Managing Uncertainty and Interdependencies in Megaprojects: A Complexity and Systems Thinking Perspective[1]

Prof. Dr. M.F. HARAKE

MESOS Business School (France)
GBSB Global Business School (Malta)
CEREGE Research Laboratory – University of Poitiers (France)

Abstract

This study explores the drivers of cost overruns and schedule delays in major and megaprojects by integrating perspectives from project management, behavioral decision-making, and complexity theory. Drawing on Flyvbjerg's work on megaproject risk, the research highlights how optimism bias and strategic misrepresentation often distort early project planning, leading to unrealistic budgets and timelines. These insights are reinforced by Kahneman and Lovallo's cognitive theory of risk taking, which explains why decision-makers tend to produce bold forecasts while underestimating uncertainty and downside risks. In addition, the study adopts a complex adaptive systems lens, to emphasize that large-scale projects function within interconnected environments where nonlinear interactions, stakeholder dynamics, and feedback loops can amplify disruptions. Williams' modelling approach further supports the need to move beyond linear planning tools and adopt methods capable of capturing complexity and emergent outcomes. Using evidence from academic literature and informed by Park's doctoral research on project delays and overruns, the abstract argues that project failure is rarely caused by single technical problems. Instead, it is largely rooted in systemic issues including biased forecasting, weak governance, and insufficient complexity-aware planning. The research concludes that improving performance in major projects requires a shift toward realism in early development stages, stronger institutional transparency, and decision frameworks that account for adaptive behavior and uncertainty. By combining behavioral economics and systems thinking, this study provides a structured explanation of why megaprojects frequently exceed planned cost and duration targets and proposes pathways for more resilient project delivery.

Key Words: Megaprojects; project complexity; emergent risks; uncertainty; interdependencies; systems thinking; nonlinear impacts; governance

[1] How to cite this work: Harake, M.F. (2026). Managing Uncertainty and Interdependencies in Megaprojects: A Complexity and Systems Thinking Perspective, *PM World Journal*, Vol. XV, Issue II, February.

1. Introduction

1.1. Megaprojects and the Challenge of Performance

Megaprojects have become central instruments for delivering large-scale infrastructure, digital transformation, and technological modernization across sectors such as transport, energy, aerospace, and enterprise information systems. Although definitions vary across the literature, megaprojects are commonly distinguished by their scale, strategic significance, long durations, and multi-organizational delivery structures, often involving budgets measured in billions and societal implications that extend beyond the boundaries of the sponsoring organization (Flyvbjerg, 2014). Despite their importance, megaprojects have repeatedly demonstrated patterns of performance instability, including cost overruns, schedule delays, and benefit shortfalls. These patterns have been widely documented and appear structural rather than exceptional, suggesting that conventional explanations based solely on isolated managerial deficiencies remain insufficient (Flyvbjerg, 2009; Park, 2021).

1.2. Limits of Traditional Project Management Logics

Conventional project management is rooted in planning and control principles that assume project work can be decomposed into manageable tasks and stabilized through front-end definition, work breakdown structures, predictive scheduling, and risk mitigation frameworks. Within this paradigm, uncertainty is often treated as a variable that can be reduced by improved information, detailed planning, and disciplined execution. However, megaproject environments frequently undermine these assumptions due to high levels of complexity, deep uncertainty, and multi-layered dependencies. In such contexts, forecasting accuracy is constrained not simply because data is missing, but because project conditions themselves evolve during execution. As a result, project control methods that rely on linear causality and stable baselines may be systematically misaligned with megaproject dynamics (Williams, 2002).

1.3. Explanations for Megaproject Failure and their Conceptual Limitations

A substantial body of literature attributes megaproject underperformance to systematic bias in early project planning and approval processes. From a cognitive perspective, the planning fallacy suggests that project planners underestimate costs and durations because they rely on an inside-view of project execution and underestimate uncertainty (Kahneman & Lovallo, 1993). From an institutional perspective, strategic misrepresentation suggests that political incentives encourage the understatement of costs and overstatement of benefits to secure legitimacy, funding, and approval (Flyvbjerg, 2009). These explanations remain influential and empirically supported, particularly in relation to business cases and early-stage forecasting. Nonetheless, they provide only partial insight into why cost and schedule disturbances often escalate throughout execution, even in cases where planning quality and managerial competence are high. Notably, these accounts do not fully theorize how disruptions propagate, interact, and amplify through dependency structures once implementation begins.

1.4. Megaprojects as Complex Adaptive Systems

This paper argues that megaproject performance cannot be adequately explained through additive models of isolated risks. Rather, megaprojects should be conceptualized as complex adaptive systems characterized by nonlinear interactions, feedback loops, time delays, and emergent behavior. Complexity theory emphasizes that in systems with high interdependence, local disturbances can create cascading consequences and disproportionate effects (Nair & Reed-Tsochas, 2019). Under such conditions, uncertainty is not simply external noise to be mitigated, but an endogenous property of system behavior that arises from interdependencies and evolving conditions (Williams, 2002). Consequently, megaproject risk cannot be fully represented through static risk registers that enumerate individual threats. Instead, risk may be better conceptualized as a dynamic network of interactions in which the impact of one disruption depends heavily on the state and coupling of the surrounding system.

1.5. Interdependencies, Scope Volatility, and Stakeholder-Driven Uncertainty

Two megaproject characteristics reinforce the need for complexity-based theorizing. First, megaproject tasks and subsystems are frequently tightly coupled, meaning disruptions in one interface constrain downstream activities and trigger chain reactions in schedule and cost (Williams, 2002). This coupling is intensified by multiple vendors, contractual interfaces, and integration-driven milestones that create significant propagation pathways for disturbances. Second, megaprojects operate over long horizons in which deep uncertainty prevails. Long durations increase exposure to policy shifts, regulatory revisions, leadership turnover, economic volatility, and technological evolution, producing a risk landscape that drifts over time (Park, 2021). Under these conditions, uncertainty cannot be addressed solely through improved forecasting, because the conditions being forecast continuously change.

In addition, megaprojects involve complex stakeholder ecosystems with heterogeneous goals, power dynamics, and legitimacy concerns. Unlike conventional organizational projects with relatively unified governance and success criteria, megaprojects typically involve multiple actors who define project success differently and impose competing constraints on decision-making (Flyvbjerg, 2014). Stakeholder conflict and fragmentation often delay decisions and increase late-stage changes, particularly in relation to requirements and scope. These dynamics contribute to reinforcing feedback loops, in which requirements ambiguity increases rework, rework increases delays, and delays intensify schedule compression and integration risk. Systems thinking suggests that such reinforcing processes may push projects into unstable trajectories unless governance and delivery structures actively dampen the amplification mechanisms (Sheffield et *al*., 2012).

1.6. Aim, Research Questions, and Contribution

The purpose of this conceptual article is to develop a systems-informed framework for managing uncertainty and interdependencies in megaprojects. The objective is not to provide a descriptive list of risk factors, but to theorize the mechanisms through which risk becomes emergent and impacts become nonlinear. Drawing on complexity theory and systems thinking, this paper proposes the Megaproject Uncertainty–Interdependency–Emergence (MUIE) framework to explain (1) how uncertainty is amplified through dependency structures, (2) why significant risks emerge endogenously through interaction effects, and (3) how adaptive governance can support resilience across long time horizons.

Accordingly, the paper addresses the following research questions:

(1) How do tightly coupled interdependencies amplify uncertainty in megaproject environments?

(2) Why do risks emerge endogenously from interactions rather than appearing as standalone threats?

(3) What governance strategies aligned with systems thinking can reduce systemic fragility and improve megaproject resilience?

By advancing a conceptual complexity-based framing, the paper contributes to a growing shift in project studies toward resilience, adaptability, and systemic intervention rather than reliance on linear planning and predictive control alone (Nair & Reed-Tsochas, 2019; Sheffield et *al*., 2012).

2. Literature Review

2.1. Megaprojects as a Distinct Project Category

Megaprojects represent a distinctive category of project delivery due to their scale, strategic importance, duration, and complexity. They typically involve multiple organizations and layers of governance that extend beyond a single sponsoring entity. This structural complexity differentiates megaprojects from conventional projects, as delivery outcomes depend not only on technical execution but also on institutional legitimacy, political continuity, and long-term stakeholder alignment (Flyvbjerg, 2014). The strategic nature of megaprojects amplifies their exposure to external change because they often intersect with national priorities such as energy security, mobility, digital sovereignty, and economic competitiveness. Consequently, performance cannot be assessed solely through conventional measures such as time, cost, and scope, but must also account for long-term value realization and societal acceptance (Flyvbjerg, 2014).

A consistent finding within the megaproject literature is the persistence of cost overruns, benefit shortfalls, and schedule delays, even in contexts with established project management standards and professionalized delivery organizations (Flyvbjerg, 2009; Park, 2021). This has generated continued scholarly debate regarding whether megaproject underperformance is primarily a function of poor execution or whether it emerges from deeper structural characteristics of megaproject environments.

2.2. Dominant Explanations for Megaproject Underperformance

A substantial portion of the literature identifies early-stage decision-making as a critical driver of megaproject outcomes. Two dominant explanations arise: optimism bias and strategic misrepresentation. Optimism bias is often linked to bounded rationality and cognitive error in forecasting, whereby planners underestimate costs and timelines due to overconfidence and reliance on internally constructed narratives (Kahneman & Lovallo, 1993). Strategic misrepresentation, by contrast, situates forecasting inaccuracies within an institutional context, arguing that project promoters intentionally distort estimates due to political incentives, competitive funding dynamics, and reputational motives (Flyvbjerg, 2009). Both explanations highlight that megaprojects frequently begin with unrealistic baselines, creating systemic vulnerability during execution.

