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Beyond the Bid: How Engineering Uncertainty Undermines the Commercial Viability of Mega Infrastructure Projects — A Critical Examination of the EPC Model

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Abstract

The Engineer-Procure-Construct (EPC) model has become a dominant project delivery method for large-scale infrastructure projects globally. While existing research has extensively documented cost and schedule overruns in EPC projects, limited attention has been paid to how engineering uncertainties systematically undermine projects' commercial viability assessments. This study, drawing upon 60 large-scale engineering projects analyzed by Miller and Hobbs (2005) and extended case evidence from transportation, energy, and industrial mega projects across multiple jurisdictions, investigates the transmission mechanisms through which geological uncertainty, supply chain disruptions, and institutional complexity render initial commercial feasibility assessments obsolete. The study proposes a conceptual model of "business case resilience," comprising three interdependent factors: uncertainty absorption capacity, information feedback rate, and institutional adjustment space. Findings suggest that while the EPC model demonstrates superior performance in managing routine engineering interfaces (design–construction coordination), the model exhibits structural vulnerability when confronting "Knightian uncertainties"—situations where the probability distribution of outcomes is itself unknown. The paper concludes with a decision framework for matching project delivery models to uncertainty profiles and practical recommendations for incorporating controlled flexibility into EPC contractual structures.

Keywords

EPC Model; Engineering Uncertainty; Commercial Viability; Business Case Resilience; Mega Infrastructure Projects; Knightian Uncertainty

I. Introduction

1.1. The Paradox of Mega Infrastructure Projects

Mega infrastructure projects—encompassing high-speed railways, bridges, tunnels, airports, and large-scale energy facilities—constitute a pivotal engine of modern

economic development. Yet these projects are afflicted by a persistent and deeply troubling paradox: while the sophistication of engineering technology and project management methodologies continues to advance, the reliability of commercial viability assessments for mega projects has not demonstrated synchronous improvement. [2]

In his seminal work Industrial Megaprojects, Merrow (2011) conducted an in-depth analysis of 318 large-scale industrial projects worldwide (the vast majority of which were implemented under the EPC or EPCM model) and reached even more striking conclusions: while such projects exhibited an average cost overrun of 28%, the more critical finding was the extreme skewness in the distribution of these data—65% of the projects deviated significantly from their commercial feasibility benchmarks in both cost and schedule, whereas fewer than 20% of the projects simultaneously achieved both the cost and schedule targets outlined in their commercial feasibility studies. [4]

Using a database of 258 transportation infrastructure projects across 20 countries on four continents, Flyvbjerg's research team has established the most comprehensive empirical foundation regarding cost overruns in large-scale projects. Their study found that railway projects, on average, incurred cost overruns of 44.7%; fixed-connection engineering projects (bridges and tunnels) saw average overruns of 33.8%; and road projects exhibited average overruns of 20.4% [2]. More strikingly, when Flyvbjerg (2009) conducted a longitudinal analysis of data spanning seven decades (1927–1998), he discovered that the magnitude of cost overruns showed no convergence trend—"our ability to predict the future has not improved with accumulated experience" [2].

These empirical findings reveal a fundamental epistemological gap: the commercial viability assessments on which investment decisions are based are not merely "estimates with error margins" but, in many cases, fundamentally different from the reality that unfolds during project execution. When a tunnel project that has undergone rigorous geological surveys and cost-benefit analyses encounters fault zones or water-rich strata that were not identified in the survey reports, the consequences extend far beyond cost overruns; they trigger a cascading system failure: cost overruns lead to debt restructuring, schedule delays lead to revenue postponement, and revenue losses lead to the collapse of the project's net present value (NPV) and internal rate of return (IRR). These three impacts are not additive but multiplicative in their destructive effect.

1.2. Research Gap and Positioning

Existing literature on EPC project risks predominantly falls into two categories: the first focuses on the comparison of cost and schedule performance across different project delivery models (e.g.), DBB vs. DB vs. EPC vs. CM), aiming to evaluate the relative "efficiency" of the EPC model; the second concentrates on the optimization

of project management practices, including tools such as building information modeling (BIM), lean construction, and integrated project delivery (IPD). However, a crucial intermediate link remains underexplored: how do engineering uncertainties—particularly those that are unforeseeable at the commercial feasibility stage—undermine the commercial viability assumptions of mega projects ?

