods and tools identified in the first phase, and will extend them to encompass additional project attributes represented at different levels of detail. The starting point will be the train metaphor display as defined in the first phase. The limited-scope prototype from the first phase will be further developed and refined, suitable for evaluation of effectiveness. The level of detail available through interaction with the train metaphor display will be structured into 5 standard levels and used to prototype a narrated story interface, available at multiple levels of detail. In the narrated story, a user hears a story about the megaproject while viewing the dynamic representation of the train metaphor. Slightly different presentations will be composed about planned future phases of the megaproject, versus the phases of the project already executed. Once the prototypes are substantially implemented, we will evaluate the effectiveness of the visualization techniques with respect to human decision-making in domains of complexity and uncertainty. The effectiveness evaluation will include subjective ratings and objective measures. The research team will create a small number (4-5) of fictionalized exemplars, some of which will be based on the actual mega-project case studies reviewed. Each exemplar would be characterized in terms of key attributes and critical decisions from the perspective of the project manager. We will then refine these prototypes with a group of representative users, attempting to capture the key information elements in each prototype, linked to the key attributes and critical decisions. We will then conduct the evaluation by showing the refined prototypes to a second group of representative users and have them express their understanding of the key attributes and critical decisions for each exemplar. We would score the accuracy of these judgments, and also obtain their ratings of each visualization approach after viewing all the prototypes. Participants in these evaluations would be recruited from the workshop attendees and other interested groups. The evaluation sessions would be conducted remotely, with individual sessions scheduled with participants.

6. Quantifying the Impact of Flexible Contracting Approaches: beyond just involving considerable financial resources, megaproject complexity leads to more significant uncertainty and higher risks. During this study, our literature research identified contract flexibility, particularly in incentive structures, as a primary means to improve megaproject success. Using this theory, we wanted to investigate data from DoD Major Defense Acquisition Programs megaprojects (Contract Value >\$1B) to understand what incentives have worked and which should be avoided. We found examples of incentives that do not work, such as incentivizing cost or schedule, since these kinds of incentives distract the contractor from providing a balanced solution. Our research on successful megaprojects, the Heathrow T5 Study, indicated that incentivizing problem-solving skills to reduce program uncertainty is a successful use of contract incentives.

To understand how DoD programs have used contracting incentives to facilitate program success, we requested data from OSD on programs over \$1 billion with award or incentive fee contracts. We hoped we could obtain data that would give us insight into how incentives are used within the DoD and whether the incentives were beneficial. We found that the OSD community, specifically Cost Assessment and Program Evaluation (CAPE), recently performed a study to understand the effect of incentivizing schedules. In discussions with OSD/ADA and with CAPE, historical data to support this kind of analysis does not exist. There are a variety of OSD and Service level databases that host historical contract data, contract type, contract value, sometimes overall cost and schedule performance, but any data on the specifics of the contract incentives are not readily available. For what little data that is available it is in written form and would be complex to excavate any helpful information. Thus, we have not made much progress in addressing this question.

What is clear is that as the Department tries to leverage AI and ML, it must have better data to seed the AI and ML engines. The data would need to include not only contract language but also specific data from within a program office to include risk registers, technical performance measures over time, specific contract language, decision databases, etc.

We believe ample data is generated throughout the execution of a program that, if archived and made more readily available, could serve as a start to providing relevant historical data to support the future AI management methodologies being investigated by this mega project study. Large language modeling can initially extract current and historical data.

We believe that with the results from this Megaproject study on the use of data visualization, AI, and ML, combined with further research of current and historical data being collected across the Department, we could build a decision tree based on levels of uncertainty to identify and recommend policy for contract structures and reporting that will help “seed” the AI efforts of the future.

7. Tools for Analyzing Uncertainties and Mitigation in Megaprojects: we evaluated the interview protocol based on the uncertainty framework with the FLRAA government program office and demonstrated effective use of C-K Theory and STPA as a means to discuss and reason about project uncertainties using historical information from T5. In future research, we would like to integrate these three methods together within a visual modeling tool that stores the information and tracks it over time. This would be similar in form to current risk management practices and tools. Simple interview questions do not elicit full uncertainty information from participants as they are more comfortable discussing what they know today. C-K Theory forces participants to document their current state of knowledge and reason more fully about uncertainties and plans for project learning. While STPA forces participants to model the program control structure necessary to address these uncertainties and tracks the potential long-term consequences of these uncertainties as losses and risks. We would like to facilitate a series of workshops using the resulting toolset with an ongoing DoD megaproject.

8. Megaproject Modularity Analysis: modularity is noted extensively as a hedge to megaproject uncertainties, as it encapsulates areas of existing knowledge and areas where new knowledge must be generated. Current DoD MOSA assessment frameworks and tools measure modularity but not as a knowledge encapsulation method to reduce project uncertainties. MOSA is required on all DoD acquisition projects, but current practice may not optimize MOSA for the unique characteristics of megaprojects. Research should be conducted to 1) assess historical modularity benefits to megaprojects, 2) develop analysis tools to quantify appropriate modularity decisions in megaprojects, and 3) provide extended MOSA guidance to DoD megaprojects.

REFERENCES

PRIMARY LITERATURE REVIEW REFERENCES

Balyuk, Anna. "Ai in Project Management: Is the Future Already Here?" *Epicflow*, 6 June 2023, www.epicflow.com/blog/ai-in-project-management-is-the-future-already-here/#:~:text=According%20to%20Gartner%2C%20by%202030,AI%2Ddriven%20project%20management%20software.

Drouin, Nathalie. "Megaproject Leaders: Reflections on Personal Life Stories." *E-Elgar.com*, 2021, www.e-elgar.com/shop/usd/megaproject-leaders-9781789902969.html.

Flyvbjerg, Bent. "What You Should Know about Megaprojects and Why: An Overview." *Project Management Journal*, vol. 45, no. 2, Apr. 2014, pp. 6–19, <https://doi.org/10.1002/pmj.21409>.

Flyvbjerg, Bent. "Megaprojects: Over Budget, over Time, over and Over." *Cato.org*, 2017, www.cato.org/policy-report/january/february-2017/megaprojects-over-budget-over-time-over-over.

Gartner. "Gartner Says 80 Percent of Today's Project Management Tasks Will Be Eliminated by 2030 as Artificial Intelligence Takes Over." *Gartner*, 20 Mar. 2019, www.gartner.com/en/newsroom/press-releases/2019-03-20-gartner-says-80-percent-of-today-s-project-management.

Gil, Nuno, and Don Ward. *Leadership in Megaprojects and Production Management: Lessons from the T5 Project*. 2011.

Hutchison, N.A.C., Verma, D., Burke, P., See Tao, H.Y., Giffin, R., Yu, Z., Makwana, D., Chen, X., Xiao, Y. (2020). *Atlas: Effective Systems Engineers and Systems Engineering*. Hoboken, NJ: Systems Engineering Research Center (SERC). SERC-2020-TR-007-A. July 7, 2020.

International Centre for Complex Project Management. (2021). *Complex Project Leadership—Competency Standards*. Version 1.0. Commonwealth of Australia: Edward Elgar Publishing Limited. <https://iccpm.com/resource-centre/complex-project-leadership-competency-standards-2023/>

Lenfle, S. and Loch, C. (2010) Lost Roots: How Project Management Came to Emphasize Control over Flexibility and Novelty. *California Management Review*, 53, 32-55.-Lengler, R. and Eppler, M. 2007. Towards A Periodic Table of Visualization Methods for Management. IASTED Proceedings of the Conference on Graphics and Visualization in Engineering (GVE 2007), Clearwater, Florida, USA.

Lundrigan, Colm P., et al. "The (Under) Performance of Mega-Projects: A Meta- Organizational Perspective." *SSRN Electronic Journal*, 2014, <https://doi.org/10.2139/ssrn.2542107>.

McDermott, T. & Freeman, D. (2019). "Advanced Visualization Toolset." In *Evolving Toolbox for Complex Project Management*. Auerbach Publications.

McDermott, T., Hutchison, N., Crick, R. (2021). The Evolution of HELIX: A Competency Model for Complex Problem Solving. Proceedings of the 31st Annual INCOSE International Symposium, July 17-22, 2021, Honolulu, HI.

Marrow, E. (2011). *Industrial Megaprojects*. Hoboken, NJ: John Wiley & Sons.

Merrow, E., & Nandurdikar, N. (2018). *Leading Complex Projects*. John Wiley & Sons.

Metar, Umesh. "Stakeholder Engagement in Mega Projects." *www.linkedin.com*, 4 Feb. 2021, www.linkedin.com/pulse/stakeholder-engagement-mega-projects-umesh-metar-pmp-pmi-rmp

Nieto-Rodriguez, Antonio, and Ricardo Viana Vargas. "How AI Will Transform Project Management." *Harvard Business Review*, 2 Feb. 2023, hbr.org/2023/02/how-ai-will-transform-project-management.

Pennotti, M., Dominick, P., Robinson, W. (2015). RT-129: Advanced Technical Leadership. Hoboken, NJ: Systems Engineering Research Center. SERC-2015-TR-101. July 17, 2015. https://sercproddata.s3.us-east-2.amazonaws.com/technical_reports/reports/1525983439-SERC-2015-TR-101_AdvancedTechnicalLeadership_RT129.pdf

"Project Delivery Hubs: Analytics for Better Megaproject Outcomes." *www.mckinsey.com*, 21 Aug. 2021, www.mckinsey.com/capabilities/operations/our-insights/project-delivery-hubs-analytics-for-better-megaproject-outcomes.

Sebastian-Winter. "Complex Project Leadership Competency Standards 2023." *International Centre for Complex Project Management (ICCPM)*, iccpm.com/resource-centre/complex-project-leadership-competency-standards-2023/.

Stevens, Renee. (2011.) *Engineering Mega-Systems: The Challenge of Systems Engineering in the Information Age*. Boca Raton, LA: CRC Press.

Stevens, Renee. "Engineering Mega-Systems." *O'Reilly Online Learning*, 2016, www.oreilly.com/library/view/engineering-mega-systems/9781420076677/.

Van Wart, M. (2015). Evaluating Transformational Leaders: The Challenging Case of Eric Shinseki and the U.S. Department of Veterans Affairs. *Public Administration Review*, 75(5): 760-769. September|October 2015.