While these perspectives are influential, they have limitations when used as primary explanatory frameworks for execution-phase instability. First, they are most effective for understanding initiation and business case distortion, yet many megaproject disruptions occur later due to integration problems, contractor interface failures, stakeholder resistance, and exogenous environmental shifts. Second, both approaches implicitly emphasize the quality of forecasts and planning assumptions rather than the dynamic interaction of uncertainties across time. As such, they may under-theorize how uncertainty evolves and amplifies through interdependencies during implementation.

2.3. Uncertainty in Megaproject Environments

Uncertainty is a core feature of megaproject delivery and manifests in multiple forms. Conceptually, uncertainty may be categorized as epistemic, aleatory, or deep uncertainty. Epistemic uncertainty reflects gaps in knowledge and is theoretically reducible through improved information and analysis. Aleatory uncertainty reflects inherent variability and is typically managed through buffers, probabilistic modelling, or robustness strategies. Deep uncertainty applies when stakeholders cannot agree on models, probability distributions, or future scenarios and when the environment may shift in discontinuous ways (Williams, 2002). Deep uncertainty is especially relevant for megaprojects due to long horizons and political exposure.

Megaproject uncertainty also spans domains. Technical uncertainty arises from innovation, complex engineering, and integration challenges. Organizational uncertainty emerges from multi-vendor delivery structures, contract fragmentation, and decision rights ambiguity. Environmental uncertainty is shaped by regulatory changes, macroeconomic volatility, and sociopolitical contestation. Temporal uncertainty emerges because long time horizons increase exposure to shifting conditions that destabilize assumptions made at early stages (Park, 2021). Collectively, these uncertainty types challenge conventional risk management logics that assume stable systems and predictable deviations.

2.4. Interdependence and Tightly Coupled Systems

Interdependencies represent one of the most critical differentiators between complex megaprojects and simpler projects. Interdependence refers to the extent to which project tasks, subsystems, and organizational units rely on one another to achieve delivery outcomes. Williams (2002) argues that complex projects are fundamentally shaped by interaction and connectivity rather than task complexity alone. Dependencies can be structural (interfaces between subsystems), temporal (sequencing constraints), resource-based (shared personnel and assets), or organizational (handoffs between teams or contractors).

In megaprojects, dependencies often become tightly coupled due to integration requirements. Tight coupling implies that disturbances propagate quickly and that there is limited slack between interconnected subsystems. Under such conditions, disruption does not remain localized, but instead cascades across multiple linked interfaces, producing compound delays and nonlinear cost impacts. In tightly coupled systems, risk management is challenged by the fact that the consequences of disruption depend not only on its magnitude, but also on where it occurs within the dependency network and how it interacts with other uncertainties.

2.5. Scope Volatility and Requirements Ambiguity

Scope volatility refers to the dynamic evolution of project objectives, requirements, and deliverables over time. In megaproject contexts, scope change is not solely a result of inadequate planning but frequently reflects institutional shifts, stakeholder pressure, regulatory adaptation, and learning processes during delivery (Flyvbjerg, 2014). Requirements ambiguity is particularly pronounced in technologically complex and digitally enabled megaprojects such as ERP rollouts, where stakeholder expectations evolve alongside business process redesign and technology constraints.

Scope volatility interacts with interdependencies to generate amplification mechanisms. When requirements are unclear, design churn and rework increase. Rework affects interface stability and reduces schedule predictability, which leads to downstream compression and coordination breakdown. From a systems perspective, this produces reinforcing feedback loops that intensify instability unless governance systems actively dampen change propagation (Sheffield et *al*., 2012). Thus, scope volatility should not be treated merely as a change control issue; it is a systemic driver of emergent risk under high coupling.

2.6. Stakeholder Complexity and Institutional Embeddedness

Megaprojects are embedded in political, regulatory, and social systems and therefore depend on legitimacy and stakeholder acceptance. Stakeholders commonly include government agencies, private sponsors, contractors, regulators, local communities, and civil society organizations, each with distinct objectives and risk tolerances (Flyvbjerg, 2014). This heterogeneity contributes to coordination complexity and decision-making friction, particularly when stakeholder success criteria are misaligned.

Stakeholder conflict and institutional instability can become endogenous sources of uncertainty, producing delays in approvals, revisions to scope, and governance renegotiations. This uncertainty is often amplified in public megaprojects, where changes in government priorities or public opinion can alter constraints and delivery objectives midstream. As a result, megaproject governance cannot be treated as a static structure; it is a dynamic negotiation space that evolves throughout the project life cycle.

2.7. Complexity Theory and Systems Thinking in Project Studies

Complexity theory provides conceptual resources for understanding megaproject behavior beyond linear and reductionist assumptions. Complex adaptive systems are characterized by multiple interacting agents whose behavior evolves through feedback and adaptation, producing emergent system-level outcomes (Nair & Reed-Tsochas, 2019). Within project environments, emergence implies that outcomes such as delays, cost escalations, and stakeholder backlash can arise without a singular causal event, but through interaction patterns across coupled subsystems.

Systems thinking complements complexity theory by offering tools for conceptualizing feedback loops, delays, system boundaries, and nonlinearity (Sheffield et *al*., 2012). Applying systems thinking to megaprojects enables scholars to interpret performance instability as a product of reinforcing and balancing processes rather than linear cause and effect. For instance, scope volatility may reinforce rework and delays, which then reinforce schedule compression and quality deterioration, creating self-sustaining cycles of instability.

2.8. Literature Synthesis and Conceptual Gap

The reviewed literature suggests that megaproject underperformance is explained through several partially complementary streams: forecasting and institutional distortion (optimism bias, misrepresentation), uncertainty and risk management, dependency theory and integration challenges, and stakeholder governance. However, conceptual integration remains limited. Specifically, much of the existing work identifies uncertainty sources but does not fully theorize the mechanisms through which uncertainty is amplified via interdependencies to create emergent risk and nonlinear impacts. Risk is often conceptualized as an exogenous set of events rather than as endogenous system behavior arising from interaction effects.

Therefore, there is a need for a conceptual framework that (1) positions interdependencies as propagation structures for uncertainty, (2) theorizes emergent risk as interaction-driven rather than purely external, and (3) reframes megaproject governance as an adaptive system required to dampen reinforcing instability loops across long time horizons.

Table 01. Thematic Synthesis of Megaproject Literature on Underperformance, Uncertainty, and Complexity

Theme	Core Focus	Key Insights
Megaprojects as a Distinct Project Category	Scale, complexity, strategic and institutional nature of megaprojects	Megaprojects differ fundamentally from conventional projects due to long durations, multi-organizational governance, political embeddedness, and societal impact. Performance should be assessed beyond time and cost to include long-term value and legitimacy. Persistent underperformance is a structural issue rather than isolated execution failure.
Dominant Explanations for Underperformance	Early-stage decision-making distortions	Optimism bias reflects cognitive forecasting errors, while strategic misrepresentation reflects intentional manipulation driven by political and institutional incentives. Both lead to unrealistic baselines that destabilize execution. However, they focus mainly on planning stages and under-theorize execution-phase dynamics.
Uncertainty in Megaproject Environments	Types and domains of uncertainty	Uncertainty includes epistemic, aleatory, and deep uncertainty. It spans technical, organizational, environmental, and temporal domains. Long horizons and political exposure intensify deep uncertainty, challenging traditional risk management approaches based on predictability and stable systems.
Interdependence and Tightly Coupled Systems	Connectivity among tasks, subsystems, and organizations	Megaprojects are characterized by dense interdependencies that often become tightly coupled. Disruptions propagate rapidly across interfaces, generating cascading delays and nonlinear cost impacts. The location of disruption within the dependency network is critical to its impact.
Scope Volatility and Requirements Ambiguity	Dynamic evolution of project scope	Scope changes arise from institutional shifts, stakeholder pressure, regulatory change, and learning processes. Ambiguous requirements increase rework and design churn. When combined with tight interdependencies, scope volatility creates reinforcing feedback loops that amplify instability and emergent risk.
Stakeholder Complexity and Institutional Embeddedness	Political and social dimensions of megaprojects	Megaprojects involve heterogeneous stakeholders with misaligned objectives. Governance structures are dynamic and subject to political shifts. Stakeholder conflict and institutional change become endogenous sources of uncertainty, affecting scope, approvals, and delivery stability.
Complexity Theory and Systems Thinking	Nonlinear and emergent project behavior	Megaprojects function as complex adaptive systems where interacting agents and feedback loops produce emergent outcomes such as cascading delays and escalating costs. Systems thinking highlights reinforcing and balancing loops, nonlinearity, and dynamic interactions rather than linear causality.
Conceptual Gap in Existing Literature	Lack of integrated theoretical framework	Existing research identifies multiple drivers of underperformance but remains fragmented. There is limited theorization of how uncertainty is amplified through interdependencies to generate emergent risk. Risk is often treated as exogenous rather than as endogenous system behavior.

Source: Author

3. Theoretical Foundations

3.1. Rational for a Complexity-based Theoretical Framing

Megaprojects operate in environments where uncertainty is persistent, interdependencies are dense, and stakeholder influence is distributed across multiple institutional layers. These attributes challenge the applicability of traditional project management assumptions grounded in linear causality, predictability, and decomposability. In conventional project theory, projects are often treated as systems that can be optimized through improved planning, front-end definition, and variance control. However, such approaches presume that project uncertainty can be sufficiently reduced through improved information and that deviations are typically proportional to their causes. Complexity theory challenges these assumptions by suggesting that large-scale systems exhibit behavior that is not fully explainable through linear or reductionist models, particularly when there are strong interdependencies and feedback loops (Williams, 2002).

Within this perspective, megaproject delivery is best conceptualized as an evolving socio-technical system in which outcomes result from interactions among technical subsystems, organizational coordination structures, institutional governance arrangements, and external environmental conditions. This implies that uncertainty cannot be treated merely as an external disturbance to be absorbed; instead, uncertainty is often produced endogenously through interactions among system components and amplified through dependency pathways.