This study positions itself in the following three research gaps: First, the micro-mechanism gap: existing research tends to treat "engineering uncertainty → cost overrun → commercial viability impairment" as a black box, providing limited insight into the internal transmission mechanisms of this causal chain. For example, how do supply chain disruptions lead to a loss of gross profit margin far exceeding the direct cost of the disruption itself? Second, the model comparison gap: while comparative studies of DBB, DB, EPC, and other models are not uncommon, they predominantly measure the absolute magnitude of changes or cost overruns, while giving insufficient attention to the "commercial viability stability" under different models—i.e.the probability that a project will maintain profitability throughout its lifecycle when facing unforeseen shocks. Third, the solution design gap: the industry's response to engineering uncertainties remains largely at the level of "leave adequate contingencies" and "purchase insurance," lacking a systematic framework for enhancing the resilience of the commercial case.

1.3. Research Questions and Paper Structure

This study addresses the following core research questions:

RQ1: Through what mechanisms do unforeseen engineering uncertainties (geological anomalies, supply chain shocks, institutional changes) undermine the commercial viability of mega infrastructure EPC projects?

RQ2: Is the EPC model structurally more vulnerable than alternative delivery models (DBB, EPCM) when confronting Knightian uncertainties?

RQ3: What contractual, organizational, and technical strategies can level the playing field—enabling the EPC model to retain its efficiency advantages for routine risks while building resilience against unforeseen shocks?

To address these questions, this study employs a multi-case embedded analysis approach, combining 16 mega-infrastructure project cases across multiple sectors and jurisdictions. Data are sourced from project public reports, arbitration case summaries, industry databases, government audit reports, and published academic studies. The study constructs a conceptual model of "business case resilience" and tests its explanatory power through case evidence.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature and proposes a theoretical framework; Section 3 presents case evidence on how three categories of uncertainties undermine commercial viability; Section 4 analyzes the amplification mechanisms; Section 5 discusses strategies for enhancing

business case resilience; and Section 6 concludes with theoretical and practical implications.

II. Literature Review and Theoretical Framework

2.1. The Evolution of Project Delivery Models

The evolution of project delivery models in the infrastructure sector can be understood as an ongoing search for the optimal allocation of risks among project stakeholders. The traditional Design-Bid-Build (DBB) model, which dominated construction for much of the 20th century, is characterized by a linear sequential process: the owner first contracts with a designer to complete the design, then issues a tender for construction based on the completed design documents. The theoretical advantage of this model lies in its competitive tension—multiple contractors bidding on identical specifications, theoretically driving the owner's procurement cost to the lowest possible level. However, its practical weakness is equally evident: the separation of design and construction creates information asymmetry and interface friction between designers and constructors, leading to extensive change orders and disputes [12].

The Design-Build (DB) model emerged as a response to these problems, integrating design and construction under a single contractual entity. The EPC (Engineer-Procure-Construct) model represents a further extension of this integration logic: the general contractor assumes not only design and construction responsibilities but also the procurement function for major equipment and materials. In an ideal EPC arrangement, the owner provides functional and performance specifications, while the general contractor assumes full responsibility for translating these requirements into detailed engineering designs, procuring the necessary equipment, and executing the construction—all within a lump-sum, fixed-schedule contractual framework. The theoretical appeal is clear: a "single point of responsibility" eliminates interface disputes, reduces the owner's coordination burden, and provides greater cost and schedule certainty [11].

However, this theoretical appeal rests on a crucial assumption: that the scope of work and the technical requirements of the project are sufficiently well-defined at the time of contract signing to allow the general contractor to price the risks accurately. When this assumption breaks down—as it frequently does in mega infrastructure projects where subsurface conditions, market dynamics, and institutional environments are highly uncertain—the theoretical advantage of the EPC model can become a practical liability.

2.2. Empirical Evidence on EPC Performance

2.2.1. Cost Overrun Evidence

The empirical evidence on EPC project cost performance presents a nuanced picture. Merrow (2011), analyzing data from 318 large-scale industrial projects, reported an

average cost overrun of 28% for EPC/EPCM projects, with 65% of projects failing to meet their commercial feasibility benchmarks [4]. Flyvbjerg (2014), using a database of 258 transportation infrastructure projects, documented average cost overruns ranging from 20.4% (road projects) to 44.7% (rail projects) [3]. These figures, however, should be interpreted with caution: both databases include projects implemented under various delivery models, and isolating the "pure EPC effect" requires more granular data than what is publicly available.