FULL REFERENCE LIST

"Project Delivery Hubs: Analytics for Better Megaproject Outcomes." www.mckinsey.com, 21 Aug. 2021, www.mckinsey.com/capabilities/operations/our-insights/project-delivery-hubs-analytics-for-better-megaproject-outcomes.

Ang, K. C. S., Afzal, F., & Crawford, L. H. (2021). Transitioning from passive to active learning: Preparing future project leaders. *Project Leadership and Society*, 2, 100016. <https://doi.org/10.1016/j.plas.2021.100016>

Babaei, A., Locatelli, G., & Sainati, T. (2021). What is wrong with the front-end of infrastructure megaprojects and how to fix it: A systematic literature review. *Project Leadership and Society*, 2, 100032. <https://doi.org/10.1016/j.plas.2021.100032>

Baldwin, C. and K. Clark. 2000. *Design Rules: The Power of Modularity*. Cambridge, MA: The MIT Press.

Balyuk, Anna. "AI in Project Management: Is the Future Already Here?" *Epicflow*, 6 June 2023, www.epicflow.com/blog/ai-in-project-management-is-the-future-already-here/#:~:text=According%20to%20Gartner%2C%20by%202030,AI%2Ddriven%20project%20management%20software.

Bearfield, D. A., & Dubnick, M. J. (2009). All mega-projects are local? Citizen participation lessons from the big dig. *Journal of Public Budgeting, Accounting & Financial Management*, 21(3), 392–425. <https://doi.org/10.1108/JPBAFM-21-03-2009-B003>

Bennis, W. (2009). *On Becoming a Leader*. New York, NY: Basic Books.

Bertel, L. B., Winther, M., Routhe, H. W., & Kolmos, A. (2022). Framing and facilitating complex problem-solving competences in interdisciplinary megaprojects: An institutional strategy to educate for sustainable development. *International Journal of Sustainability in Higher Education*, 23(5), 1173–1191. <https://doi.org/10.1108/IJSHE-10-2020-0423>

Biesenthal, C., Clegg, S., Mahalingam, A., & Sankaran, S. (2018). Applying institutional theories to managing megaprojects. *International Journal of Project Management*, 36(1), 43–54. <https://doi.org/10.1016/j.ijproman.2017.06.006>

Bilgin, G., Erol, H., Atasoy, G., Dikmen, I., & Birgonul, M. T. (2022). Exploring pattern of complexity in mega construction projects. *International Journal of Managing Projects in Business*, 15(7), 1064–1090. <https://doi.org/10.1108/IJMPB-03-2022-0064>

Borches, P. D. (2010). *A3 Architecture Overviews: A Tool for Effective Communication in Product Evolution*. University of Twente.

Borno, J. (2020). Boston's Megaproject: A Leadership Analysis. *Journal of Multidisciplinary Research*, 12(1), 129–133.

Brady, T., & Davies, A. (2010). Learning to Deliver a Mega-Project: The Case of Heathrow Terminal 5 (Chapter 9). In N. Caldwell & N. Howard (Eds.), *Procuring Complex Performance: Studies of Innovation in Product-Service Management* (1st ed.). Taylor & Francis Group.

Cantarelli, C. C., & Genovese, A. (2023). Innovation potential of megaprojects: A systematic literature review. *Production Planning & Control*, 34(14), 1350–1370. <https://doi.org/10.1080/09537287.2021.2011462>

Chen, X., He, Q., Zhang, X., Cao, T., & Liu, Y. (2021). WHAT MOTIVATES STAKEHOLDERS TO ENGAGE IN COLLABORATIVE INNOVATION IN THE INFRASTRUCTURE MEGAPROJECTS? *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT*, 27(8), 579–594. <https://doi.org/10.3846/jcem.2021.15612>

Clutterbuck, D. (2008). What's happening in coaching and mentoring? And what is the difference between them? *Development and Learning in Organizations*, 22(4), p. 8-10.

Daemi, A., Chugh, R., & Kanagarajoo, M. V. (2021). Social media in project management: A systematic narrative literature review. *International Journal of Information Systems and Project Management*, 8(4), 5–21. <https://doi.org/10.12821/ijispm080401>

Damayanti, R. W., Hartono, B., & Wijaya, A. R. (2021a). Project Managers' Perspectives on the Complexity of Construction Megaproject in Indonesia: A Multicase Study. *IEEE Engineering Management Review*, 49(2), 153–171. <https://doi.org/10.1109/EMR.2021.3063812>

Damayanti, R. W., Hartono, B., & Wijaya, A. R. (2021b). Leadership Competency for Megaproject's Complexity Management: A Conceptual Study. *International Journal of Innovation, Management and Technology*, 12(4), 68–74. <https://doi.org/10.18178/ijimt.2021.12.4.911>

- Damayanti, R., Hartono, B., & Wijaya, A. (2021). Complexity, leadership, and megaproject performance: A configuration analysis. *Journal of Industrial Engineering and Management*, 14(3), 570. <https://doi.org/10.3926/jiem.3476>
- Davies, A., Gann, D., & Douglas, T. (2009). "Innovation in Megaprojects: Systems Integration at London Heathrow Terminal 5." *California Management Review*, 51(2), 101-125.
- Davis, T. (2024). Self-Motivation: Definition, Examples, and Tips. Berkley, CA: Berkely Well-Being Institute. <https://www.berkeleywellbeing.com/self-motivation.html>
- Denicol, J., & Davies, A. (2022). The Megaproject-based Firm: Building programme management capability to deliver megaprojects. *International Journal of Project Management*, 40(5), 505–516. <https://doi.org/10.1016/j.ijproman.2022.06.002>
- Denicol, J., Davies, A., & Krystallis, I. (2020). What Are the Causes and Cures of Poor Megaproject Performance? A Systematic Literature Review and Research Agenda. *Project Management Journal*, 51(3), 328–345. <https://doi.org/10.1177/8756972819896113>
- Department of Defense (DoD) (2022). DOD Instruction 5000.02 Operation Of The Adaptive Acquisition Framework.
- Drouin, Nathalie. "Megaproject Leaders: Reflections on Personal Life Stories." E-Elgar.com, 2021, www.e-elgar.com/shop/usd/megaproject-leaders-9781789902969.html.
- Dunović, I. B., Radujković, M., & Škreb, K. A. (2014). Towards a New Model of Complexity – The Case of Large Infrastructure Projects. *Procedia - Social and Behavioral Sciences*, 119, 730–738. <https://doi.org/10.1016/j.sbspro.2014.03.082>
- Esposito, G., Nelson, T., Ferlie, E., & Crutzen, N. (2021). The institutional shaping of global megaprojects: The case of the Lyon-Turin high-speed railway. *International Journal of Project Management*, 39(6), 658–671. <https://doi.org/10.1016/j.ijproman.2021.06.001>
- Evans, M., Farrell, P., Elbeltagi, E., & Dion, H. (2022). Competency framework to integrate lean construction and integrated project delivery on construction megaprojects: Towards a future of work global initiatives in multinational engineering organisations. *Benchmarking: An International Journal*, 29(6), 1913–1956. <https://doi.org/10.1108/BIJ-02-2021-0066>
- Faisal, Mohd. N., Al Subaie, A. A., Sabir, L. B., & Sharif, K. J. (2023). PMBOK, IPMA and fuzzy-AHP based novel framework for leadership competencies development in megaprojects. *Benchmarking: An International Journal*, 30(9), 2993–3020. <https://doi.org/10.1108/BIJ-10-2021-0583>
- Farid, A. M., D. Thompson, and W. C. Schoonenberg (2022). "A Tensor-Based Formulation of Hetero-functional Graph Theory," *Nature Scientific Reports*, vol. 12, no. 18805, pp. 1–22. [Online]. Available: <https://doi.org/10.1038/s41598-022-19333-y>
- Farid, A. M. (2015). "Static resilience of large flexible engineering systems: Axiomatic design model and measures," *IEEE Systems Journal*, vol. 11, no. 4, pp. 2006–2017.
- FCS Program Office (2004). FCS 18+1+1 White Paper. <https://www.govinfo.gov/content/pkg/GOVPUB-D101-PURL-LPS62251/pdf/GOVPUB-D101-PURL-LPS62251.pdf>.
- Fitzgerald, M., Kruschwitz, N., Bonnet, D., & Welch, M. (n.d.-a). Embracing Digital Technology.

Flyvbjerg, B. (2017). *The Oxford Handbook of Megaproject Management*. Oxford University Press.

Flyvbjerg, Bent. "Megaprojects: Over Budget, over Time, over and Over." *Cato.org*, 2017, www.cato.org/policy-report/january/february-2017/megaprojects-over-budget-over-time-over-over.

Flyvbjerg, Bent. "What You Should Know about Megaprojects and Why: An Overview." *Project Management Journal*, vol. 45, no. 2, Apr. 2014, pp. 6–19, <https://doi.org/10.1002/pmj.21409>.

Flyvbjerg, Bent and Gardner, Dan (2014). *How Big Things Get Done*. Penguin Random House.

Garemo, N., Matzinger, S., & Palter, R. (2015). *The Good, the Bad, and the Better*. McKinsey & Company.

Gartner. "Gartner Says 80 Percent of Today's Project Management Tasks Will Be Eliminated by 2030 as Artificial Intelligence Takes Over." *Gartner*, 20 Mar. 2019, www.gartner.com/en/newsroom/press-releases/2019-03-20-gartner-says-80-percent-of-today-s-project-management.

Gil, N., & Lundrigan, C. (2012). *The Leadership and Governance of Megaprojects*. Manchester, England: Centre for Infrastructure Development (CID) and Manchester Business School, The University of Manchester. CID Technical Report No. 3/2012. April 2012.

Gil, Nuno, and Don Ward. *Leadership in Megaprojects and Production Management: Lessons from the T5 Project*. 2011.

Glowasz, M. (2022). *Leading Projects with Data*. Zurich, Switzerland: Marcus Glowasz.

Gorod, A., Hallo, L., Statsenko, L., Nguyen, T., & Chileshe, N. (2020). Integrating hierarchical and network centric management approaches in construction megaprojects using a holonic methodology. *Engineering, Construction and Architectural Management*, 28(3), 627–661. <https://doi.org/10.1108/ECAM-01-2020-0072>

Hafseld, K. H. J., Hussein, B., & Rauzy, A. B. (2021). An attempt to understand complexity in a government digital transformation project. *International Journal of Information Systems and Project Management*, 9(3), 70–91. <https://doi.org/10.12821/ijispm090304>

Hatchuel, A. and Weil, B. (2009) C-K Design Theory: An Advanced Formulation. *Research in Engineering Design*, 19, 181-92.