3.2. Complex Adaptive Systems Theory

Complex adaptive systems (CAS) theory provides a foundational lens for analyzing systems composed of multiple interacting agents that adapt to changing conditions. CAS are typically characterized by nonlinearity, emergence, self-organization, and continuous adaptation (Nair & Reed-Tsochas, 2019). While CAS theory is more frequently associated with ecological or biological systems, it has increasingly been applied to organizational and project settings where multi-actor coordination and environmental turbulence shape performance.

In megaprojects, agents include project sponsors, government bodies, contractors, subcontractors, consultants, regulators, local communities, and technical teams. Each agent adapts to constraints and incentives, which may change during delivery due to shifting political priorities, contractual renegotiations, or evolving technical information. Because agent behavior adjusts over time, the project system cannot be fully stabilized through initial planning. Instead, performance emerges from iterative interactions among agents and subsystems.

CAS theory is particularly useful for conceptualizing why megaproject outcomes often remain unpredictable even when planning processes are robust. This unpredictability does not necessarily imply randomness; rather, it reflects the system’s sensitivity to interaction patterns, meaning small disturbances can escalate depending on where they occur and how they propagate through the system.

3.3. Systems Thinking as a Structuring Logic

Systems thinking provides conceptual tools for mapping complex systems and analyzing the relationships among system components rather than focusing exclusively on individual elements. Systems thinking emphasizes holistic interpretation of system behavior through constructs such as system boundaries, feedback loops, delays, stocks and flows, and reinforcing and balancing mechanisms (Sheffield et *al*., 2012). These constructs are particularly relevant to megaprojects, where disruptions often arise from the interaction between components rather than from isolated causal events.

A key contribution of systems thinking is its emphasis on feedback loops. Reinforcing feedback loops amplify change and can create runaway dynamics, while balancing loops stabilize systems and resist change. In megaproject delivery, scope volatility and rework often create reinforcing loops that intensify instability. For example, increasing rework creates delays, delays generate schedule pressure, pressure increases shortcuts or coordination failures, and these failures create further rework. Conversely, governance interventions such as buffer policies, integration sequencing, and stable decision-rights structures can function as balancing mechanisms that dampen instability.

Systems thinking also emphasizes time delays. In megaprojects, the impacts of managerial decisions may occur with significant delay, meaning that corrective actions taken to address an immediate problem can unintentionally reinforce the underlying instability driver. This creates a dynamic environment in which controlling outcomes requires understanding systemic structure, not simply managing observable symptoms.

3.4. Interdependency Structures and Coupling Strength

Interdependencies represent the structural pathways through which uncertainty propagates. Interdependency refers to the degree to which tasks, resources, decisions, or subsystems depend on outputs from other components. While interdependence exists in most projects, megaprojects exhibit unusually high interdependency density and complexity due to their scale, multi-vendor execution, and integration requirements (Williams, 2002).

Coupling strength further explains how interdependencies create fragility. Tightly coupled systems have low slack, limited buffering, and limited capacity to isolate disruptions. In such systems, disturbances rapidly spread and constrain downstream activities. Loose coupling allows partial isolation of disruptions, enabling local adaptation without necessarily affecting the entire system. In megaproject contexts, coupling is frequently tight because interface milestones, contractual dependencies, and integration sequencing reduce flexibility. This is particularly evident in digitally intensive megaprojects such as ERP implementations, where integration failure in one module can halt progress across multiple functions.

The theoretical implication is that megaproject uncertainty management requires structural analysis of interdependency networks rather than an exclusive focus on managing individual risks. A disruption's systemic effect depends not only on its magnitude but on its position within the dependency network and the level of coupling across system components.

3.5. Emergence and Emergent Risk

Emergence refers to the phenomenon where system-level behavior arises from interactions among components and cannot be fully predicted through analysis of components in isolation. In project contexts, emergence explains why significant delivery disruptions often develop without a single identifiable cause. Instead, they result from interaction effects that accumulate across dependencies and become visible only once they reach critical thresholds (Nair & Reed-Tsochas, 2019).

Emergent risk may therefore be defined as risk that arises endogenously from the interaction of uncertainties, interdependencies, and adaptive behavior. This contrasts with conventional risk management approaches, where risks are treated as discrete events that can be identified, quantified, and mitigated through pre-defined controls. In megaproject environments, many of the most consequential disruptions are emergent rather than listable during planning. Examples include cascading integration failures, legitimacy crises driven by stakeholder backlash, or systemic contractor coordination breakdowns.

The conceptual importance of emergent risk is that it shifts risk management from prediction to adaptation and resilience. Managing emergent risk requires continuous monitoring of interaction patterns, early warning signals, and structural vulnerabilities, rather than reliance on static risk registers.

3.6. Nonlinearity and Disproportionate Outcomes

Nonlinearity refers to relationships in which outputs are not proportional to inputs. In nonlinear systems, small disturbances can produce disproportionately large consequences, while large interventions may yield minimal effect. Megaprojects often display nonlinear dynamics due to tight coupling, delays, and feedback loops.

A common nonlinear mechanism in megaprojects is the tipping point. Early-stage disturbances may appear manageable, but once schedule slack is exhausted or stakeholder tolerance thresholds are crossed, the project may experience rapid escalation in cost, conflict, and rework. These tipping points are often linked to system structure, such as dependency bottlenecks or governance fragmentation, rather than to any singular risk event.

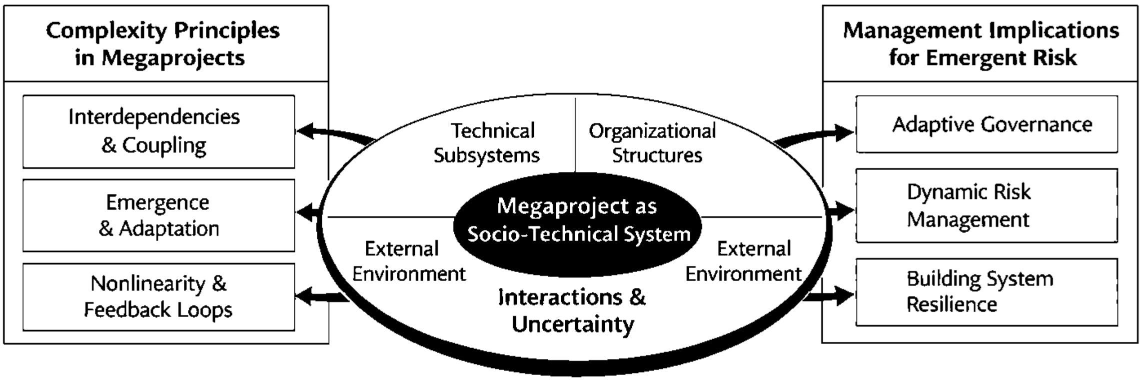
The implication for megaproject management is that performance cannot be reliably stabilized by incremental corrective action alone. Linear variance control may be ineffective if underlying reinforcing loops continue to amplify disruption. Therefore, nonlinear systems require interventions targeted at system structure, such as reducing coupling, redesigning governance pathways, or increasing buffering capacity.

3.7. Implications for Megaproject Governance and Management

The integration of CAS theory and systems thinking has direct implications for megaproject governance. If megaprojects behave as complex adaptive systems, then governance should be conceptualized not as a static hierarchy of control but as an adaptive coordination mechanism capable of responding to evolving uncertainty. Governance arrangements must therefore (1) support rapid decision-making under ambiguity, (2) manage interdependency and integration explicitly, and (3) maintain legitimacy across heterogeneous stakeholders.

This theoretical framing suggests that successful megaproject delivery depends less on achieving perfect forecasts and more on designing adaptive capacity. Such capacity includes the ability to absorb shocks, detect early warning signals, reconfigure plans as conditions evolve, and manage stakeholder alignment dynamically over long-time horizons.

Figure 01. Complexity-Based Theoretical Framework for Megaprojects



Source: Author

4. Conceptual Framework Development

4.1. Purpose and Positioning of the Framework

The purpose of this section is to develop an integrative conceptual framework for understanding how uncertainty and interdependencies shape megaproject outcomes through emergent and nonlinear dynamics. While existing megaproject research provides rich descriptive accounts of cost overruns, schedule delays, and benefit under-realisation (Flyvbjerg, 2009; 2014), much of this work remains fragmented across separate explanatory streams. Some literature emphasizes forecasting bias and early-stage misrepresentation (Flyvbjerg, 2009), while other strands focus on project execution challenges, complexity, and system integration (Williams, 2002). These streams are complementary but often insufficiently integrated.

This paper addresses this integration gap by proposing a complexity-informed framework that positions interdependencies not as a background feature of megaprojects but as a central mechanism through which uncertainty is transformed into emergent risks and nonlinear impacts. In contrast to conventional project management models that treat risks as identifiable and separable events, this framework conceptualizes risk as an endogenous system property. It assumes that significant disruptions arise from interaction effects among uncertainties rather than from single isolated causes. This is consistent with complexity theory and systems thinking perspectives that emphasize emergence, feedback loops, and coupling (Sheffield et *al*., 2012; Nair & Reed-Tsochas, 2019).

4.2. Overview of the MUIE Framework

This paper proposes the Megaproject Uncertainty-Interdependency-Emergence (MUIE) framework, which theorizes how megaproject performance outcomes emerge from the interaction of four primary system domains:

1. **Uncertainty sources** (multi-dimensional and evolving)
2. **Interdependency structures** (coupling pathways for propagation)
3. **Emergent dynamics** (feedback-driven amplification and cascades)
4. **Performance outcomes** (cost, time, quality, legitimacy, and value)

The MUIE framework assumes that uncertainty is not merely additive. Instead, uncertainty interacts with interdependencies to generate emergent dynamics that shape outcomes nonlinearly. Accordingly, the framework shifts the analytical unit from individual risk events (e.g., "supplier delay") to risk interaction patterns (e.g. supplier delay combined with integration coupling and decision delays creating cascading schedule destabilization).