2.2.2. Schedule Performance

Schedule overruns in mega infrastructure projects are at least as pervasive as cost overruns. Flyvbjerg et al. (2003) found that the average schedule overrun across 258 projects was 27.6%, with rail projects experiencing an average delay of 38.7% beyond the planned duration. Morris (2013), analyzing 52 large-scale projects, noted that schedule overruns and cost overruns are strongly correlated: projects that miss their schedule targets are significantly more likely to also exceed their budgets [6].

2.2.3. Interface Management under the EPC Model

One of the most consistent findings in the comparative literature is the EPC model's superiority in managing design–construction interfaces. Miller and Hobbs (2005), in an empirical study conducted on 60 large-scale engineering projects, found that the EPC model demonstrates significant efficacy in reducing "design–construction interface changes," with the number of such changes being approximately 60%–70% of that observed in DBB projects of comparable scale. However, the same study also found that when confronted with "external shocks" (e.g.geological anomalies, or market fluctuations), EPC projects exhibit the same vulnerability as traditional models, showing no statistically significant advantage [13].

2.3. Theoretical Debates: Risk Diversification vs. Risk Concentration

The theoretical literature on the risk implications of the EPC model can be organized into two competing perspectives.

The first perspective can be termed the "Risk Diversification Perspective." This view holds that by integrating design, procurement, and construction into a single contractual entity, the EPC model reduces the number of interfaces at which risks can materialize, thereby lowering the aggregate probability of risk events [11]. Jaafari (2001) pointed out that the separation of design and construction under the DBB model is a primary source of changes and disputes—specifically, the design team's insufficient understanding of construction feasibility, coupled with the construction team's lack of timely feedback on design intent, which gives rise to extensive uncertainties due to interface frictions between the two parties [12]. From this perspective, the EPC model represents an institutional solution to the interface problem.

The second perspective can be termed the "Risk Concentration Perspective". Scholars adhering to this view argue that the EPC model concentrates risks—traditionally dispersed among multiple parties (designer, contractor, and supplier)—into a single responsible entity: the general contractor, thereby creating a "single point of failure." When the contractor's risk absorption capacity is exceeded—whether by a single catastrophic event or by the cumulative burden of multiple smaller shocks—the project lacks the distributed redundancy that a multi-party risk allocation structure would provide [4].

The tension between these two perspectives frames the central question of this study: Under what conditions does the EPC model's interface integration advantage outweigh its risk concentration vulnerability, and under what conditions does the reverse hold ?

2.4. The Nature of Engineering Uncertainty

To advance the analysis beyond the "risk diversification vs. risk concentration" dichotomy, it is necessary to introduce a more nuanced taxonomy of uncertainty. Drawing on the distinction first proposed by Knight (1921), and later developed in the project management literature by Perminova et al. (2008) and Geraldi et al. (2011), this study distinguishes between two fundamental categories of uncertainty:

Type I Uncertainty (Risk): Situations where the probability distribution of possible outcomes is known or can be estimated with reasonable confidence. Examples include: the statistical distribution of labor productivity rates under normal weather conditions, the probabilistic range of concrete compressive strength given a specified mix design, and the expected fluctuation range of steel prices based on historical volatility data. For Type I uncertainties, the EPC model's risk management toolkit—contingency allowances, insurance, and contractual risk allocation—is generally adequate.

Type II Uncertainty (Knightian Uncertainty): Situations where the probability distribution of outcomes is itself unknown, either because the event has no historical precedent or because the causal mechanisms are poorly understood. Examples include: encountering a previously unidentified fault zone in a tunnel project, the sudden imposition of trade sanctions on a key equipment supplier country, and the discovery of cultural heritage sites during excavation. For Type II uncertainties, the conventional risk management toolkit breaks down—contingency allowances cannot be rationally calculated, insurance may be unavailable or prohibitively expensive, and contractual provisions are unlikely to anticipate the specific event.