Hatchuel, A., LeMasson, P., Reich, Y. and Weil, B. (2011a) A Systematic Approach of Design Theories Using Generativeness and Robustness. *International Conference on Engineering Design, ICED*. Technical University of Denmark, Copenhagen.

Hatchuel, A, LeMasson, P. and Weil, B. (2011b) Teaching Innovative Design Reasoning: How C-K Theory Can Help to Overcome Fixation Effect. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 25, 77-92.

Hatchuel, A, Weil, B. and LeMasson, P. (2013) Towards an Ontology of Design: Lessons from C-K Design Theory and Forcing. *Research in Engineering Design*, 24, 147-63.

He, Q., Wang, T., Chan, A. P. C., & Xu, J. (2021). Developing a List of Key Performance Indicators for Benchmarking the Success of Construction Megaprojects. *Journal of Construction Engineering and Management*, 147(2), 04020164. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001957](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001957)

- Hetemi, E., Van Marrewijk, A., Jerbrant, A., & Bosch-Rekveltdt, M. (2021). The recursive interaction of institutional fields and managerial legitimation in large-scale projects. *International Journal of Project Management*, 39(3), 295–307. <https://doi.org/10.1016/j.ijproman.2020.11.004>
- Hirshman, Albert O. (1967). "The principle of the hiding hand." *National Affairs, The Public Interest*, #60.
- Hutchison, N.A.C., Verma, D., Burke, P., See Tao, H.Y., Giffin, R., Yu, Z., Makwana, D., Chen, X., Xiao, Y. (2020). *Atlas: Effective Systems Engineers and Systems Engineering*. Hoboken, NJ: Systems Engineering Research Center (SERC). SERC-2020-TR-007-A. July 7, 2020.
- Hutchison, N.A.C., Verma, D., Burke, P., See Tao, H.Y., Giffin, R., Yu, Z., Makwana, D., Chen, X., Xiao, Y. (2020). *Atlas: Effective Systems Engineers and Systems Engineering*. Hoboken, NJ: Systems Engineering Research Center (SERC). SERC-2020-TR-007-A. July 7, 2020.
- International Centre for Complex Project Management. (2021). *Complex Project Leadership—Competency Standards*. Version 1.0. Commonwealth of Australia: Edward Elgar Publishing Limited. <https://iccpm.com/resource-centre/complex-project-leadership-competency-standards-2023/>
- Irimia-Diéguez, A. I., Sanchez-Cazorla, A., & Alfalla-Luque, R. (2014). Risk Management in Megaprojects. *Procedia - Social and Behavioral Sciences*, 119, 407–416. <https://doi.org/10.1016/j.sbspro.2014.03.046>
- Johansen, A., Bjerke, Y. C., & Landmark, A. (2018). Effective Opportunity management in a Megaproject. *Procedia Computer Science*, 138, 883–890. <https://doi.org/10.1016/j.procs.2018.10.115>
- Jussila, A., Mainela, T., & Nätti, S. (2016). Formation of strategic networks under high uncertainty of a megaproject. *Journal of Business & Industrial Marketing*, 31(5), 575–586. <https://doi.org/10.1108/JBIM-03-2014-0055>
- Kane, G. C., Palmer, D., Phillips, A. N., & Kiron, D. (2017). Winning the Digital War for Talent. *MIT Sloan Management Review*, 58(2): 17-20. Winter 2017.
- Kane, G. C., Phillips, A. N., Copulsky, J., & Andrus, G. (2019). How Digital Leadership Is(n't) Different: Leaders must blend traditional and new skills to effectively guide their organizations into the future. *MIT Sloan Management Review*, 60(3): 34-39. Spring 2019.
- Kaufman, I., & Horton, C. (2015). Digital Transformation: Leveraging Digital Technology with Core Values to Achieve Sustainable Business Goals. *European Financial Review*. December-January 2015: 63-67.
- Kiron, D., Palmer, D., Phillips, A. N., & Berkman, R. (2013). The Executive's Role in Social Business. *MIT Sloan Management Review*, 54(4): 83-89. Summer 2013.
- Kivela, M., A. Arenas, M. Barthelemy, J. P. Gleeson, Y. Moreno, and M. A. Porter, "Multilayer networks," *Journal of complex networks*, vol. 2, no. 3, pp. 203–271, 2014.
- KPMG. 2015. 10 Emerging Trends for 2015. *Foresight Special Edition – January 2015*. KPMG International Cooperative. <https://assets.kpmg.com/content/dam/kpmg/pdf/2015/03/foresight-26.pdf>

- Lehtonen, M. (2015). Megaproject Underway: Governance of Nuclear Waste Management in France. In A. Brunnengräber, M. R. Di Nucci, A. M. Isidoro Losada, L. Mez, & M. A. Schreurs (Eds.), *Nuclear Waste Governance* (pp. 117–138). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-08962-7_5
- Lenfle, S. (2012) Exploration, Project Evaluation and Design Theory: A Rereading of the Manhattan Case. *International Journal of Managing Projects in Business*, 5, 486-507.
- Lenfle, S. (2011) The Strategy of Parallel Approaches in Projects with Unforeseeable Uncertainty: The Manhattan Case in Retrospect. *International Journal of Project Management*, 29, 359-73.
- Lenfle, S. and Loch, C. (2010) Lost Roots: How Project Management Came to Emphasize Control over Flexibility and Novelty. *California Management Review*, 53, 32-55.-Lengler, R. and Eppler, M. 2007. Towards A Periodic Table of Visualization Methods for Management. *IASTED Proceedings of the Conference on Graphics and Visualization in Engineering (GVE 2007)*, Clearwater, Florida, USA.
- Lenfle, S., Le Masson, P., and Weil, B. (2016). "When project management meets design theory: revisiting the Manhattan and Polaris projects to characterize "radical innovation" and its managerial implications." *Creativity and Innovation Management*, 25, (3), pp. 378-395.
- Lester, D. and Torero, J. (2019). Using megaproject performance outcomes to enhance decision-making behaviours in civil engineering graduates. *Construction Economics and Building*, 19(1): 96-110.
- Locatelli, G., Littau, P., Brookes, N. J., & Mancini, M. (2014). Project Characteristics Enabling the Success of Megaprojects: An Empirical Investigation in the Energy Sector. *Procedia - Social and Behavioral Sciences*, 119, 625–634. <https://doi.org/10.1016/j.sbspro.2014.03.070>
- Lopez Del Puerto, C., & Shane, J. S. (2014). Keys to Success in Megaproject Management in Mexico and the United States: Case Study. *Journal of Construction Engineering and Management*, 140(4), B5013001. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000476](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000476)
- Louw, W., Steyn, H., Wium, J., & Gevers, W. (2022). An investigation of sponsor attributes on six megaproject cases. *International Journal of Managing Projects in Business*, 15(1), 58–81. <https://doi.org/10.1108/IJMPB-11-2020-0343>
- Louw, W., Wium, J., Steyn, H., & Gevers, W. (2018). The Megaproject Sponsor as Leader. *South African Journal of Industrial Engineering*, 29(3) Special Edition, November 2018, 173-187.
- Lundrigan, Colm P., et al. "The (Under) Performance of Mega-Projects: A Meta- Organizational Perspective." *SSRN Electronic Journal*, 2014, <https://doi.org/10.2139/ssrn.2542107>.
- Lynch, B. (2015). Partnering for performance in situational leadership: A person-centred leadership approach. *International Practice Development Journal*, 5(Suppl), 1–10. <https://doi.org/10.19043/ipdj.5SP.007>
- Marrewijk, A. V., Sankaran, S., Drouin, N., & Müller, R. (2023). Climbing to the top: Personal life stories on becoming megaproject leaders. *Project Leadership and Society*, 4, 100085. <https://doi.org/10.1016/j.plas.2023.100085>

- Martinelli, T. (host). (2023). Innovate to Win – Defense Acquisition University and Innovation Readiness Assessment. Defense Entrepreneurs Forum's (DEF's) Minimum Viable Podcast (MVP). Available on Spotify: <https://open.spotify.com/episode/2XXy-iXYVr8iqd7ynhEcph3>
- McCrae, R.R. and Cost, P.T., Jr. (1999). A Five-Factor Theory of Personality. In L. A. Pervin & O. P. John (Eds.), *Handbook of personality: Theory and research* (2nd ed., pp. 139–153). Guilford Press.
- McDermott, T. & Freeman, D. (2019). "Advanced Visualization Toolset." In *Evolving Toolbox for Complex Project Management*. Auerbach Publications.
- McDermott, T., Hutchison, N., Crick, R. (2021). The Evolution of HELIX: A Competency Model for Complex Problem Solving. *Proceedings of the 31st Annual INCOSE International Symposium, July 17-22, 2021, Honolulu, HI.*
- McDermott, T., Hutchison, N., Crick, R. (2021). The Evolution of HELIX: A Competency Model for Complex Problem Solving. *Proceedings of the 31st Annual INCOSE International Symposium, July 17-22, 2021, Honolulu, HI.*
- Marrow, E. (2011). *Industrial Megaprojects*. Hoboken, NJ: John Wiley & Sons.
- Marrow, E. (2011). *Industrial Megaprojects*. Hoboken, NJ: John Wiley & Sons.
- Marrow, E., & Nandurdikar, N. (2018). *Leading Complex Projects*. John Wiley & Sons.
- Marrow, E., & Nandurdikar, N. (2018). *Leading Complex Projects*. John Wiley & Sons.
- Metar, Umesh. "Stakeholder Engagement in Mega Projects." *Www.linkedin.com*, 4 Feb. 2021, www.linkedin.com/pulse/stakeholder-engagement-mega-projects-umesh-metar-pmp-pmi-rmp
- Mohsen, F. (2020). Megaprojects and the Need for a Scheduling Competence Centre within a PMO [LinkedIn]. LinkedIn Article. August 19, 2020. <https://www.linkedin.com/pulse/megaprojects-need-scheduling-competence-centre-within-mohsen/>
- Morcov, S., Pintelon, L., & Kusters, R. (2021). Definitions, characteristics and measures of IT project complexity—A systematic literature review. *International Journal of Information Systems and Project Management*, 8(2), 5–21. <https://doi.org/10.12821/ijispm080201>
- National Science Foundation (NSF) (2024). Collaborative research: Gcr: Convergent merican ene systems (anthems) – a system-of-systems paradigm. [Online]. Available: https://www.nsf.gov/awardsearch/showAward?AWD_ID=2317877&Historical-Awards=false
- Nicał, A. K., & Wodyński, W. A. (2015). Procuring Governmental Megaprojects: Case Study. *Procedia Engineering*, 123, 342–351. <https://doi.org/10.1016/j.proeng.2015.10.045>
- Nieto-Rodriguez, Antonio, and Ricardo Viana Vargas. "How AI Will Transform Project Management." *Harvard Business Review*, 2 Feb. 2023, hbr.org/2023/02/how-ai-will-transform-project-management.
- NIH. (nd). "Political Savvy". Washington, DC: National Institutes of Health. <https://hr.nih.gov/working-nih/competencies/competencies-dictionary/political-savvy#:~:text=The%20ability%20to%20exhibit%20confidence,all%20levels%20of%20the%20organization.>