4.3. Core Constructs and Definitions

To ensure conceptual clarity, the MUIE framework specifies constructs and their theoretical meaning.

4.3.1. Uncertainty Sources

Uncertainty sources refer to the conditions and unknowns that limit predictability in megaproject delivery and decision-making. Megaproject uncertainty is conceptualized as multi-domain and includes:

- **Technical uncertainty**, relating to engineering challenges, innovation requirements, and integration difficulty
- **Scope uncertainty**, including evolving requirements, unclear success criteria, and late-stage change
- **Institutional and political uncertainty**, including changes in governance priorities, regulatory revisions, and public legitimacy dynamics
- **Environmental uncertainty**, including macroeconomic shocks, supply market volatility, and external disruptions
- **Temporal uncertainty**, arising from long project horizons and the compounding effect of delayed outcomes (Park, 2021)

While some of these forms may be epistemic and reducible through analysis, megaprojects are particularly exposed to deep uncertainty over long horizons, where future states cannot be reliably specified (Williams, 2002).

4.3.2. Interdependency Structures

Interdependency structures refer to the architecture of task, resource, contractual, technical, and organizational linkages that connect components of the megaproject delivery system. These structures serve as propagation channels for disturbances. Interdependencies are not merely operational constraints but determine the degree to which local disturbances escalate into system-wide disruptions.

Within the framework, interdependency structures are characterized through three properties:

- **Density**, referring to the number of dependencies relative to project size
- **Coupling strength**, referring to how tightly linked components are (tight coupling implies low slack and high propagation risk)
- **Criticality**, referring to centrality or bottleneck status of interfaces within the system (Williams, 2002)

Interdependency structures are treated as a core determinant of systemic fragility. A megaproject with low uncertainty but extremely tight coupling may still experience significant cascading risk due to limited buffering capacity. Conversely, a project with higher uncertainty but looser coupling may adapt more effectively due to modularity and isolatable disturbances.

4.3.3. Emergent Dynamics

Emergent dynamics refer to system-level behaviors that result from interactions among uncertainty sources and interdependency structures. These dynamics include:

- **Cascading failures**, where a disruption propagates across multiple subsystems and contract layers
- **Feedback loops**, especially reinforcing loops that amplify instability over time
- **Path dependency**, where early decisions constrain later options and create lock-in effects
- **Risk amplification**, where interacting uncertainties increase overall volatility beyond what would be expected from independent risks (Nair & Reed-Tsochas, 2019)

Emergent dynamics are central to the framework because they explain why megaproject performance breakdowns are often difficult to diagnose and why they frequently appear to "accelerate" after specific execution thresholds. Systems thinking suggests such escalation occurs when reinforcing feedback loops dominate balancing mechanisms (Sheffield et *al*., 2012).

4.3.4. Megaproject Performance Outcomes

Megaproject performance is conceptualized as multi-dimensional. Traditional measures such as time and cost remain important, but megaproject outcomes often include additional dimensions:

- **Cost performance**, including budget escalation and financing instability

- **Schedule performance**, including delay accumulation and milestone disruptions
- **Technical performance**, including quality, reliability, safety, and integration stability
- **Value realization**, including long-term benefits and operational performance
- **Legitimacy outcomes**, including stakeholder satisfaction, public acceptance, and political continuity (Flyvbjerg, 2014)

The inclusion of legitimacy reflects that megaprojects operate under public visibility and institutional contestation, and therefore their success depends partly on sociopolitical stability, not solely on delivery metrics.

4.4. Structural Relationships within the Framework

The MUIE framework proposes three core relationships.

Relationship 01: Uncertainty sources shape disruption likelihood

Uncertainty increases the probability that deviations will occur from baseline plans. While this is widely acknowledged, the framework stresses that uncertainty is dynamic and evolves throughout the project life cycle. Uncertainty sources influence the frequency and magnitude of deviations and increase the need for iterative adjustment.

Relationship 02: Interdependency structures shape disruption propagation

Interdependencies determine whether deviations remain localised or become systemic. Dense dependency networks and tight coupling increase the likelihood that small deviations will trigger cascading consequences (Williams, 2002). Therefore, project fragility is not a simple function of uncertainty magnitude, but a function of uncertainty interacting with system coupling.

Relationship 03: Emergent dynamics shape nonlinearity in outcomes

Emergency dynamics, generated by the interaction of uncertainty and interdependency, explain why megaproject outcomes are nonlinear and often experience sudden performance breakdown. For example, delays may remain manageable early in execution while slack exists. However, once slack is exhausted, schedule compression amplifies quality failures and rework, resulting in acceleration of delay and cost escalation. This corresponds to a tipping point mechanism typical of complex adaptive systems (Nair & Reed-Tsochas, 2019).

4.5. Theoretical Implications of the Framework

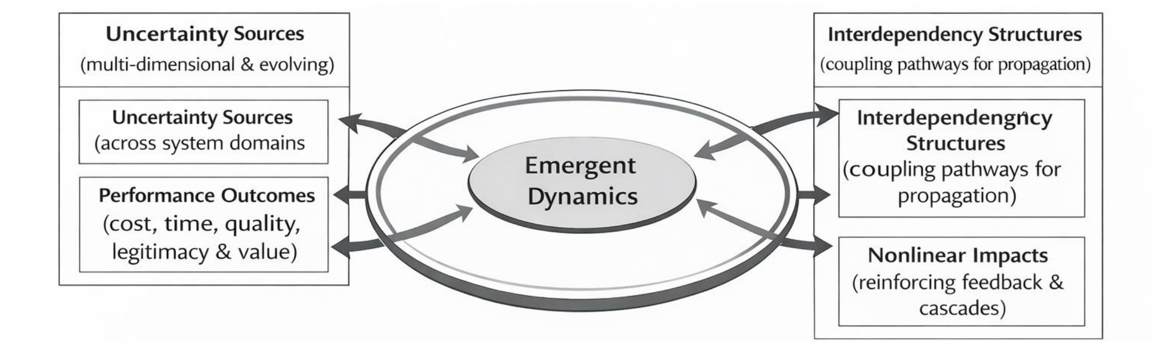
The MUIE framework implies that megaproject risk governance should shift from a focus on prediction and control toward system design, adaptation, and resilience. Several implications follow.

First, risk management should be reconceptualized as managing risk interaction patterns rather than managing standalone threats. This requires mapping dependency networks and monitoring integration stress points.

Second, performance management should focus on early identification of systemic vulnerabilities. Instead of solely tracking schedule variance or cost variance, managers must observe signals related to coupling stress, rework cycles, stakeholder decision latency, and contract renegotiation frequency.

Third, governance becomes a balancing system. In complexity terms, governance is not merely compliance and reporting, but a dynamic coordination mechanism required to dampen reinforcing instability loops and maintain legitimacy (Sheffield et *al*., 2012).

Figure 02. Megaproject Uncertainty-Interdependency-Emergence (MUIE) Framework



Source: Author

5. Mechanisms and Propositions

5.1. Purpose of the Mechanisms Section

Conceptual frameworks require explanatory depth to move beyond descriptive classification. Accordingly, this section develops the causal mechanisms within the Megaproject Uncertainty–Interdependency–Emergence (MUIE) framework, specifying how uncertainty and interdependencies interact to generate emergent risk and nonlinear outcomes. Consistent with systems thinking and complexity theory, mechanisms are conceptualized as dynamic processes that unfold over time through interaction effects, feedback loops, and propagation pathways (Sheffield et *al*., 2012; Williams, 2002). The objective is to articulate theorized relationships as a set of propositions that can guide future empirical research and support theory refinement.

Four primary mechanisms are proposed: (1) interdependency amplification, (2) scope volatility and rework reinforcement, (3) stakeholder conflict as a generator of uncertainty, and (4) long-horizon risk drift and governance destabilization.

5.2. Mechanism 01: Interdependency Amplification and Cascading Disruption

5.2.1. Mechanism Description

The first mechanism addresses how tightly coupled interdependencies amplify disturbances. In megaprojects, delivery is distributed across multiple subsystems and organizations, which must align outputs through interfaces and sequential milestones. When coupling is tight and slack is limited, even small deviations in one node of the system can propagate across dependency networks, creating cascading disruption (Williams, 2002). Importantly, this amplification does not depend solely on the magnitude of an initiating event, but on the disturbance's position within the interdependency structure.

For example, a modest delay in a vendor deliverable may trigger failure to meet an integration milestone. This can then constrain downstream testing, delay regulatory approval, and necessitate re-sequencing across multiple teams. Such cascades are reinforced when contractual structures increase coordination friction, for instance by separating responsibilities across multiple suppliers with unclear integration accountability.

5.2.2. Nonlinear Implications

Interdependency amplification creates nonlinear effects because propagation can transform an initially manageable disruption into system-level instability. Once a cascade begins, the system may experience compounding delays, schedule compression, and reduced ability to recover. This aligns with complexity theory's emphasis on sensitivity to interaction patterns rather than solely to event magnitude (Nair & Reed-Tsochas, 2019).

5.2.3. Proposition

Proposition 1 (P1): Megaprojects with higher interdependency density will exhibit greater susceptibility to cascading disruption, resulting in disproportionate schedule and cost escalation relative to the magnitude of initiating disturbances.

Proposition 2 (P2): Tighter coupling strength in megaproject subsystem interfaces increases the likelihood of nonlinear escalation in project delays through propagation effects.

5.3. Mechanism 02: Scope Volatility, rework cycles, and reinforcing feedback

5.3.1. Mechanism Description

The second mechanism addresses the relationship between scope uncertainty and systemic instability. Scope volatility refers to the continued evolution of project objectives, requirements, and constraints during execution. In megaproject contexts, scope volatility is common due to evolving stakeholder expectations, regulatory adaptation, technology change, and discovery of technical constraints (Flyvbjerg, 2014). However, scope volatility becomes particularly destabilizing when it interacts with high coupling and complex integration sequences.