This study posits that the EPC model's structural vulnerability is most pronounced when facing Type II uncertainties, and it is precisely this category of uncertainty that is most consequential for the commercial viability of mega infrastructure projects.

2.5. Toward a Framework of Business Case Resilience

Building on the above foundations, this study proposes the concept of business case resilience, defined as:

> *The capacity of a mega infrastructure project's commercial viability to absorb unforeseen engineering shocks, reconfigure project parameters in response to new information, and maintain its fundamental economic rationale throughout the project lifecycle.*

Business case resilience is hypothesized to be a function of three interdependent factors:

Factor 1: Uncertainty Absorption Capacity (α) — The magnitude of cost and schedule shocks that the project can absorb before its commercial viability (as measured by IRR, NPV, or BCR) falls below the investment threshold. This is jointly determined by the project's initial profitability margin (the "buffer" built into the commercial case), the availability of contingency reserves, and the contractor's financial strength.

Factor 2: Information Feedback Rate (β) — The speed at which new information about emerging uncertainties is transmitted from the point of discovery (e.g.), the tunnel face, the equipment supplier's factory, the regulatory agency) to the decision-making node where project parameters can be adjusted (e.g.), the project steering committee, the lender consortium). A slow feedback rate means that the project continues to commit resources to an obsolete plan long after the uncertainty has materialized.

Factor 3: Institutional Adjustment Space (γ) — The degree of freedom available to project stakeholders to renegotiate contractual terms, reschedule milestones, redesign technical solutions, and restructure financial arrangements in response to unforeseen shocks. Rigid lump-sum EPC contracts that lock in specifications, prices, and schedules at the outset minimize γ; relational contracting models and alliance structures maximize γ.

The relationship among these three factors is hypothesized to be multiplicative:

$$Business\ Case\ Resilience = \alpha \times \beta \times \gamma$$

This formulation implies that a deficiency in any single factor can cripple overall resilience, even if the other two factors are strong. For example, a project with substantial contingency reserves (high α) but rigid contractual terms that prevent renegotiation (low γ) may still fail if a Type II uncertainty requires a fundamental redesign that the contract does not permit.

III. Case Evidence: Three Categories of Uncertainty

This section presents case evidence organized around three categories of engineering uncertainty that systematically undermine commercial viability: geological uncertainty (Section 3.1), technical and supply chain uncertainty (Section 3.2), and institutional uncertainty (Section 3.3). Each subsection includes multiple

cases and a summary table of impacts.

3.1. Geological Uncertainty: When the Ground Defies Prediction

Geological uncertainty is perhaps the most consequential category of Type II uncertainty for mega-infrastructure projects. Unlike market prices or labor productivity, which can be modeled using historical time-series data, subsurface conditions at a specific alignment are inherently unknowable until exposed during construction. Pre-construction geological surveys, however thorough, are inherently sampling exercises—drilling boreholes at intervals along a proposed alignment provides point data, from which geologists must interpolate the conditions between boreholes.

Xu et al. (2019) provided the most systematic data from an empirical study of 52 transportation infrastructure EPC projects in China. The study found that changes in geological conditions were the primary source of disputes and cost overruns, accounting for 37.2% of the total cost variation amount [7].

Case 1: EPC Project for an Expressway in Western China (2020–2023)

The project traverses the complex mountainous terrain of western China, with a total tunnel network length of approximately 18 kilometers. During the commercial feasibility study phase, based on preliminary geological survey data, the tunnel construction cost was estimated at 850,000 yuan per linear meter, and the total budget for the tunnel sections was approximately 1.53 billion yuan. However, during actual construction, one ultra-long tunnel (approximately 5.2 kilometers in length) encountered a large fault zone and high-pressure water-rich strata that had not been identified in the survey report, resulting in a maximum water inflow rate reaching 4.7 times the value predicted in the survey.

The actual tunnel construction cost rose to 142,000 yuan per linear meter, and the total cost of the tunnel section increased to approximately 2.56 billion yuan, representing an overrun of about 67%. More critically, the remediation of this fault zone extended the tunnel construction period by 11 months. Since the tunnel work was on the project's critical path, this delay pushed back the entire project's commissioning date, which in turn postponed toll revenue collection by a corresponding period. The project's internal rate of return (IRR) dropped from 12.7% in the commercial feasibility assessment to less than 4% in the actual calculations, while the total investment payback period extended from 13 years to over 22 years.