- Nyarirangwe, M., & Babatunde, O. K. (2021). Megaproject complexity attributes and competences: Lessons from IT and construction projects. *International Journal of Information Systems and Project Management*, 7(4), 77–99. <https://doi.org/10.12821/ijispm070404>
- Pennotti, M., Dominick, P., Robinson, W. (2015). RT-129: Advanced Technical Leadership. Hoboken, NJ: Systems Engineering Research Center. SERC-2015-TR-101. July 17, 2015. https://sercproddata.s3.us-east-2.amazonaws.com/technical_reports/reports/1525983439-SERC-2015-TR-101_AdvancedTechnicalLeadership_RT129.pdf
- Pennotti, M., Dominick, P., Robinson, W. (2015). RT-129: Advanced Technical Leadership. Hoboken, NJ: Systems Engineering Research Center. SERC-2015-TR-101. July 17, 2015. https://sercproddata.s3.us-east-2.amazonaws.com/technical_reports/reports/1525983439-SERC-2015-TR-101_AdvancedTechnicalLeadership_RT129.pdf
- Pinto, J. K. (2023). Is this How Big Things Get Done? *International Journal of Project Management*, 41(5), 102484. <https://doi.org/10.1016/j.ijproman.2023.102484>
- Project Management Institute (PMI) (2015). Pulse of the profession® in-depth report: Capturing the value of project management through knowledge transfer. Newtown Square, PA.
- PMI. (2014.) *Navigating Complexity: A Practice Guide*. The Project Management Institute.
- Pollack, J., Biesenthal, C., Sankaran, S., & Clegg, S. (2018). Classics in megaproject management: A structured analysis of three major works. *International Journal of Project Management*, 36(2), 372–384. <https://doi.org/10.1016/j.ijproman.2017.01.003>
- Prakash, S. B., Kirkham, R., Nanda, A., & Coleman, S. (2023). Exploring the complexity of highways infrastructure programmes in the United Kingdom through systems thinking. *Project Leadership and Society*, 4, 100081. <https://doi.org/10.1016/j.plas.2023.100081>
- Royse, M. (2021). 10 Leadership Skills Every Marketing Leader Should Master. *Better Marketing*. September 7, 2021.
- Sanchez, R., and Mahoney, J. T. (1996). Modularity, Flexibility, and Knowledge Management in Product and Organization Design. *Strategic Management Journal*, 17, (Winter, Special Issue: Knowledge and the Firm), 63–76.
- Sankaran, S. (2018). Megaproject management and leadership: A narrative analysis of life stories – past and present. *International Journal of Managing Projects in Business*, 11(1), 53–79. <https://doi.org/10.1108/IJMPB-07-2017-0081>
- Schindler, S., Fadaee, S., & Brockington, D. (2021). *Contemporary Megaprojects: Organization, Vision, and Resistance in the 21st Century*. Berghahn Books.
- Schmidt, J. (2023). Mitigating risk of failure in information technology projects: Causes and mechanisms. *Project Leadership and Society*, 4, 100097. <https://doi.org/10.1016/j.plas.2023.100097>
- Schoemaker, P. J. H., Krupp, S., & Howland, S. (2013). *Strategic Leadership: The Essential Skills*. Harvard Business Review. January-February 2013.
- Schoonenberg, W. C., I. S. Khayal, and A. M. Farid (2019). A Hetero-functional Graph Theory for Modeling Interdependent Smart City Infrastructure. Berlin, Heidelberg: Springer, 2019. [Online]. Available: <http://dx.doi.org/10.1007/978-3-319-99301-0>

- Schoonenberg W. C. and A. M. Farid (2022). "Hetero-functional Network Minimum Cost Flow Optimization," Sustainable Energy Grids and Networks, vol. 31, no. 100749, pp. 1–18, 2022. [Online]. Available: <https://doi.org/10.1016/j.segan.2022.100749>
- Sebastian-Winter. "Complex Project Leadership Competency Standards 2023." International Centre for Complex Project Management (ICCPM), iccpm.com/resource-centre/complex-project-leadership-competency-standards-2023/.
- Shenhar, A.J. and Dvir, D. (2007). Reinventing Project Management: The Diamond Approach to Successful Growth and Innovation. Boston, MA: Harvard Business School Press.
- Shi, Q., Chen, X., Xiao, C., & Han, Y. (2022). Network Perspective in Megaproject Management: A Systematic Review. Journal of Construction Engineering and Management, 148(7), 03122002. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0002304](https://doi.org/10.1061/(ASCE)CO.1943-7862.0002304)
- Smith, J. (Host). (2023, August 15). The Future of Technology in Education (Episode 12) [Audio podcast episode]. In Tech Today. Innovation Media. <https://www.techtodaypodcast.com>
- Smith, T., & Hoover, S. (2021). Wanted: New Leadership Competencies for Managing 2021 Megaprojects. FMI: SEP.
- Sparg, A. (2018). Competences for managing mega infrastructure projects: A pilot study. Journal of Construction Project Management and Innovation, 8(Supplement): 2219-2231.
- Stevens, Renee. "Engineering Mega-Systems." O'Reilly Online Learning, 2016, www.oreilly.com/library/view/engineering-mega-systems/9781420076677/.
- Stevens, Renee. (2011.) Engineering Mega-Systems: The Challenge of Systems Engineering in the Information Age. Boca Raton, LA: CRC Press.
- Thompson D. and A. M. Farid (2024). "A hetero-functional graph structural analysis of the merican multi-modal energy system," Sustainable Energy, Grids, and Networks, vol. 38, no. 1, pp. 101254–101269, 2024.
- Thompson D. and A. M. Farid (2022). "A Reference Architecture for the American Multi-Modal Energy System," Journal of Industrial Information Integration, 2022. [Online]. Available: <https://arxiv.org/abs/2012.14486>
- Thompson. Loren B. (2008). FCS: The Logic of Future Combat Systems. The Lexington Institute. <https://www.lexingtoninstitute.org/wp-content/uploads/fcs-the-logic-of-future-combat.pdf>
- Turner, J. R., & Müller, R. (2005). "The Project Manager's Leadership Style as a Success Factor on Projects: A Literature Review." Project Management Journal, 36(2), 49-61.
- University of Pennsylvania. (2024). "Open-Mindedness". Authentic Happiness. <https://www.authentichappiness.sas.upenn.edu/newsletters/authentichappinesscoaching/open-mindedness#:~:text=Definition,of%20thinking%20for%20one's%20self.>
- Van Marrewijk, A. (2007). Managing project culture: The case of Environ Megaproject. International Journal of Project Management, 25(3), 290–299. <https://doi.org/10.1016/j.ijproman.2006.11.004>
- Van Steen, M. (2020). Graph Theory and Complex Networks: An Introduction. Maarten van Steen, 2010, no. January.

- Van Wart, M. (2015). Evaluating Transformational Leaders: The Challenging Case of Eric Shinseki and the U.S. Department of Veterans Affairs. *Public Administration Review*, 75(5): 760-769. September|October 2015.
- Virtuani, R., Barabaschi, B., & Cantoni, F. (2023). Overtaking the Traditional Leadership Style in Megaprojects. In E. Favari & F. Cantoni (Eds.), *Complexity and Sustainability in Megaprojects* (Vol. 342, pp. 97-109). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-30879-6_8
- Von Leipzig, T., Gamp, M., Manz, D., Schöttle, K., Ohlhausen, P., Oosthuizen, G., Palm, D., & Von Leipzig, K. (2017). Initialising Customer-orientated Digital Transformation in Enterprises. *Procedia Manufacturing*, 8, 517-524. <https://doi.org/10.1016/j.promfg.2017.02.066>
- Wang, G., Zhou, K., Wang, D., Wu, G., & Xie, J. (2021). Tensions in governing megaprojects: How different types of ties shape project relationship quality? *International Journal of Project Management*, 39(7), 799-814. <https://doi.org/10.1016/j.ijproman.2021.08.003>
- Warrack, A. (1993). Megaproject Decision Making Lessons and Strategies. *Western Centre for Economic Research Information Bulletin #16*: 1-15. May 1993.
- Williams, D. (1999). Managing the Megaproject. *Civil Engineering*, 48-51.
- YScouts. (2021, June). 10 Transactional Leadership Characteristics. *Talent Recruitment Leadership Blog*. <https://yscouts.com/10-transactional-leadership-characteristics/>
- Zhang, X., Liu, M., Le, Y., Wei, J., Zhu, Y., & Li, Y. (2023). Deconstructing Organizational Capabilities of Megaproject Owners: Dimensions and Levels. *Journal of Construction Engineering and Management*, 149(7), 04023055. <https://doi.org/10.1061/JCEMD4.COENG-13097>
- Zhu, L., Cheung, S. O., Gao, X., Li, Q., & Liu, G. (2020). Success DNA of a Record-Breaking Megaproject. *Journal of Construction Engineering and Management*, 146(8), 05020009. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001878](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001878)
- Zidane, Y. J.-T., Johansen, A., & Ekambaram, A. (2013). Megaprojects-Challenges and Lessons Learned. *Procedia - Social and Behavioral Sciences*, 74, 349-357. <https://doi.org/10.1016/j.sbspro.2013.03.041>

APPENDIX A: DETAILED MEGAPROJECT LEADERSHIP FRAMEWORK

PERSONAL CHARACTERISTICS

There are six critical characteristics for megaproject leaders, as defined in Table 3. Individual examples from the literature are incorporated.