Scope uncertainty increases rework and design churn. Rework then consumes schedule slack and produces delays, which generate schedule pressure. Schedule pressure often leads to compromised coordination and quality assurance, thereby producing defects and technical debt. Defects then increase rework, reinforcing the cycle. Systems thinking conceptualizes this as a reinforcing feedback loop in which scope ambiguity and coordination failures intensify one another over time (Sheffield et al., 2012).

5.3.2. Mechanism Implications

In the early stages of execution, rework may appear manageable and absorbed through buffers. However, as buffers are depleted, schedule compression increases sharply. At this point, even minor additional changes can generate major disruption because rework affects multiple coupled interfaces, pushing the system toward tipping points. Nonlinearity thus emerges from delayed reinforcement, where accumulated rework reaches a threshold that suddenly destabilizes downstream integration.

5.3.3. Propositions

Proposition 3 (P3): Higher levels of early-stage requirements ambiguity increase the likelihood of reinforcing rework cycles, leading to accelerating schedule instability as the project progresses.

Proposition 4 (P4): The relationship between scope volatility and cost escalation is mediated by rework intensity, and this mediation effect is stronger in tightly coupled megaprojects.

5.4. Mechanism 03: Stakeholder Conflict as an Endogenous Uncertainty Generator

5.4.1. Mechanism Description

The third mechanism explains how stakeholder complexity generates uncertainty endogenously. Megaprojects involve diverse stakeholder groups with heterogeneous objectives, asymmetric power, and competing success criteria (Flyvbjerg, 2014). This heterogeneity increases the risk of conflict regarding scope, benefits, risk tolerance, and implementation priorities. Stakeholder conflict often delays decisions, prolongs approvals, and produces late-stage changes to design or execution plans.

Such delays and changes are not exogenous disturbances. They are produced internally through institutional interaction. For instance, disagreements between regulators and contractors may delay permits, which then trigger schedule compression and re-sequencing. Similarly, changes in political leadership may redefine project objectives, generating new requirements and governance constraints.

Stakeholder conflict therefore functions as an endogenous uncertainty generator, producing decision latency and destabilizing the project baseline. This interacts with interdependencies by shifting constraints at nodes that are tightly connected to multiple downstream activities.

5.4.2. Nonlinear Implications

Stakeholder uncertainty is particularly prone to nonlinearity because legitimacy thresholds and political tolerance are not continuous variables. Once stakeholder trust is lost or public opposition becomes salient, governance can quickly shift from support to constraint, leading to project pauses, redesign mandates, or cancellation. Thus, stakeholder dynamics can rapidly change the boundary conditions of delivery.

5.4.3. Proposition

Proposition 5 (P5): Greater stakeholder heterogeneity increases endogenous uncertainty by raising decision latency and increasing the frequency of late-stage scope changes.

Proposition 6 (P6): The negative impact of stakeholder conflict on megaproject performance is amplified by interdependency centrality, such that conflicts affecting high-centrality interfaces generate disproportionately large downstream disruption.

5.5. Mechanism 04: Long-Horizon Risk Drift and Governance Destabilization

5.5.1. Mechanism Description

The fourth mechanism addresses the long-time horizons of megaprojects. Long durations increase exposure to exogenous change including economic cycles, supply market fluctuations, regulatory shifts, and technological evolution (Park, 2021). This creates risk drift, a phenomenon in which the risk landscape evolves continuously while planning baselines become increasingly misaligned with actual conditions.

Risk drift undermines the effectiveness of static governance structures and traditional risk registers, which are often designed under assumptions of relatively stable environments. As drift increases, forecasting becomes less reliable and governance must continuously renegotiate priorities, constraints, and scope. These renegotiations add coordination friction and can destabilize delivery.

5.5.2. Nonlinear Implications

Risk drift contributes to nonlinearity because discontinuous environmental change can produce sudden constraint shifts. For example, a regulatory change may create new compliance requirements that require redesign. Market volatility may increase input costs beyond contingency limits. Over time, drift accumulates and gradually erodes buffers until the system becomes fragile. At that point, a moderate shock can push the project into rapid escalation of delays, renegotiations, and cost blowouts.

5.5.3. Proposition

Proposition 7 (P7): Longer megaproject timelines are associated with increased risk drift, which reduces the predictive accuracy of baseline planning and increases the frequency of re-baselining.

Proposition 8 (P8): The relationship between long time horizons and performance instability is mediated by governance adaptation capacity, such that projects with adaptive governance experience lower escalation under risk drift conditions.

5.6. Integrative Propositions: Emergence and Governance as Balancing Capacity

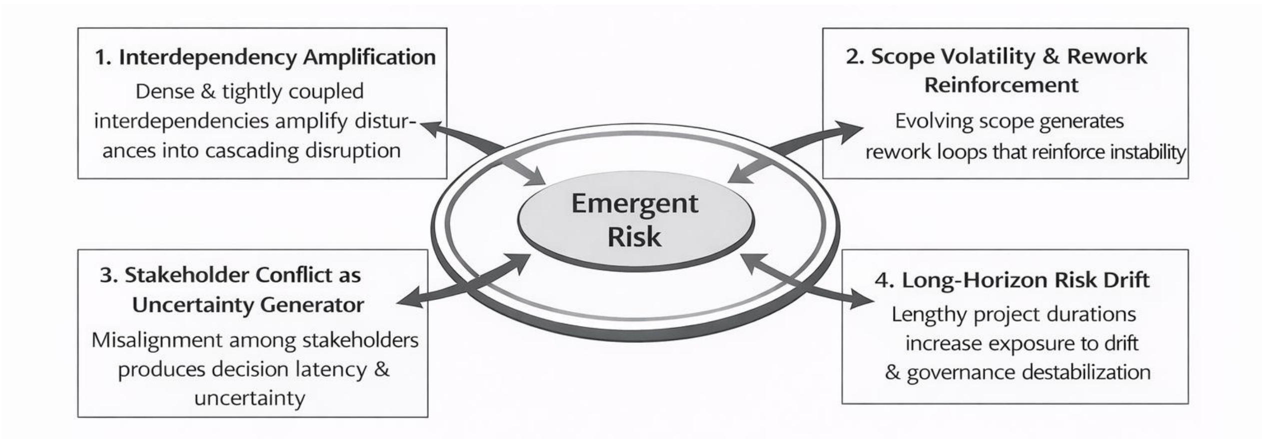
The mechanisms above suggest that emergent risk is produced by interaction effects rather than by isolated events. Therefore, governance that is designed around prediction alone is insufficient. In complex systems, governance functions as a balancing structure that can dampen reinforcing feedback loops through adaptive decision-making and structural interventions (Sheffield et *al*., 2012).

Examples of balancing governance capacity include flexible sequencing, modular delivery design to reduce coupling, decision-right clarity to reduce latency, and monitoring systems to detect early warning signals.

Proposition 9 (P9): Megaprojects that implement adaptive governance mechanisms reduce the escalation of emergent risk by weakening reinforcing feedback loops generated by interdependency amplification and scope volatility.

Proposition 10 (P10): The shift from risk registers to risk network governance improves megaproject resilience by increasing early detection of interaction-driven vulnerability clusters.

Figure 02. Four Core Mechanisms in the Megaproject Uncertainty-Interdependency Emergence (MUIE) Framework



Source: Author

6. Managerial Implications

6.1. Reframing Megaproject Management from Prediction to Resilience

The MUIE framework positions megaprojects as complex adaptive systems in which uncertainty and interdependencies interact to produce emergent risks and nonlinear outcomes. This implies that the managerial challenge is not simply to improve forecasting accuracy, increase schedule discipline, or expand risk registers. Rather, the core task is to design delivery and governance systems capable of absorbing shocks, detecting destabilising interaction patterns early, and adapting plans without triggering cascading disruption (Sheffield et al., 2012; Williams, 2002).

This section translates the conceptual mechanisms developed in Section 5 into practical implications for megaproject leaders. Specifically, it proposes that effective megaproject management requires a shift in emphasis: from managing isolated risks to managing interdependency structures and feedback loops; from fixed baselines to adaptive governance; and from linear control to resilience-oriented intervention.

6.2. Managing Interdependencies: From Interface Control to Dependency Governance

6.2.1. Dependency Mapping as a Core Planning Activity

Interdependency amplification is a primary mechanism driving megaproject fragility (Williams, 2002). Consequently, megaproject leaders should treat interdependency mapping as a first-order governance activity rather than as a technical coordination tool limited to engineering teams. Traditional work breakdown structures can obscure systemic coupling because they prioritise decomposition over connectivity. A complexity-informed approach therefore requires explicit representation of dependency networks across tasks, subsystems, and organizations.

Dependency mapping should include:

- technical interface dependencies (system integration points)
- organizational handoffs (between contractors, teams, suppliers)
- contractual dependencies (approval gates, deliverable sign-offs)
- regulatory dependencies (permit sequencing, compliance milestones)

The managerial objective is not merely to document dependencies, but to identify criticality within the dependency network. Interfaces with high centrality create disproportionate propagation risk, and thus require enhanced governance attention.

6.2.2. Reducing Coupling through Modularity and Buffer Design

Tightly coupled systems are inherently less resilient. While coupling cannot be eliminated in megaprojects, it can be reduced through architectural decisions that increase modularity and create isolatable subsystems. Modularity allows local disruptions to remain contained rather than triggering system-wide cascades. In practice, this implies designing:

- Phased integration sequences
- modular contracting structures that reduce cross-vendor coordination overload
- interface "firebreaks" such as buffer milestones and decoupling inventories (where applicable)

Buffers and contingency should therefore be treated not as inefficiencies but as resilience investments. Traditional efficiency-driven planning often removes slack, unintentionally increasing coupling strength and propagation vulnerability.