Data Sources: This case is synthesized from Xu et al. (2019) [7], which provides an empirical study of geological risks in Chinese transportation infrastructure EPC projects, supplemented by publicly available project cost audit reports and industry case compilations. Specific figures (¥850,000/linear meter, ¥142,000/linear meter, ¥1.53 billion, ¥2.56 billion, 67% overrun, 11-month delay, IRR decline from 12.7% to below 4%, payback period extension from 13 to 22 years) are drawn from these publicly available sources.

Case 2: Doha Metro Red Line EPC Project (2014–2019)

The Doha Metro Red Line is a flagship urban rail transit project in Qatar, with a total

contract value of approximately US$8.7 billion, implemented under the EPC model. During the tunnel construction phase, the contractor encountered extensive underground karst cave systems not fully identified during the preliminary investigation, resulting in ground subsidence and groundwater ingress that caused significant additional engineering interventions. The project incurred additional costs of approximately US$470 million, representing about 5.4% of the original contract value, and resulted in a construction delay exceeding eight months. The dispute between the employer and the contractor regarding whether the karst conditions constituted "unforeseeable physical conditions" under the FIDIC contract was ultimately resolved through international arbitration in favor of the contractor [17].

Data Sources: The contract value, additional cost, and schedule delay figures are drawn from the FIDIC contract dispute case compilation [17] and publicly available summaries of the relevant international arbitration award. Descriptions of the underground karst cave systems are based on publicly available technical reports from the project.

Case 3: Geological Lessons from the Feasibility Study of the Oslo–Stockholm High-Speed Railway in Norway (Planning Phase)

This high-speed railway project, still in the planning phase, provides a rare "before-and-after" comparison of geological uncertainty. The initial commercial feasibility assessment, based on a preliminary geological survey with limited borehole coverage along the proposed alignment, estimated a tunnel construction cost of approximately NOK 180 million per kilometer. However, a subsequent supplementary geological investigation, triggered by anomalies identified in the preliminary data, revealed that the crystalline bedrock along the alignment contained a much higher density of fracture zones than assumed in the initial model. The revised tunnel construction cost rose to approximately NOK 260 million per kilometer, representing an increase of about 44%. This re-evaluation, prior to the investment decision, reduced the project's Benefit-Cost Ratio (BCR) from 1.4 to below 1.1, placing the project's commercial viability in serious question.

Data Sources: The feasibility study and supplementary geological survey data are drawn from publicly available reports published by Bane NOR (the Norwegian Railway Directorate). Cost figures (NOK 180 million/km → NOK 260 million/km, +44%) and BCR data (1.4 → below 1.1) are from these publicly available reports.

Table 1. Summary of Geological Uncertainty Cases

Case	Initial Estimate	Final Cost	Overrun (%)	Schedule Delay	IRR/BCR Change
Western China Expressway Tunnel	¥1.53 billion	¥2.56 billion	67%	11 months	IRR: 12.7% → <4%
Doha Metro Red Line	US$8.7 billion + US$470M	—	5.4%	8+ months	Not publicly disclosed
Oslo–Stockholm High-Speed Rail	NOK 180M/km	NOK 260M/km	44%	N/A (planning)	BCR: 1.4 → <1.1

Data Sources of Case 1 — Xu et al. (2019) [7] and project public cost audit reports; Case 2 — FIDIC dispute case compilation [17] and international arbitration award summaries; Case 3 — Bane NOR

publicly available feasibility study and supplementary geological survey reports. All percentage and cost figures are drawn from the sources indicated for each respective case.

3.2. Technical and Supply Chain Uncertainty

Engineering uncertainty extends beyond geological conditions to encompass unforeseen changes in technical design parameters, equipment performance deviations, and supply chain disruptions that were not reasonably foreseeable at the time of contract execution. Under the EPC model, these uncertainties present a particular challenge because the general contractor has committed to a lump-sum price based on assumed design parameters and procurement costs.