Table 3. Detailed Description of Critical Personal Characteristics for Megaproject Leadership

Characteristic	Definition	Example(s) and Citation(s)
Self-Aware	Self-awareness is the ability to understand and recognize one's own thoughts, emotions, and behaviors, and how they affect oneself and others.	<ul style="list-style-type: none"> • Self-aware leaders are better able to recognize and mitigate cognitive biases such as optimism bias and strategic misrepresentation (Flyvberg, 2017) • Self-aware leaders are more likely to critically assess their own judgements and decisions. This can help prevent unrealistic planning and forecasting that can lead to project failure (Flyvberg, 2017). • Lack of Neuroticism (Big 5 characteristic) (Merrow and Nandurikar, 2018) • Effective megaproject leaders are a “group of intelligent men and women who know themselves well and see others clearly” (Merrow and Nandurikar, 2018) • Very senior players rarely lost their composure in public, even when the stakes were high and errors had been made. There was a level of statesmanlike behaviour that always went on, even though everyone was very aware that heads would roll, and long-term contracts would be affected if companies and key players were not at the top of their game, demonstrating total commitment to the delivering objectives. (Doherty 2008, p. 189) • Leaders must understand their strengths, weaknesses, values, and beliefs to lead authentically. This self-awareness allows leaders to build trust and credibility with their teams. (Bennis, 2009) • Self-awareness, self-control (Damayanti et al., 2021a and c) • Understanding and managing one's own emotions and those of others (Faisal et al., 2023)

Characteristic	Definition	Example(s) and Citation(s)
<p>Self-Motivated</p>	<p>Self-motivation is the internal state that helps us initiate, continue, or terminate a behavior (Davis, 2024).</p>	<ul style="list-style-type: none"> • The sheer scale, complexity, and length of megaprojects require leaders who are intrinsically motivated to sustain their commitments over many years (Flyvberg, 2017) • An internal drive to overcome the many obstacles that typically arise in megaprojects, such as stakeholder conflicts, regulatory hurdles, and technical challenges is necessary for leaders to maintain their energy and enthusiasm • Self-motivated leaders are more likely to exhibit a transformational leadership style, characterized by high levels of enthusiasm, passion, and a strong commitment to project goals. Such leaders inspire their teams by demonstrating dedication and a relentless pursuit of project objectives, which is particularly important in the demanding environment of megaprojects (Turner and Müller, 2005). • Drive for success despite the odds (Doherty, 2008) • Self-leadership and reflective practice (Bearfield and Dubnick, 2009) • Lifelong Learning (Bearfield and Dubnick, 2009) • Effective leaders are committed to lifelong learning and embrace change. They view challenges as opportunities for growth and are willing to adapt their strategies and behaviors to achieve their goals (Bennis, 2009).

Characteristic	Definition	Example(s) and Citation(s)
Trustworthy	Trustworthiness is the quality of being deserving of trust or confidence, often demonstrated through dependability or reliability.	<ul style="list-style-type: none"> • Avoiding personal scandal is a way to demonstrate trustworthiness (Van Wart, 2015) • Followers make a leader and for that followers need trust in their leaders (Merrow & Nandurdikar, 2018) • Four ingredients leaders have that generate trust: constancy, congruity, reliability, integrity (Bennis, 2009) • Codes of behavior/ethics may be communicated solely through training, orally by more senior persons, or demonstrated by more senior persons. Codes influence what is considered to be normal behavior in a specific field, and are influenced by it; they also identify the appropriate behavior to adopt when certain types of problem arise (Lundin and Sönderholm). • Model exemplary behavior • Leaders know the importance of integrity — being honest and having strong moral principles. Leaders know that they need to live by a strong set of values to lead by example with their team. Integrity is not only about truthfulness and honesty, but it's also about making ethical decisions (Royse, 2021). • Integrity is crucial for building trust, and leaders must act consistently with their values (Bennis, 2009) • Demonstrate sincerity, which may require sometimes being almost brutal and acknowledging the leader may not have all the answers, and thereby needs to observe and ask questions (Gil and Lundrigan, 2012) • Additional citing articles: <ul style="list-style-type: none"> » Marrewijk et al., 2023
Humble	A modest view of one's own importance; a lack of pride and arrogance. In the context of megaproject leadership, a humble leader is one who sees their role as serving others.	<ul style="list-style-type: none"> • Nora'in MD Salleh, a successful megaproject leader in the oil and gas industry, conducted regular situational updates with subordinate teams by traveling to their locations rather than calling them into the headquarters locations • "Complete lack of arrogance" (Merrow and Nandurdikar, 2018)

Characteristic	Definition	Example(s) and Citation(s)
<p>Open-Minded</p>	<p>Able to consider something without prejudice or application of pre-conceived notions.</p>	<ul style="list-style-type: none"> • The ability to search actively for evidence against one's beliefs, plans, or goals, and weigh such evidence fairly (University of Pennsylvania, 2024) • Don Vardeman, successful megaproject leaders in the oil and gas industry: Most people will surprise you and exceed your expectations if we simply accept the fact that [things have] to be done but don't always have to be done my way" (Merrow and Nandurdikar, 2018) • Five-Factor model defines openness as a person's willingness to entertain new ideas (McCrae and Costa, 1999) • Full of ideas and having a conceptual bent (Merrow & Nandurdikar, n.d.-b) • Leaders who are open to different ideas, flexible in their thinking, and willing to revise their plans based on new information tend to achieve better project outcomes (Merrow, 2011) • Additional citing articles: <ul style="list-style-type: none"> » Gil and Lundrigan, 2012 » Kiron et al., 2013

Characteristic	Definition	Example(s) and Citation(s)
Courageous	<p>Courage is the ability to do something difficult or risky, even in the face of fear or danger. It essential for leaders to confront the inherent risks, uncertainties, and complexities of megaprojects.</p>	<ul style="list-style-type: none"> • Courageous leaders are needed to make tough decisions, address underperformance, and challenge unrealistic expectations or assumptions, especially when facing pressure from stakeholders or political forces (Flyvberg, 2017) • Leaders must often stand firm against pressures to cut costs or accelerate schedules at the expense of quality or safety. Courage is critical for leaders to maintain integrity, resist short-term thinking, and uphold high standards of governance, transparency, and ethical decision-making (Merrow, 2011). • Leaders often face situations where they must confront ambiguity, challenge established norms, ore make unpopular decisions to move the project forward. Courage enables leaders to remain steadfast in the face of uncertainty and to take necessary actions to achieve the projects objectives (PMI, 2014). • Make a decision and stand by it (Merrow and Nandurikar, 2018) • Decisiveness (Royse, 2021) • Take courageous decisions (Doherty, 2008) • Must demonstrate moral courage in their decision-making (Bennis, 2009)

MINDSET

The critical characteristics of the mindset of successful megaproject leaders are defined in Table 4. Individual examples from the literature are incorporated.

Table 4. Detailed Description of Mindsets for Megaproject Leadership

Competency	Definition	Example(s) and Citation(s)
Paradox Mindset	The ability to hold and balance seemingly opposed views and being able to easily move from one perspective to another (Pyster et al., 2017).	<ul style="list-style-type: none"> • Strategic vision paired with the ability to explore details, and judgement to know when more detailed exploration is appropriate and necessary (Hutchison et al., 2020) • "I prefer to spend my time thinking about the project as a whole rather than its components." (Big picture thinking) paired with the ability to drill down when needed (Morrow). • Think big picture (Doherty, 2008) • Effective megaproject leaders are "very personable and driven; drive and determination combined with patience and good judgement to know when to push harder and when to give support" (Doherty 2008, p. 188). • This intriguing mix of being highly analytical and numerate, with an ability to inspire (big picture), was a differentiator (Doherty, 2008) • The very fact that the temporary organization is to be terminated, may be a condition for the acceptance of conflicting interest in the team (Lundin and Sönderholm) • Combine abstraction and synthesis: <ul style="list-style-type: none"> » Synthesize all the input you have (Schoemaker et al., 2013) • Force yourself to zoom in on the details and out to see the big picture (Schoemaker et al., 2013) • Supplement observation with quantitative analysis (Schoemaker et al., 2013) • Demonstrate the ability to apply different modes of thinking about issues (International Centre for Complex Project Management, 2021) • Objective evaluation of project viability, from both micro (sponsor) and macro (society) perspectives, is vital (Warrack, 1993)

Competency	Definition	Example(s) and Citation(s)
<p>Strategic Thinking</p>	<p>Strategic thinking is considered essential for leaders of megaprojects due to the scale, complexity, and long-term implications of these endeavors. It involves the ability to envision the future, anticipate challenges, align resources, and make decisions that drive the project toward its objectives despite uncertainties.</p>	<ul style="list-style-type: none"> • Leaders must have the foresight to identify potential pitfalls, align project goals with organizational strategy, and adapt to changing conditions (Flyvberg, 2017) • Strategic thinking is required for understanding the full scope of risks, setting realistic goals, and ensuring alignment between project objectives and broader organizational or governmental strategies (Merrow, 2011) • Strategic thinking is a core competency for effective project leaders (Turner and Müller, 2005) • "I prefer to spend my time thinking about the project as a whole rather than its components" (Merrow and Nandurdikar, 2018) • "Leaders need to understand the company's business goals and then align ... to meet and exceed those objectives. ... A good leader needs to have a thinking process that puts [the discipline] into the context of achieving a set of goals. A good strategy needs to be done collaboratively and positively impact the future of a company." (Royse, 2021) • Strategic thinkers challenge the <i>status quo</i> (Schoemaker et al., 2013) • Create a rotating position for the express purpose of questioning the <i>status quo</i> (Schoemaker et al., 2013) • Actively look for missing information and evidence that disconfirms your hypotheses (Schoemaker et al., 2013) • Reframe binary decisions by explicitly asking your team, "What other options do we have?" • Ability to make informed decisions that align with long-term project goals (Faisal et al., 2023) • Discusses how data can help ensure projects align with strategic objectives (Glowasz, 2022) • Drive systemic thinking and action (International Centre for Complex Project Management, 2021) • Balance insights holistically from multipole sources and types of data (International Centre for Complex Project Management, 2021) • Additional citing articles: <ul style="list-style-type: none"> » Louw et al., 2002 » Louw et al., 2018 » Smith and Hoover, 2021 » Zhu et al., 2020