6.3. Monitoring Emergent Risk: From Risk Registers to Risk Networks

6.3.1. Limits of Conventional Risk Management

Traditional risk management typically assumes that risks can be identified, listed, evaluated, and treated. Such processes remain useful but are structurally limited in complex systems where the most consequential risks are emergent. Emergent risks arise from interactions among uncertainties and dependencies and cannot always be predicted at the initiation stage (Nair & Reed-Tsochas, 2019). Therefore, risk governance must extend beyond periodic risk workshops and static probability-impact matrices.

6.3.2. Establishing an Emergent Risk Monitoring Capability

Megaproject governance should incorporate an emergent risk monitoring function focused on interaction-driven signals, including:

- rapid growth in change request volume
- rising rework rates and defect recurrence
- instability in integration test results
- decision latency and prolonged approval cycles
- increasing contract disputes and claims
- decreasing stakeholder support or public legitimacy signals

These signals are not simply indicators of current problems but early warnings of reinforcing feedback loops. For example, a rising rework rate may indicate that scope volatility is entering a reinforcement phase that could trigger nonlinear delay escalation if not dampened.

6.3.3. Risk Network Review Practices

A complexity-based alternative to risk reviews is the risk network review. Rather than discussing risks independently, this practice focuses on:

- clusters of interacting uncertainties
- dependencies connecting risks
- cascade scenarios and tipping-point conditions
- vulnerability hotspots (high centrality interfaces)

This approach aligns with the MUIE framework by prioritising systemic structure over isolated event probability.

6.4. Managing Scope Volatility through Adaptive Design and Change Governance

6.4.1. Scope Volatility as a Systemic Risk Driver

Scope volatility is frequently treated as a failure of discipline, typically framed through inadequate front-end planning or weak change control. However, the MUIE framework treats scope volatility as a normal feature of megaproject environments due to shifting stakeholder expectations, regulatory change, and discovery during delivery (Flyvbjerg, 2014). The managerial implication is that projects must be designed with scope adaptiveness in mind rather than assuming early scope stabilisation is always achievable.

6.4.2. Designing for Controlled Adaptability

Rather than pursuing absolute scope freeze, managers should aim for controlled adaptability by:

- establishing modular delivery packages with stable boundaries
- prioritising requirements through staged elaboration
- using rolling-wave planning for high uncertainty domains
- freezing requirements selectively based on interdependency criticality

Highly central and tightly coupled components should be stabilised earlier because change at those nodes produces cascades. More loosely coupled modules can accommodate later change with lower systemic consequence.

6.4.3. Strengthening Change Control through System Impact Assessment

Change governance should require impact assessment not only in terms of time and cost, but also interdependency consequences. A systems-oriented change governance process assesses:

- which interfaces are affected
- propagation pathways
- likely reinforcement cycles (rework-feedback risk)
- downstream testing and regulatory implications

This transforms change control from administrative approval into systemic risk management.

6.5. Stakeholder Governance as a Resilience Mechanism

6.5.1. Reframing Stakeholder Management

Stakeholder complexity is not an external constraint but a central system driver that produces endogenous uncertainty through conflict, decision latency, and scope renegotiation (Flyvbjerg, 2014). Therefore, stakeholder management in megaprojects should be reframed as stakeholder governance, meaning the design of ongoing alignment mechanisms rather than episodic communication.

6.5.2. Mechanisms for Reducing Stakeholder-Induced Uncertainty

Key governance mechanisms include:

- early agreement on multi-dimensional success criteria (not only time/cost)
- formal decision-rights architecture clarifying authority under uncertainty
- escalation pathways to reduce decision latency
- transparency mechanisms to maintain legitimacy during disruption

Legitimacy is particularly important because stakeholder tolerance thresholds are nonlinear. Once legitimacy erodes, institutional support can shift quickly and create discontinuous constraints, such as project pauses or major redesign mandates.

6.6. Managing Long-Horizon Uncertainty and Risk Drift

6.6.1. Planning for Dynamic Risk Landscapes

The MUIE framework highlights risk drift as a systemic challenge in long-horizon megaprojects (Park, 2021). Risk drift requires governance that continually updates assumptions and adjusts plans. Static baselines tend to become increasingly misaligned with evolving conditions, producing repeated re-baselining and growing uncertainty.

Megaproject governance should therefore incorporate:

- structured scenario planning cycles
- periodic re-validation of assumptions (cost, regulatory, technology)
- monitoring of external signals that indicate drift (policy change, macroeconomic instability)

6.6.2. Adaptive Governance Cycles

Adaptive governance cycles provide a mechanism for resilience by institutionalizing learning and plan adaptation. Such cycles may include:

- frequent integration readiness reviews
- cross-contract coordination councils
- “governance sprints” during high volatility phases
- re-prioritisation protocols for constrained resources

The objective is to prevent drift from accumulating unnoticed until the project reaches tipping points.

6.7. Synthesis: A Resilience-Oriented Megaproject Management Toolkit

Drawing on the MUIE framework, this paper proposes that megaproject management should be organized around four resilience capabilities:

1. **Structural resilience**: reducing coupling and governing dependencies
2. **Cognitive resilience**: shifting from risk lists to systemic risk sensemaking
3. **Institutional resilience**: adaptive governance and stakeholder legitimacy maintenance
4. **Temporal resilience**: managing risk drift through scenario cycles and re-validation mechanisms

Together these capabilities represent a coherent management approach aligned with complexity theory and systems thinking. They enable leaders to dampen reinforcing feedback loops, prevent cascading disruptions, and maintain both delivery performance and institutional legitimacy.

Figure 03. Resilience Strategies in Megaproject Management

Source: Author

7. Discussion

7.1. Reinterpreting Megaproject Underperformance through Complexity Mechanisms

The MUIE framework suggests that megaproject underperformance should be understood less as a deviation from "good planning" and more as a system-level outcome produced by the interaction of uncertainty and interdependency. While the megaproject literature has traditionally foregrounded initiation-stage problems such as optimism bias and strategic misrepresentation (Kahneman & Lovallo, 1993; Flyvbjerg, 2009), the present framework emphasizes that execution-phase instability emerges even when early-stage planning is improved. Megaprojects frequently experience escalating disturbances through cascades, reinforcing feedback loops, and tipping-point dynamics that exceed the explanatory reach of linear control assumptions.

This framing does not contradict institutional and behavioral explanations but rather extends them. Optimism bias and misrepresentation explain why projects begin with fragile baselines; however, the MUIE framework explains how fragility becomes amplified into failure trajectories during delivery due to systemic structure. In this sense, the framework links early-stage baseline vulnerability to execution-phase emergent disruption by identifying interdependencies as propagation mechanisms.

7.2. From Additive Risk to Interaction-Driven Risk

A central theoretical implication of this paper concerns the conceptualization of risk. Conventional project risk management assumes that risks can be isolated, enumerated, assessed, and mitigated. This assumption aligns with decomposability, where project tasks can be managed independently and uncertainty is treated as a set of external disturbances. In megaprojects, however, the most consequential risks may be interaction-driven rather than event-based. That is, risk arises not primarily from singular hazards, but from interactions among scope volatility, integration coupling, stakeholder decision latency, and long-horizon environmental drift.

This reconceptualization is consistent with systems thinking, which emphasises that outcomes are produced by system structure, not simply by component-level variance (Sheffield et *al*., 2012). It is also consistent with CAS theory, which suggests that the system-level outcome is emergent and cannot be understood through reductionist risk decomposition alone (Nair & Reed-Tsochas, 2019). The paper therefore advances the argument that megaproject risk should be managed as a dynamic network rather than as a static list.

7.3. Interdependencies as the Missing Explanatory Link

Existing megaproject research frequently acknowledges complexity but often operationalises it as a descriptive property (e.g., project size, stakeholder count, technology novelty). The MUIE framework instead treats interdependency structure as an explanatory variable that shapes project behaviour. This enables theorisation of how uncertainty is transformed into cascading disruption, and why impacts become nonlinear.

Williams (2002) argues that complex projects cannot be adequately modelled using traditional deterministic planning methods because interdependencies alter both predictability and controllability. The present framework builds on this foundation by demonstrating that interdependencies function as risk propagation networks, shaping both the distribution and escalation of disruptions across the system. Therefore, projects with similar levels of uncertainty may perform very differently depending on their coupling strength and dependency density. This helps explain why megaproject performance varies widely even within similar sectors and governance settings.

7.4. Scope Volitivity and Rework as Reinforcing System Dynamics

A significant contribution of the MUIE framework is its theorisation of scope volatility not as an isolated governance failure, but as a systemic driver of emergent disruption through rework reinforcement. While scope creep is often framed as poor discipline or inadequate front-end definition, megaproject environments frequently require continuous adaptation due to evolving stakeholder expectations, regulatory changes, and learning effects during implementation (Flyvbjerg, 2014). Systems thinking suggests that in tightly coupled systems, change is not local: it propagates.

The proposed scope–rework–pressure feedback mechanism explains why megaproject performance may degrade rapidly once buffers are depleted and schedule compression becomes dominant. This advances a dynamic explanation of instability: delays and overruns are not merely accumulated variance but can be produced by reinforcing structural processes that accelerate over time.

7.5. Stakeholder Dynamics and Legitimacy as Nonlinear Boundary Conditions

Stakeholder complexity is widely cited in megaproject studies as a source of managerial challenge. The MUIE framework extends this view by theorising stakeholder conflict as an endogenous uncertainty generator that alters project boundary conditions. In other words, stakeholder dynamics do not merely constrain managerial action; they shape the project system itself through decision delays, requirement renegotiation, institutional contestation, and legitimacy shifts (Flyvbjerg, 2014).