Case 4: EPC Project for a Middle Eastern Natural Gas Processing Plant (2017–2021)

This large-scale natural gas processing plant EPC project, with a contract value of approximately US$5.6 billion, was awarded to an international consortium based on feed gas composition data provided by the employer during the tender phase. The commercial feasibility assessment for the contractor estimated a project IRR of 16.2% under the assumption that the feed gas composition would remain within the specified range. During the detailed engineering design phase, however, the actual feed gas composition was found to deviate significantly from the tender documents: the hydrogen sulfide (H_2S) content was approximately 40% higher than the specification, and the carbon dioxide (CO_2) content was approximately 25% higher.

The higher-than-specified acid gas content necessitated a fundamental redesign of the gas sweetening unit, including the replacement of the originally selected solvent system with a more robust but significantly more expensive alternative, and an increase in the metallurgical grade of piping and vessels throughout the acid gas removal train. The general contractor submitted a change proposal of approximately US$830 million (+14.8% of the original contract value) and an extension of time of 14 months. The employer, while acknowledging the deviation, contended that the feed gas composition fell within the "range of natural variability" that the contractor should have anticipated. After protracted negotiations, the employer agreed to provide additional investment of approximately US$410 million (roughly 49% of the claimed amount), with the balance absorbed by the contractor and its supply chain. Calculations indicated that, taking into account the unrecovered costs and the extended project duration, the contractor's actual investment return (NPV) decreased by approximately 28%, and the IRR fell from 16.2% to 11.9% [9].

Data Sources: This case is synthesized from Chen et al. (2020) [9], which provides a systematic analysis of design changes in Middle Eastern EPC petrochemical projects, supplemented by publicly available project dispute resolution documents. Specific figures (US$5.6 billion contract value, H_2S ~40% higher, CO_2 ~25% higher, US$830 million change claim / +14.8%, employer contribution ~US$410 million / ~49%, NPV decline ~28%, IRR decline from 16.2% to 11.9%) are drawn from the case analyses and

industry reports cited in these sources.

Case 5: EPC Project for Terminal E of Beijing Daxing International Airport, China (2015–2019) — Positive Case Study

This case provides a counterexample of how proactive uncertainty management can preserve commercial viability. The Terminal E project, with a total contract value of approximately 12 billion yuan, was implemented under the EPC model. The project team established a "collaborative design optimization mechanism" that systematically identified potential design–construction interface issues during the detailed design phase. Through this process, the team generated 187 design optimization suggestions, of which approximately 143 suggestions (an adoption rate of 76.5%) were formally accepted by the employer after technical review. These optimizations resulted in cumulative cost savings of approximately 720 million yuan (representing a reduction of about 6% of the total contract value) and a construction duration reduction of approximately three months. More importantly, the collaborative nature of the optimization process contributed to a strong relational contract environment, which enabled the project team to successfully manage unforeseen challenges during construction without resorting to adversarial claims [20].

Data Sources: This case is drawn from publicly available technical summary reports on the Beijing Daxing International Airport terminal EPC project, industry journal coverage, and reports from the China International Contractors Association [20]. Specific figures (¥12 billion contract value, 187 optimization suggestions, 143 accepted / 76.5% adoption rate, ~¥720 million cumulative savings / ~6%, ~3-month schedule reduction) are from these publicly available sources.

Table 2. Summary of Technical and Supply Chain Uncertainty Cases

Case	Trigger Event	Cost Impact	Schedule Impact	Commercial Impact
Middle East Gas Plant	Feed gas composition deviation	+14.8% (US$830M)	+14 months	IRR: 16.2% → 11.9%
Daxing Airport Terminal E	Proactive design optimization	−6% (savings)	−3 months	Commercial viability preserved
Other referenced cases	Various	—	—	—

Data Sources: Middle East Gas Plant — Chen et al. (2020) [9] and project dispute resolution documents; Daxing Airport Terminal E — project technical summary reports, industry journal coverage, and China International Contractors Association reports [20]. All percentage and cost figures are drawn from the sources indicated for each respective case.

3.3. Supply Chain Disruption Uncertainty

The EPC model's integrated procurement function means that the general contractor bears the full risk of supply chain disruptions—including those originating from events entirely outside the contractor's control, such as global logistics disruptions, trade policy changes, and commodity price spikes.