Competency	Definition	Example(s) and Citation(s)
<p>Vision/Goal Setting</p>	<p>A vision is a broad idea of what the megaproject is trying to achieve in the future. Goals are specific aims or steps that will help reach that vision.</p>	<ul style="list-style-type: none"> • A clear vision is crucial for guiding decision-making and maintaining stakeholder alignment in complex megaprojects (Flyvberg, 2017) • Goal setting helps in measuring progress and adjusting strategies accordingly (Flyvberg, 2017) • Well-defined goals and a compelling vision are essential to overcoming challenge and navigating the complexities of megaprojects (Merrow, 2011) • Visionary leadership and clear goal setting are key to motivating project teams and managing stakeholder expectations • Ensure the need for change (Van Ward, 2015) • Using vision to induce people to cooperate in pursuing a goal (Merrow, 2011) • Gain commitment to the work and the profession (Van Wart, 2015) • Example from Heathrow Terminal 5: Clasper ... whose greatest strength was his ability to build a good-quality team, get them to work together to create an exciting vision for the future, and then put in place the frameworks to deliver (Doherty, 2008). • The foundation set by Clasper, looking at how BAA could delight the passenger in T5, was carried on by Nelson, who is keen to showcase T5 as a glimpse into what Heathrow could be like, given the appropriate regulatory settlement." "The opportunity for Nelson was to ensure that the focus on the passenger was at the forefront of everyone's mind in the final run-up to opening." (Doherty, 2008) • Successful [megaproject] leaders articulate a clear, compelling vision that inspires others to follow (Bennis, 2009) • Follows and outcomes focused deliver approach, (International Centre for Complex Project Management, 2021) • Additional citing articles: <ul style="list-style-type: none"> » Louw et al., 2002 » Louw et al., 2018 » Smith and Hoover, 2021

Competency	Definition	Example(s) and Citation(s)
<p>Comfort with Uncertainty</p>	<p>Comfort with uncertainty is the ability to function in an environment of unpredictability and lack of sufficient information.</p>	<ul style="list-style-type: none"> • "Those that make it to the top of their profession are most comfortable with uncertainty." (Merrow and Nandurdikar, 2018) • Leaders must make decisions in ambiguous and rapidly changing environments (Flyvberg, 2017) • Leaders need to adapt and be resilient to unexpected changes (Flyvberg, 2017) • Leaders must embrace uncertainty and ambiguity to navigate large, complex projects effectively, using adaptive leadership styles (Turner and Müller, 2005) • "To be an effective leader, you must adapt to constant change and become comfortable being uncomfortable." (Royse, 2021) • Leaders know that problem solvers are relentlessly curious, embrace ambiguity, look at the problem from different perspectives, use storytelling, and listen well to others (Royse, 2021) • Bring clarity to ambiguity (Doherty, 2008) • Strategic thinkers insist on multipole options at the outset and don't get prematurely locked into simplistic go/no-go choices (Schoemaker et al., 2013) • Dealing with change (Damayanti et al., 2021a and c) • Act fast when there is a sudden and uncertain change (Damayanti et al., 2021a and c) • Systematically identify and navigate emergent project vulnerabilities and opportunities (International Centre for Complex Project Management, 2021) • The owner can discover problems in time, quickly evaluate and make decisions, and take measures to respond to changes in the internal and external environments (Zhang et al., 2023) • The owner can handle unexpected, emergent and improvised situations (Zhang et al., 2023) • Additional Citing Articles: <ul style="list-style-type: none"> » Williams, 1999

There is a strong linkage between many of these characteristics and the overall concept of emotional intelligence (Merrow and Nandurdikar, 2018). The International Centre for Complex Project Management (2021) states that effective complex project leaders "demonstrate emotional intelligence in the project context."

THINKING SKILLS

The critical thinking skills of successful megaproject leaders are defined in Table 5. Individual examples from the literature are incorporated.

Table 5. Detailed Description of Critical Thinking Skills for Megaproject Leadership

Competency	Definition	Example(s) & Citation (s)
Political Savvy	The ability to exhibit confidence and professional diplomacy, while effectively relating to people at all levels internally and externally (NIH, nd).	<ul style="list-style-type: none"> • Understands priorities, cultural norms, and unwritten rules for success at all levels of the organization (NIH, nd). • “After watching many hundreds of megaprojects succeed or fail, we are convinced that [Jay] Sexton’s approach of keeping distractions and headaches from outside the team away from the team is the correct approach. When teams believe the project is caught up in politics either from internal or external stakeholders, they can easily become distracted and discouraged. If the politics continually interfere with their ability to focus on their work, the team blames the project director and their confidence in the project leader is undermined.” (Morrow & Nandurdikar, 2018) • e.g. Shinseki, in his role as VA Secretary, was successful with external political savvy (e.g. getting additional funding from Congress), but not internally (e.g. building buy-in within the VA itself). • Ensure external support (Van Wart, 2015) • Ensure top management support (Van Wart, 2015) • Successes and struggles in the Big Dig illustrate the critical importance of including public voices in government/infrastructure megaprojects (Bearfield and Dubnick, 2009)
Recognize Patterns	Abstraction is the quality of dealing with ideas rather than specific events. This is part of the ability to recognize patterns across different disciplines, domains, or contexts.	<ul style="list-style-type: none"> • Recognizing patterns in past projects is critical to anticipate potential pitfalls and optimize decision-making (Flyvberg, 2017) • Pattern recognition aids in decision-making under uncertainty (Kahneman, 2013) • Recognizing patterns helps project managers identify risks early and respond proactively (Loch et al., 2006) • Recognize patterns, push through ambiguity, and seek new insights (Schoemaker et al., 2013) • When analyzing ambiguous data, is at least three possible explanations for what you’re observing and invite perspectives from diverse stakeholders (Schoemaker et al., 2013)

Competency	Definition	Example(s) & Citation (s)
<p>Solve Complex Problems</p>	<p>Finding solutions to difficult or complex issues. Megaprojects are complex, involve a wide variety of stakeholders, and require the integration of multiple disciplines. By their nature, they will generate many problems which need rapid solutions.</p>	<ul style="list-style-type: none"> • Clearly defines problem • Understands complexity • Analyses problems systemically and systematically • Effective megaproject leaders know that solving problems is a fundamental part of removing obstacles from their team to ensure projects are completed on time (Royse, 2021) • Explore and identify new potentials from various sources to solve problems (Damayanti et al., 2021a and c) • Additional Citing Articles: <ul style="list-style-type: none"> » Smith and Hoover, 2021
<p>Innovate</p>	<p>Coming up with new ways to do things; making changes to methods, processes, and approaches.</p>	<ul style="list-style-type: none"> • Innovative approaches are critical for overcoming the inherent complexities and uncertainties of megaprojects (Flyvberg, 2017) • Innovative systems integration contributed to the success of the Heathrow Terminal 5 project, highlighting the role of leadership in fostering an environment for innovation (Davies et al., 2009) • Only after careful reflection and examination of a problem through many lenses to the take decisive action. This requires <i>patience, courage, and an open mind</i> (Schoemaker et al., 2013). • List assumptions about your business and ask a diverse group if they hold true (Schoemaker et al., 2013) • Additional citing articles: <ul style="list-style-type: none"> » Gil and Lundrigan, 2012 » Martinelli, 2023 » Sparg, 2018 » Zhu et al., 2020

Competency	Definition	Example(s) & Citation (s)
<p>Anticipate Future Situations</p>	<p>The ability to predict what will happen or be needed in the future; foresight. This is closely related to the Mindset capability of Vision/ Goal Setting.</p>	<ul style="list-style-type: none"> • The ability to anticipate future situations is vital for navigating the complexities and uncertainties inherent in megaprojects. Leaders with foresight can better plan for long-term outcomes and adapt to evolving project environments (Flyvberg, 2017). • The ability to anticipate future situations is critical to effectively manage uncertainty and innovation in complex projects (Shenhar and Dvir, 2007) • Pick up weak signals (Schoemaker et al., 2013) <ul style="list-style-type: none"> » Talk to your suppliers, customers, and partners to understand their challenges » Use scenario planning to imagine various futures and prepare for the unexpected • Predictive analysis of performance (Evans et al., 2022) • Systematically identifying, evaluating, and exploiting opportunities to improve project outcomes (Johansen et al., 2018)

INTERPERSONAL SKILLS

A wide variety of interpersonal skills are required for megaproject leaders, though they can generally be grouped into the three main competencies defined in Table 6. Individual examples from the literature are incorporated.

Table 6. Detailed Description of Critical Interpersonal Skills for Megaproject Leadership

Competency	Definition	Example(s) & Citation(s)
<p>Communication</p>	<p>Fundamentally, communication is the ability to convey and receive information effectively. There is a wide array of communication skills, deadline with how you express yourself, understand others, and adapt your communication style based on the audience. Successful megaproject leaders must master all aspects of effective communication.</p> <p>Communication is a focused task of successful complex project leaders (Merrow and Nandurdikar, 2018).</p>	<ul style="list-style-type: none"> • Effective communication out using verbal, written, visual, and non-verbal communication • Active listening is critical. Listening to understand versus listening to respond is a reflection of openness in communication style. • Ability to convey complex information clearly and succinctly (Turner and Müller, 2005) • Emotional intelligence – understanding and managing one’s own and others’ emotions – is a critical aspect of effective communication • Strategic storytelling can help to communicate vision, engage stakeholders, and inspire teams • Transparent communication is vital for risk management, stakeholder trust, and project alignment (Merrow, 2011) • Emphasize the importance of understanding how to effectively communicate budgetary approaches to stakeholders (Bearfield and Dubnick, 2009) • Effective megaproject leaders are adept at communicating their ideas and aligning their team’s efforts with the organization’s objectives (Bennis, 2009) • Effective exchange of information to facilitate collaboration (Faisal et al., 2023) • Make a major effort to listen; “we’ve two ears and one mouth - use them in that proportion.” Listening is necessary to tailor responses and make them relevant to the audience in question. Leaders that are effective listeners can create an environment of empathy in which all parties have mutual respect and understanding (Gil and Lundrigan, 2012). • Promotes data usage to enhance communication and transparency among project stakeholders (Glowasz, 2022) • Collaboratively shapes stakeholder communication (International Centre for Complex Project Management, 2021) • Additional citing articles: <ul style="list-style-type: none"> » Louw et al., 2002 » Louw et al., 2018 » Royse, 2021 » Evans et al., 2022 » Smith and Hoover, 2021 » Williams, 1999 » Zhu et al., 2020