This has particular importance for public megaprojects where legitimacy operates as a threshold variable. Once public support or regulatory confidence declines beyond a tolerance threshold, governance demands may change discontinuously, resulting in project pauses, major redesign requirements, or institutional withdrawal of support. This helps explain why some megaproject disruptions appear sudden and politically driven rather than gradually evolving from technical issues. Under the MUIE framing, such shifts are consistent with nonlinear system behavior.

7.6. Long-Horizon Uncertainty and the Erosion of Predicative Control

The long duration of megaprojects creates structural exposure to risk drift, in which external conditions evolve, and assumptions embedded in baseline planning lose validity (Park, 2021). While traditional project management frameworks seek greater forecasting accuracy, the MUIE framework suggests that beyond a certain horizon, forecasting improvements may yield diminishing returns, because the underlying system conditions evolve faster than predictive tools can accommodate.

This supports a theoretical shift from accuracy-oriented planning to adaptability-oriented governance. In complexity terms, the strategic problem is not uncertainty reduction alone, but uncertainty accommodation through system design, buffering capacity, and adaptive decision structures. This suggests a stronger role for scenario planning, periodic assumption revalidation, and governance cycles designed for iterative learning rather than fixed compliance.

7.7. Theoretical Contribution of the MUIE Framework

This paper contributes to megaproject theory and project studies in three primary ways.

First, it integrates uncertainty, interdependencies, emergence, and nonlinearity into a single explanatory framework. Prior research has often examined these constructs separately. The MUIE framework conceptualizes them as linked mechanisms that jointly shape system behavior.

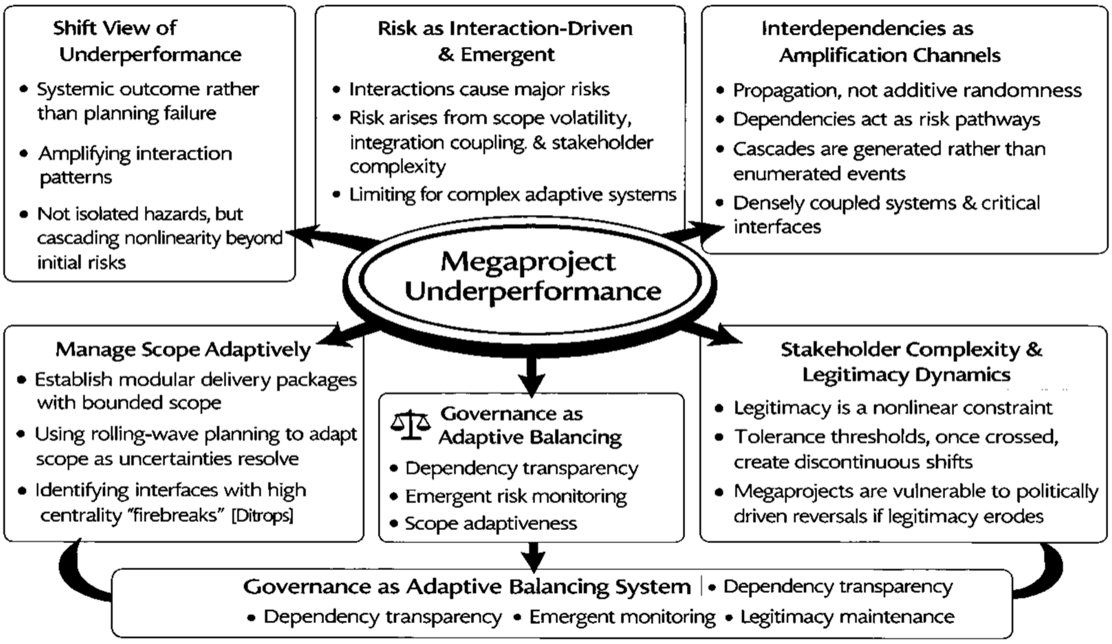
Second, the paper advances an interaction-based theory of megaproject risk, reframing risk from event-based to network-based governance. This addresses the conceptual limitation of static risk registers in complex systems.

Third, by articulating explicit mechanisms and propositions, the paper provides a platform for future empirical research. The propositions translate complexity constructs into testable claims about coupling density, scope reinforcement, stakeholder centrality, and governance adaptation capacity.

7.8. Practical Implication for Governance Design

The MUIE framework implies that megaproject governance should be treated as a balancing system rather than solely as a compliance structure. Governance should be designed to dampen reinforcing instability loops through interventions such as coupling reduction, modular delivery design, decision-latency reduction, and emergent risk monitoring. This requires rethinking governance as an adaptive capacity embedded in the delivery system, rather than a hierarchy imposed externally (Sheffield et *al*., 2012).

Figure 04. The Theoretical Implications of MUIE Framework



Source: Author

8. Limitations and Future Research Agenda

8.1. Conceptual Scope and Limitations

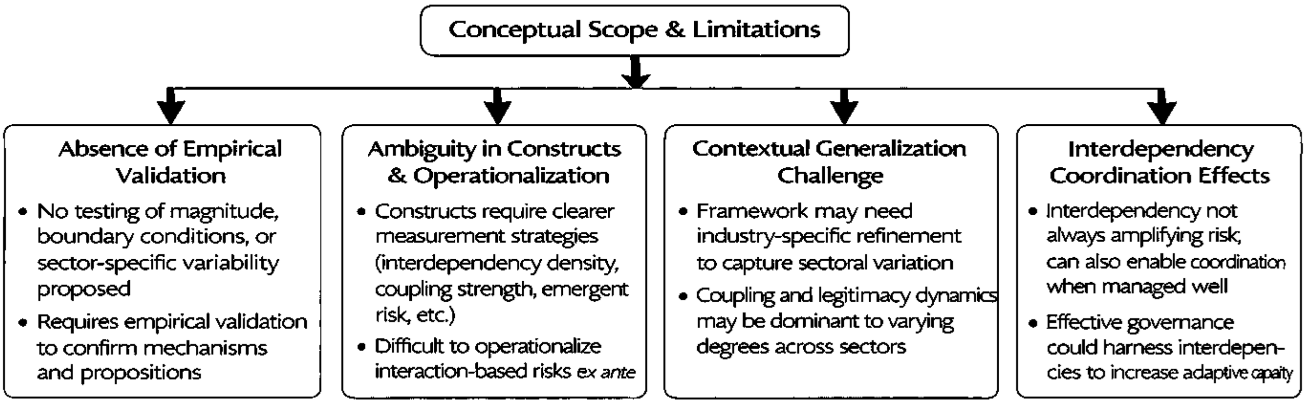
As a conceptual paper, this study aims to advance theory by developing an integrative framework and propositions rather than by empirically testing causal claims. While the MUIE framework is grounded in established streams of megaproject literature, systems thinking, and complexity theory (Williams, 2002; Sheffield et *al*., 2012; Flyvbjerg, 2014), its core limitation is the absence of empirical validation. Specifically, the framework proposes mechanisms linking uncertainty and interdependencies to emergent risk and nonlinear performance outcomes, yet it does not provide evidence regarding the magnitude, boundary conditions, or sector-specific variability of these relationships.

A second limitation concerns construct ambiguity and operationalization. Constructs such as interdependency density, coupling strength, emergent risk, and governance adaptation capacity are conceptually meaningful but require clearer measurement strategies to support future empirical testing. The operational challenge is non-trivial because many critical dependencies exist at multiple levels simultaneously (technical, organizational, and contractual), and because emergent risks are by definition difficult to identify ex ante. Future studies will need to develop robust indicators and measurement models that capture interaction-based risk rather than only discrete events.

A third limitation relates to contextual generalisation. Megaprojects vary widely across sectors. For example, transport infrastructure megaprojects may be dominated by regulatory and stakeholder legitimacy dynamics, whereas ERP and digitally intensive megaprojects may exhibit stronger dependence on integration complexity and requirements volatility. Although the framework aims to be cross-sectoral, it may require contextual refinement to account for industry-specific coupling patterns and governance environments. Therefore, the MUIE framework should be viewed as a general explanatory structure rather than as a one-size-fits-all model.

Finally, the framework assumes that interdependencies serve primarily as propagation channels that amplify uncertainty. While this is often true, interdependence can also function as coordination enablers when governance and integration mechanisms are effective. Future research should therefore explore conditions under which interdependence produce positive adaptive capacity, such as knowledge integration, innovation, and emergent coordination benefits.

Figure 05. Limitations of the Megaproject MUIE



8.2. Future Research Agenda

To advance megaproject scholarship, future research should focus on developing empirical and methodological approaches capable of testing interaction-driven mechanisms. Four promising directions are proposed.

8.2.1. Operationalizing Interdependency Structures and Coupling

A primary research opportunity lies in developing metrics for interdependency density, coupling strength, and interface criticality. Such metrics may be derived from:

- dependency structure matrices (DSM) of project tasks and interfaces
- contract structures and supplier networks
- integrated master schedules and milestone linkage analysis

- technical architecture interface maps (e.g. systems engineering structures)

Future work could test whether projects with high coupling density experience systematically greater escalation, and whether modular design correlates with reduced propagation intensity. These research efforts would contribute to moving complexity constructs from abstract theory toward measurable explanatory variables.

8.2.2. Empirical Testing of Propositions through Comparative Designs

The propositions offered in Section 5 provide a structured basis for empirical testing. One particularly useful design would be comparative research across megaprojects with similar scale but varying performance outcomes. For example, comparative analysis could test whether underperformance correlates more strongly with coupling properties than with baseline uncertainty magnitude. Research designs could include:

- cross-case comparative studies across sectors
- longitudinal case studies tracking feedback loops and tipping points
- quasi-experimental comparisons of modular versus tightly coupled delivery designs

Importantly, these studies would help determine whether the MUIE framework explains performance variance beyond existing baseline distortion explanations such as optimism bias and strategic misrepresentation (Flyvbjerg, 2009).