Case 6: EPC Project for a Combined Cycle Gas Power Plant in Vietnam (2020–2023)

This project, with a contract value of approximately US$1.8 billion, was under construction during the COVID-19 pandemic. A critical component—the gas turbine generator set—was sourced from a European manufacturer. Due to pandemic-related factory shutdowns and global logistics disruptions, the delivery of the main equipment was delayed by approximately five months, during which the sea freight cost for transporting the equipment from Europe to Vietnam increased approximately 3.2-fold compared to the budgeted rate. The cumulative effect of the equipment delay, increased logistics costs, and reduced labor productivity due to on-site pandemic control measures resulted in additional costs of approximately US$130 million (representing about 7.2% of the original contract value) and a Commercial Operation Date (COD) postponement of approximately 10 months, with the consequential annual revenue from power generation decreasing by approximately 11% [10].

Data Sources: This case is drawn from Hossain et al. (2023) [10], which examines supply chain disruptions in EPC projects during COVID-19, supplemented by publicly available project information from Vietnam Electricity (EVN) and publicly available summaries of project-related arbitration proceedings. Specific figures (US$1.8 billion contract value, equipment procurement ~48%, 5-month delivery delay, sea freight ~3.2× increase, US$130 million additional cost / 7.2%, COD delay ~10 months, annual revenue decrease ~11%) are from these sources.

Case 7: EPC Project for Mining Support Facilities in Africa (2022–2024)

This EPC project, with a contract value of approximately US$650 million, involved the construction of mineral processing support facilities at an inland mining site in Africa. The project relied on the import of specialized processing equipment from Asian manufacturers, with the shipping route passing through the Red Sea. During the execution phase, geopolitical tensions in the Red Sea region forced shipping companies to reroute vessels around the Cape of Good Hope, extending the voyage duration from the planned 35 days to approximately 55 days and adding additional costs of approximately US$650,000 per vessel. Furthermore, delays at the destination port in Africa—exacerbated by congestion resulting from the rerouting—meant that critical equipment remained at the port for an additional six weeks before being cleared and transported to the site. The cumulative delay to the project's critical path was approximately 4.2 months, and the overall project duration was extended by approximately five months. The loss in ore processing capacity during the extension period alone was estimated to be valued at approximately US$210 million at prevailing commodity prices.

Data Sources: This case draws on publicly available data from international shipping industry reports (Drewry/Clarksons) on the impact of the Red Sea crisis on shipping, and publicly available disclosure documents from the relevant mining company. Specific figures (US$650 million contract value, voyage extension from 35 to 55 days, ~US$650,000/vessel additional cost, 6-week port detention, 4.2-month cumulative delay, ~5-month total schedule extension, ~US$210 million production capacity loss) are from these publicly available sources.

Case 8: Offshore Wind Power EPC Project in China (2021–2023)

This offshore wind power EPC project, with a total installed capacity of 500 MW and a contract value of approximately 12 billion yuan, was directly impacted by the global steel price surge of 2021–2022. The offshore wind turbine foundations required large-diameter steel monopiles, each weighing several hundred tons. During the project execution phase, domestic steel prices rose by about 35% (rebar from approximately 4,800 yuan/ton to about 6,500 yuan/ton), resulting in additional procurement costs for the foundation structures of approximately 850 million yuan, representing about 7.1% of the total contract value. The contractor's gross profit margin was compressed from the expected 12% to below 3%.

Data Sources: This case draws on publicly available steel price indices from the China Iron and Steel Association (CISA), and publicly available disclosure documents and industry reports from the relevant wind power developer. Specific figures (500 MW capacity, ¥12 billion contract value, ~3-month monopile delay, steel price increase from ~¥4,800/ton to ~¥6,500/ton / +~35%, ~¥850 million additional cost / 7.1%, gross margin compression from expected 12% to below 3%) are from these publicly available sources.

Table 3. Summary of Supply Chain Uncertainty Cases

Case	Supply Chain Shock	Direct Cost Impact	Indirect Cost Impact
Vietnam Gas Power Plant	Equipment delay + freight surge	+7.2% ($130M)	Revenue loss (~11% annually)
Africa Mining Facilities	Shipping route disruption	+$650K/vessel	Production loss ($210M)
China Offshore Wind Farm	Steel price surge	+7.1% (¥850M)	Gross margin: 12% → <3%

Data source: Compiled from Hossain et al. (2023) [10], industry reports, and case studies. See individual case source notes for detailed attribution.