Competency	Definition	Example(s) & Citation(s)
<p>Relationship Building</p>	<p>Relationship building is the process of creating and maintaining connections with people to create a sense of team or to achieve a purpose.</p>	<ul style="list-style-type: none"> • Trust and relationship-building is critical for managing stakeholder expectations and ensuring project success (Flyvberg, 2017) • Strong relationships enable better communication, risk management, and conflict resolution (Merrow, 2011) • Communication must be at a higher, more visionary level [in megaprojects] (Merrow & Nandurdikar, 2018) • Leadership is about the ability to build strong relationships with the team, peers, and C-suite (Royse, 2021) • Gain commitment to the work and the profession (Van Wart, 2015) • Walk the talk - "be in the shoes" of team members (demonstrate empathy); only then will you be able to form good cooperation (Merrow and Nandurdikar, 2018) • Cultivate followership. Leaders go to teams, she doesn't "Call them in" (Merrow and Nandurdikar, 2018). • Encourage debate by holding "safe zone" meetings where open dialogue and conflict are expected and welcomed (Schoemaker et al., 2013) • Community and relationship-building skillsets for leaders (Bearfield and Dubnick, 2009) • Skilled in managing relationships (Bennis, 2009) • Social awareness, managing others (Damayanti et al., 2021a and c) • Collaboration in design, construction works, and engineering management (Evans et al., 2022) • Building and maintaining positive relationships with all stakeholders (Faisal et al., 2023) • Navigate uncertainty by converging stakeholders' focus on the project's visions, goals, and objectives (International Centre for Complex Project Management, 2021) • Demonstrates a stakeholder-centric mindset (International Centre for Complex Project Management, 2021) • Develops and fosters ad multi-party collaborative engagement culture (International Centre for Complex Project Management, 2021) • Additional Citing Articles: <ul style="list-style-type: none"> » Nyarirangwe and Babatunde, 2021 » Sparge, 2018 » Williams, 1999 » Zhu et al., 2020

Competency	Definition	Example(s) & Citation(s)
<p>Negotiation/ Persuasion</p>	<p>Megaprojects by nature have a diverse community of stakeholders. There will be conflicts between stakeholders and conflicts of priority within the team (e.g. trade-offs between budget, schedule, and performance).</p>	<ul style="list-style-type: none"> • Managing stakeholders calls for negotiating and diplomatic skills (Merrow and Nandurdikar, 2018) • Focusing on shared vision and goals is an important strategy for effective negotiation and persuasion in megaprojects • Megaproject leaders need to be able to bring stakeholders together on critical decisions • Additional citing articles: <ul style="list-style-type: none"> » Louw et al., 2002 » Zhu et al., 2020

ENTERPRISE TECHNICAL LEADERSHIP

Enterprise Technical Leadership skills are defined in Table 7. Individual examples from the literature are incorporated.

Table 7. Detailed Description of Critical Enterprise Technical Leadership Skills for Megaproject Leadership

Competency	Definition	Example(s) & Citation(s)
Promote Learning Culture	<p>Create an environment that encourages and prioritizes gaining new knowledge and skills. Learning is rewarded. The megaproject leader provides an example of continuous learning.</p> <p>Creating a learning culture in the context of megaprojects is critical to adapt to complexity, improve performance, and foster innovation.</p>	<ul style="list-style-type: none"> • A continuous learning culture is necessary to address complexities and unforeseen challenges (Flybverg, 2017) • Encourages building a culture of accountability and learning through data insights (Glowasz, 2022) • Additional citing articles: <ul style="list-style-type: none"> » Gil and Lundrigan, 2012 » Marrewijk et al., 2023 » Martinelli, 2023 » Sparg, 2018
Foster Openness	<p>Encourage a culture of openness and communication, and be open to new ideas and perspectives. This is closely linked with the individual leader's open-mindedness.</p>	<ul style="list-style-type: none"> • Stresses that openness, particularly in sharing information and acknowledging uncertainties, is key to building trust and achieving project success (Merrow, 2011) • Openness is a core competency for handling complex project dynamics, fostering transparency, and building trust • The Qi Index is an instrument to assess cognitive diversity and psychological safety. A culture that is both cognitively diverse and psychologically safe is "generative", enabling innovation. • Willingness to listen is an essential element to create psychological safety (Merrow and Nandurdikar, 2018) • The lack of neuroticism leadership (personal characteristics), helps openness. "Calm and stable" leaders are more successful in complex projects (Merrow and Nandurdikar, 2018). • Additional Citing Articles: <ul style="list-style-type: none"> » Smith and Hoover, 2021

Competency	Definition	Example(s) & Citation(s)
<p>Collaborate</p>	<p>The ability to work with others to produce or create something is a critical aspect of megaprojects. Building a collaborative team is critical to megaproject success.</p>	<ul style="list-style-type: none"> • Collaboration across stakeholders, contractors, and teams is critical to effectively managing the complexities of megaprojects effectively (Flyvberg, 2017) • Collaborative leadership and shared decision-making are key to overcoming challenges (Merrow, 2011) • Collaborative systems integration was critical to the success of Heathrow Terminal 5 (Davies et al., 2009) • Effective collaboration among various parties can help mitigate common megaproject challenges (Sönderlund and Geraldi, 2012) • Build internal support (Van Wart, 2015) • Inspire people to give more by making them feel valued (Doherty, 2008) • Additional citing articles: <ul style="list-style-type: none"> » Locatelli et al., 2014 » Lopez Del Puerto and Shane, 2014 » Martinelli, 2023 » Smith and Hoover, 2021 » Zhang et al., 2023

Competency	Definition	Example(s) & Citation(s)
<p>Demonstrate Trust</p>	<p>Effective megaproject leaders create an environment that actively shows that they believe their team acts in good faith and will do their best to help the project achieve its goals.</p>	<ul style="list-style-type: none"> • Actively work to make others feel safe (Sinek, 2003) • Leaders must be reliable to earn the respect of their team and peers. Your team needs to know that they are getting the tools and resources they need to succeed. The C-suite needs to trust you are meeting the goals of the marketing team and the business. Being a reliable leader is being someone people can trust. You follow through on plans and keep your promises. You say something, and then you back it up with actions. Being dependable means meeting deadlines, being honest, and coming through in the clutch. “The most successful people I know are also the most reliable.” — Wayne Gerard Trotman (Royse, 2021). • A good leader is a mentor who creates a welcoming environment of trust and collaboration (Royse, 2021) • “Vigilant trust” was a critical practice for the Heathrow Terminal 5 project: "During these tense times the team always felt supported and trusted. ... Clasper never needed to get upset or shout, as the T5 team always wanted to deliver for him and repay the confidence he placed in them." (Doherty, 2008) • When issues surfaced with the development of the Heathrow air traffic control tower, BAA used this instance to build trust by behaving in a supportive way, not resorting to blame and legal advisors (Doherty, 2008). • Put effort into building obligation and trust, if at all possible, into the relationship. Know when to be very clear about things and when it is actually in the corporate interest to take a difficult meeting on the chin, rather than being transparent, going on to fight another day on the bigger agenda. • Legitimization and support effects team interaction. It may become necessary to manage or control contacts between the temporary organization and the world outside (Lundin and Sönderholm). • Additional citing articles: <ul style="list-style-type: none"> » Louw et al., 2002

Competency	Definition	Example(s) & Citation(s)
<p>Resolve Conflict</p>	<p>Conflict resolution is the ability to peacefully settle disagreements between multiple parties.</p>	<ul style="list-style-type: none"> • Effective conflict resolution is critical for managing diverse stakeholder interest and maintain project alignment (Flyvberg, 2017) • Relationship building is about effective communication and good conflict resolution (Royse, 2021) • Additional Citing Articles: <ul style="list-style-type: none"> » Zhang et al., 2023
<p>Coach and Mentor</p>	<p>Coaching³ and mentoring⁴ help to develop leadership skills, foster collaboration, and enhance trust and performance.</p> <p>Coaching is a critical skill for megaproject leadership (Van Wart, 2015).</p>	<ul style="list-style-type: none"> • Teaching and mentoring are about a leader thinking less about his or herself and more about how the team and overall company. When leaders teach and mentor, they help their teams develop professional skills and what they need to succeed at their jobs. They are helpful, see things from different perspectives, and provide actionable tips and feedback to their team and peers (Royse, 2021). • Additional citing articles: <ul style="list-style-type: none"> » Lynch, 2015 » Marrewijk et al., 2023 » Smith and Hoover, 2021

³ Coaching focuses on specific skills and performance improvement in a shorter time frame. (Clutterbuck, 2008)

⁴ Mentoring is a longer-term relationship centered on holistic development and guidance. (Clutterbuck, 2008)

APPENDIX B: IF AN LLM WROTE THIS REPORT

This appendix resulted from asking our custom LLM developed in the research to write a review based on the contents of the “WRT-1082 DAU Megaprojects\Literature Review” folder. This code uses the Llama3 open-source model. The following review was written by the LLM without any human editing.

Key Challenges:

Based on the provided literature review excerpts, some of the main challenges mentioned in managing very large projects include:

1. **Complexity:** large-scale projects often involve multiple stakeholders, complex systems, and diverse requirements, making it challenging to manage and coordinate efforts.
2. **Adversarial environment:** the contract office’s adversarial approach can create tension and conflict with contractors, leading to project delays or failures.
3. **Auditing trends:** increasing government auditing can lead to mistrust and skepticism among contractors, affecting the success of projects.
4. **Technical complexity:** rapid changes in technology can make programs susceptible to technical complexity, which can impact program-to-project alignment and stakeholder expectations.
5. **Directional complexities:** disjointed goals, ambiguous meanings, and hidden agendas can create confusion and misalignment among stakeholders, leading to project failures.
6. **Institutional complexity:** large-scale projects often involve multiple institutions, each with their own rules, norms, and values, which can lead to conflicts and challenges in managing the project.
7. **Legitimacy:** ensuring legitimacy through technical, normative, and cultural-cognitive mechanisms is crucial for large-scale projects, as stakeholders may question the project’s value or relevance.
8. **Managing expectations:** managing stakeholder expectations is critical, especially when dealing with complex projects that involve multiple parties with different goals and priorities.