8.2.3. Simulation-Based Methods for Emergent Risk Dynamics

Because emergent risk is challenging to observe directly, simulation methods may be particularly valuable. Systems dynamics modelling is well suited for representing feedback loops, time delays, rework reinforcement, and resource constraints. Agent-based modelling may also be appropriate for simulating adaptive stakeholder behavior and institutional dynamics across long project horizons.

Simulation research could explore:

- tipping-point thresholds where reinforcing loops dominate balancing loops
- sensitivity of outcomes to coupling density and buffer design
- effects of governance adaptation frequency on disruption containment

Such modelling approaches align with the complexity framing and can generate testable implications that inform empirical work.

8.2.4. Governance as an Adaptive Capability

The MUIE framework proposes governance adaptation capacity as a moderating or mediating variable shaping performance under risk drift conditions. Future research should therefore explore governance not only as structure (e.g. committees, hierarchy, reporting, etc.) but as adaptive capability. Possible research questions include:

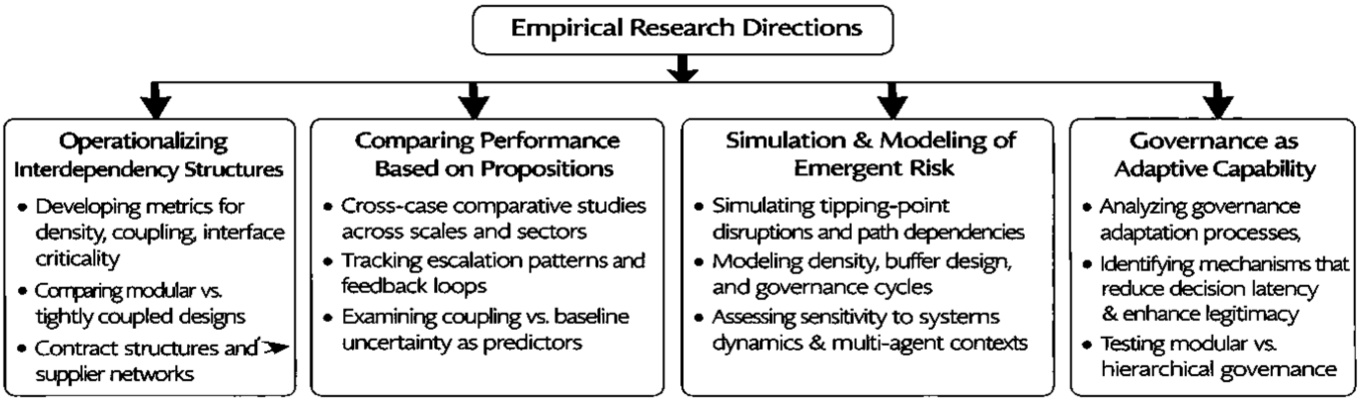
- *What governance mechanisms reduce decision latency under uncertainty?*
- *How do projects institutionalize learning and rapid reconfiguration?*
- *Which governance forms best balance legitimacy demands and delivery speed?*

Comparative studies of governance models across public and private megaprojects could clarify whether adaptive governance is consistently associated with resilience, and under what boundary conditions such effects hold.

8.3. Implications for Theory Development

From a theoretical perspective, the future research agenda implies a shift from event-based explanations of megaproject risk toward interaction-based explanations. This shift requires methods capable of capturing network dynamics, feedback loops, and emergent behavior. It also requires conceptual refinement of risk as a system-level property rather than a discrete hazard. Advancing theory in this direction would strengthen the explanatory power of megaproject studies by linking the structural and dynamic properties of projects to performance outcomes.

Figure 06. Directions for Future Research



9. Conclusion

9.1. Summary of the Problem and Argument

Megaprojects remain essential instruments for delivering large-scale infrastructure, technological transformation, and long-term societal development. Yet persistent evidence indicates that megaproject delivery is frequently characterized by cost overruns, schedule delays, and benefit shortfalls (Flyvbjerg, 2009, 2014; Park, 2021). Conventional project management approaches have sought to address this performance instability through improved forecasting, tighter control systems, and more rigorous risk management. However, such approaches rely on assumptions of linear causality, predictability, and decomposability that are often inconsistent with the structural realities of megaproject environments.

This conceptual paper argued that megaproject outcomes are better explained through a complexity-based lens that views projects as dynamic socio-technical systems shaped by uncertainty, interdependencies, and adaptive behavior. Under such conditions, major disruptions frequently emerge endogenously through interaction effects rather than through isolated and predictable risk events. Consequently, megaproject risk should be conceptualized not simply as a set of discrete threats, but as a system-level property arising from coupling structure, feedback loops, stakeholder dynamics, and long-horizon drift.

9.2. Key Contributions of the Conceptual Framework

The primary contribution of this article is the development of the Megaproject Uncertainty–Interdependency–Emergence (MUIE) framework, which integrates insights from complexity theory and systems thinking to explain how megaproject instability develops and escalates over time (Sheffield et *al*., 2012; Nair & Reed-Tsochas, 2019). The framework advances three central claims.

First, uncertainty in megaprojects is multi-dimensional and dynamic, often shaped by deep uncertainty across long time horizons rather than only by reducible information gaps (Williams, 2002). Second, interdependency structures determine whether disturbances remain localized or propagate systemically through tightly coupled interfaces, producing cascading disruption. Third, the interaction of uncertainty and interdependency generates emergent risk and nonlinear impacts, often through reinforcing feedback loops such as scope volatility leading to rework, rework leading to delays, and delays leading to compression-induced failures that further increase rework.

A second contribution lies in mechanism development. The paper proposed four causal mechanisms: (1) interdependency amplification, (2) scope volatility and reinforcing rework cycles, (3) stakeholder conflict as endogenous uncertainty generation, and (4) long-horizon risk drift and governance destabilisation. These mechanisms were formalised into propositions that provide a clear agenda for future empirical research and theory refinement.

A third contribution concerns governance implications. The MUIE framework suggests that megaproject governance should shift from a logic of predictive control toward a logic of resilience and adaptive capacity. This implies moving from risk registers to risk network management, strengthening dependency governance, institutionalizing adaptive decision cycles, and focusing on legitimacy and stakeholder alignment as core stability conditions (Flyvbjerg, 2014).

9.3. Implications for Practice

For megaproject practitioners, the conceptual findings suggest that improving delivery performance requires more than optimizing technical planning methods or imposing stricter compliance systems. Instead, managers must actively design the project system for resilience by reducing excessive coupling where possible, strengthening interface governance, and monitoring interaction-driven early warning signals. Scope governance should also evolve from strict scope freeze assumptions toward controlled adaptability, recognizing that scope change is often a structural feature of megaprojects rather than a managerial failure. Additionally, stakeholder governance should be treated as a system function that stabilizes legitimacy, reduces decision latency, and prevents late-stage requirement renegotiation that can destabilize tightly coupled integration sequences.

9.4. Closing Statement

Ultimately, megaproject success and failure are not fully explained by isolated risk events or by the competence of individual actors. Rather, outcomes emerge from the dynamic interaction of uncertainty, interdependencies, institutional environments, and governance capacity. By reframing megaprojects as complex adaptive systems, the MUIE framework provides a structured conceptual foundation for both scholarly research and practical intervention. Future work testing and refining the framework can support improved theory development and contribute to more resilient delivery approaches in some of the most consequential project environments in contemporary society.

Disclosure of AI and Digital Tools Used

This manuscript was finalized with the assistance of standard digital and AI-enabled tools used for routine text preparation. No AI system was used to generate, expand, or create the conceptual, theoretical, or analytical contributions of the paper, which remain entirely the author’s own work.

10.References

Flyvbjerg, B. (2009). Optimism and Misrepresentation in Early Project Development. In: Williams, T.M., Samset, K., Sunnevåg, K.J. (eds) Making Essential Choices with Scant Information. Palgrave Macmillan, London. https://doi.org/10.1057/9780230236837_8

Flyvbjerg, B. (2014). What you should know about megaprojects and why: An overview. *Project Management Journal, 45*(2), 6–19. https://doi.org/10.1002/pmj.21409

Kahneman, D., & Lovallo, D. (1993). Timid Choices and Bold Forecasts: A Cognitive Perspective on Risk Taking. *Management Science*, *39*(1), 17–31. http://www.jstor.org/stable/2661517

Nair, A., & Reed-Tsochas, F. (2019). Revisiting the complex adaptive systems paradigm: Leading perspectives for researching operations and supply chain management issues. *Journal of Operations Management, 65*(2), 80–92. https://doi.org/10.1002/joom.1022

Park, J. E. (2021). *Cost overruns and schedule delays of major projects: Why we need reference class forecasting* (Doctoral dissertation, Columbia University). https://doi.org/10.7916/d8-9cn7-c433

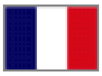
Sheffield, J., Sankaran, S., & Haslett, T. (2012). Systems thinking: Taming complexity in project management. *On the Horizon, 20*(2), 126–136. https://doi.org/10.1108/10748121211235787

Williams, T. (2002). *Modelling complex projects*. Wiley.

About the Author

Prof. Dr. M. F. HARAKE

Bordeaux, France



Prof. Dr. M. F. HARAKE is a management professor based in France. He currently serves as the Assistant General Manager and Dean of Academic Affairs at MESOS Business School (France). In addition, he is the Manager of the Research Center at GBSB Global Business School (Malta). He is also affiliated as an Associate Research Fellow at the CEREGE Research Laboratory, University of Poitiers (France). Prof. Harake's research interests include Post-Conflict Public Management, Crisis and Urgent Operations Management, Humanitarian Logistics, and Project Management in Unstable Environments. His academic and professional contributions focus on bridging strategic theory with high-impact practical execution, especially in volatile and complex contexts.

He can be contacted at mfharake@mesos-bs.com