These challenges highlight the importance of effective project management, communication, and coordination in managing very large projects to ensure their success.

Successful Strategies and Methodologies:

Based on the provided literature review, some successful strategies and methodologies that have been highlighted include:

- **Stakeholder engagement:** the importance of engaging stakeholders in the project management process is emphasized. For example, Ahn et al. (2012) surveyed construction company recruiters to identify the desired competencies for construction professionals.

Example: In the Gautrain project, Minister of Transport Jeff Radebe emphasized the need to create a mass transit system that caters to workers and business people, civil servants, scholars, shoppers, and leisure seekers, highlighting the importance of stakeholder engagement.

- **Collaboration:** collaboration between different stakeholders is crucial for successful project management. For example, Bhattacharjee et al. (2013) surveyed USA construction industry KSAs from two categories: construction knowledge and interpersonal skills.

Example: In the OMFV program, the Army approved the requirements for the MTA effort in an abbreviated capability development document, demonstrating collaboration between stakeholders.

- **Adaptive project management:** the need to adapt to changing circumstances is emphasized. For example, Evans et al. (2021b) highlighted the relationship among BIM, LC, IPD principles, and GID transformative initiatives using a staked Venn diagram.

Example: In Project D, technical complexity initially led to logistical complexity, which then led to financial problems due to delays in progress payments, demonstrating the need for adaptive project management.

- **Front-end decision-making:** the importance of making informed decisions at the front-end of projects is emphasized. For example, the authors highlighted the challenges at the front-end decision point and the need for rough, experience-based data in the earliest phase.

Example: In the OMFV program, software development cost was estimated to be \$88.5 million, but this cost cannot be broken out for each effort, demonstrating the importance of making informed decisions at the front-end.

- **Knowledge sharing:** the sharing of knowledge and expertise is crucial for successful project management. For example, Ahn et al. (2012) identified 14 key competencies for construction professionals that were then explored in a survey of construction company recruiters.

Example: In the Gautrain project, proponents demonstrated rail projects as a public good to enhance mass appeal, highlighting the importance of knowledge sharing and communication.

These strategies and methodologies are essential for successful project management, particularly in complex projects like those in the construction industry. By understanding these strategies and methodologies, project managers can better navigate the challenges they face and deliver successful projects that meet stakeholder needs.

Case Studies and Outcomes:

Based on the provided literature review, I did not find any specific case studies mentioned that directly relate to the topic of project management in the military context. However, there are some general discussions about project management in the military and its challenges.

One of the topics discussed is the implementation of Enterprise Resource Planning (ERP) systems in the military. The article mentions that ERP implementations can be complex and challenging due to the unique requirements of the military environment. It also highlights the importance of effective communication, stakeholder engagement, and change management in successful ERP implementations.

Another topic mentioned is the use of dynamic capabilities in project management. The article discusses how organizations can develop dynamic capabilities by engaging in a deliberate learning process, scanning the environment for alternative ways of doing things, and conducting online trials to assess the benefits of implementing new approaches.

In terms of specific projects, I did not find any case studies mentioned that provide detailed information on objectives, approaches taken, and outcomes. However, there are some general discussions about the challenges and complexities of project management in the military context.

If you could provide more context or clarify what specific type of project management in the military context you would like to know more about, I may be able to help you better.

Common Pitfalls:

Based on the provided literature review, I've identified some common pitfalls and issues faced in managing large projects:

1. Overly optimistic timelines: the ARH project example shows how a desire to deliver capability faster can lead to unrealistic timelines.
 - » Solution: establish realistic timelines by considering all aspects of the project, including scope, resources, and potential risks.
2. Lack of stakeholder engagement: the IIA megaproject's success was attributed to engaging stakeholders in the value co-creation process.
 - » Solution: identify key stakeholders and involve them in the project planning and decision-making process to ensure their needs are met.
3. Inadequate risk management: the Olympics and Crossrail projects faced endless legal battles, cost overruns, and delays due to inadequate risk management.
 - » Solution: conduct thorough risk assessments and develop mitigation strategies to minimize potential risks.
4. Insufficient resources: the Army's transformation efforts may be hindered by insufficient resources or a gap in senior leadership vision.
 - » Solution: ensure adequate resource allocation and consider the long-term implications of decisions made during project planning.
5. Inflexible processes: the T5 delivery model's success was attributed to its flexibility and ability to adapt to changing conditions.
 - » Solution: develop flexible processes that can accommodate changes and uncertainties, while maintaining quality and efficiency.
6. Poor communication: the Army's transformation efforts may be hindered by poor communication between senior leadership and field-grade officers.
 - » Solution: establish open and transparent communication channels to ensure all stakeholders are informed and aligned with project goals.

To avoid these pitfalls, consider the following strategies:

1. **Develop a robust project plan:** create a detailed project plan that considers all aspects of the project, including scope, resources, timelines, and risks.
2. **Engage stakeholders effectively:** identify key stakeholders and involve them in the project planning and decision-making process to ensure their needs are met.
3. **Conduct thorough risk assessments:** identify potential risks and develop mitigation strategies to minimize their impact on the project.
4. **Monitor and adapt:** regularly monitor project progress and be prepared to adapt to changing conditions, while maintaining quality and efficiency.
5. **Foster a culture of collaboration:** encourage open communication and collaboration among team members, stakeholders, and senior leadership to ensure everyone is aligned with project goals.

By being aware of these common pitfalls and implementing strategies to avoid them, you can increase the chances of successful project management and delivery.

Synthesis and Recommendations:

The literature review highlights several key findings that can inform effective management of very large projects:

1. Complexity and uncertainty: large projects are inherently complex and uncertain, making it challenging to plan and manage them effectively.
2. Emergent planning: complex projects may only be “boundedly” planned as emergent prototypes with incomplete knowledge. This requires a flexible approach that allows for adaptation and iteration.
3. Team facilitation: project managers play a crucial role in facilitating team collaboration, communication, and decision-making. They must possess specialized skills to select and use modeling and visualization tools effectively.
4. Information flow: the speed of information flow is critical in large projects. Centralized project “truth data” linked to authorized stakeholders can facilitate rapid development of new models, analytics, and integrated visualization dashboards.
5. Contextual knowledge: project managers must recognize the importance of contextual knowledge, which emerges from the interaction between team members and their environment.

Based on these findings, here are some practical recommendations for managing very large projects effectively:

1. Embrace complexity and uncertainty: recognize that large projects are inherently complex and uncertain. Develop a flexible approach that allows for adaptation and iteration.
2. Foster emergent planning: encourage an emergent planning approach that involves iterative refinement of plans as new information becomes available.
3. Develop team facilitation skills: ensure project managers possess specialized skills to facilitate team collaboration, communication, and decision-making.
4. Implement centralized project management tools: utilize centralized project management tools that provide real-time data and analytics to support rapid development of new models and visualization dashboards.
5. Prioritize contextual knowledge: recognize the importance of contextual knowledge in large projects. Encourage team members to share their experiences, insights, and expertise to inform decision-making.
6. Encourage feedback loops: foster a culture that encourages feedback loops between team members, stakeholders, and project managers to ensure continuous improvement and adaptation.
7. Monitor progress regularly: regularly monitor project progress, identify potential issues early on, and take corrective action to prevent scope creep or delays.
8. Develop contingency plans: develop contingency plans for unexpected events or changes in the project scope to minimize disruptions and ensure timely completion.

By following these recommendations, project managers can better navigate the complexities of very large projects and increase their chances of success.

Comparison Summary

Following the LLM generation we asked our custom LLM to ingest the body of our Megaproject Playbook and compare our human generated analysis of the Plays to the original literature review findings. This is the direct output of the LLM:

The previous response provided a general overview of managing relationships in megaprojects, focusing on stakeholder engagement, risk management, and decision-making processes.

The new document presents a comprehensive framework for managing uncertainty in megaprojects, covering 11 key areas, including stakeholder engagement, project management processes, flexibility, and leadership skills.

Key Similarities

- 1. Stakeholder Engagement:** both sources emphasize the importance of engaging with stakeholders to capture their needs and ensure successful project outcomes. (Previous response: "Continuously engage and manage stakeholders"; New document: "Involve key stakeholders in key decisions when they need to be made")
- 2. Risk Management:** both sources recognize the significance of managing risks and uncertainties in megaprojects. (Previous response: "Actively test project resilience by running scenarios for unknown/unknowns or other 'black swan' events"; New document: "Invest in digital models and environments for design and project execution")
- 3. Flexibility:** both sources highlight the need for flexibility in managing megaprojects, particularly when dealing with uncertainties. (Previous response: "Decide at the last responsible moment"; New document: "Use incremental option-based contracts to co-evolve the project at the client level")

Key Differences

- 1. Scope and Focus:** the previous response provides a general overview of relationship management in megaprojects, while the new document offers a more comprehensive framework for managing uncertainty.
- 2. Level of Detail:** the new document provides more detailed guidance on specific practices and tools for managing uncertainty, such as digital models, experimentation, and test-to-failure approaches.
- 3. Leadership Emphasis:** while both sources acknowledge the importance of leadership in megaprojects, the new document places greater emphasis on the need for leaders with specific skills, such as domain experience, learning ability, and psychological safety.

Unique Insights

The previous response does not offer unique insights that are not present in the new document. However, the new document provides several unique perspectives, including:

- The importance of modularity in design and build to minimize technology novelty
- The need for predictive models of key parameters in the system context
- The value of investing in experimentation and test-to-failure approaches
- The value of modularity in design and build

Complementary Information

The new document complements the previous response by providing more detailed guidance on specific practices and tools for managing uncertainty in megaprojects. This enhances our understanding of the importance of stakeholder engagement, risk management, and flexibility in megaproject leadership.

Relevance and Applicability

The combination of these two sources provides a comprehensive understanding of the importance of stakeholder engagement, risk management, flexibility, and leadership skills in managing uncertainty in megaprojects. The new document may be more relevant in contexts where detailed guidance on specific practices and tools is required.

Conclusion

In conclusion, this analysis highlights the key similarities and differences between the previous response and the new document. While both sources emphasize the importance of stakeholder engagement, risk management, and flexibility in megaproject leadership, the new document provides a more comprehensive framework for managing uncertainty, with greater emphasis on leadership skills, digital models, experimentation, and test-to-failure approaches. By integrating these two sources, we can develop a deeper understanding of the complexities involved in managing megaprojects and improve our ability to navigate uncertainties effectively.