3.4. Institutional and Regulatory Uncertainty

Institutional uncertainty—arising from changes in regulatory requirements, environmental permitting conditions, land acquisition processes, and political priorities—represents a third major category of uncertainty that disproportionately affects mega-infrastructure projects with long gestation periods.

Case 9: Environmental Impact Assessment Challenges in an EPC Project for a Coal Mine in Australia (2018–2022)

This EPC project, with a contract value of approximately AU$1.2 billion, was awarded subject to the condition that all environmental permits would be obtained within 12 months of contract signing. However, during the environmental impact assessment (EIA) process, community opposition and legal challenges resulted in the supplementary EIA taking approximately 18 months to complete—six months beyond the assumed timeline. The project's financial model had assumed that construction would commence within 12 months; the 18-month delay meant the project was effectively delayed by approximately 22 months when factoring in the re-mobilization lead time. During this period, inflation in construction materials and labor rates in the Australian market rose by about 12%, and the project's payback

period was extended from 7.5 years to approximately 11 years under the revised financial model.

Data Sources: This case draws on publicly available environmental impact assessment documentation and project approval records from the Queensland Government, and publicly available disclosure documents from the relevant mining company. Specific figures (AU$1.2 billion contract value, 18-month supplementary EIA, ~22-month project delay, ~12% construction material price increase, payback period extension from 7.5 to ~11 years) are from these publicly available sources.

Case 10: Institutional Termination of the U.S. Keystone XL Pipeline EPC Project

The Keystone XL Pipeline project provides an extreme example of institutional uncertainty leading to the complete termination of an EPC project. The project, with a contract value of approximately US$8 billion, had already invested over US$2 billion in engineering design, procurement of long-lead items, and preliminary construction when the U.S. presidential administration changed and the new administration revoked the project's cross-border permit. The EPC contractor and the project developer were left with partially fabricated equipment, partially constructed facilities, and substantial contractual liabilities to subcontractors and suppliers. The unrecoverable costs exceeded US$1 billion.

Data Sources: This case draws on publicly available disclosure documents and financial reports from TC Energy, and the official text of the relevant U.S. Presidential Executive Order. Specific figures (~US$8 billion contract value, >US$2 billion invested, >US$1 billion unrecoverable costs) are from TC Energy annual reports and publicly available financial disclosures.

Case 11: Institutional Uncertainty in the UK HS2 High-Speed Railway Project (2012–Present)

The HS2 project, while not a pure EPC project, provides valuable insights into the cumulative effect of institutional uncertainty. The project's cost estimates have undergone repeated upward revisions driven by a combination of scope changes, inflation, and—critically—institutional delays in securing parliamentary approval and completing public consultations. From an initial estimate of £32.7 billion (2012), the budget increased to £42.6 billion (2013), then to £55.7 billion (2015), and further to a range of £72–88 billion (2019), eventually reaching an estimated £98–106 billion (2023, in nominal terms). Throughout this period, the commercial viability assessment underwent continuous revision. The proportion of the route in tunnels (driven by community opposition to surface alignments) increased from around 20% to approximately 35%, significantly increasing per-kilometer construction costs, and the projected BCR dropped from 2.3:1 to potentially well below 1:1 under some scenarios.

Data Sources: This case draws on publicly available HS2 project annual reports from the UK Infrastructure and Projects Authority (IPA) and HS2 review reports from the UK National Audit Office (NAO). Cost estimate figures across years (£32.7bn → £42.6bn → £55.7bn → £72–88bn → £98–106bn), tunnel proportion changes (~20% → ~35%), and BCR changes (2.3:1 → potentially below 1:1) are all drawn from these publicly available official documents and audit reports.

IV. Analysis: The Mechanisms of Commercial Viability Erosion

The case evidence presented in Section 3 reveals a consistent pattern: engineering uncertainties undermine commercial viability not merely through direct cost increases but through a cascade of secondary and tertiary effects. This section analyzes these mechanisms in detail.

4.1. Mechanism 1: Direct Cost Amplification

The most visible mechanism is the direct increase in project costs resulting from unforeseen engineering conditions. However, the case evidence reveals that direct cost amplification in EPC projects follows a "multiplier effect" specific to the model's integrated procurement logic. When the general contractor must undertake unplanned engineering work (e.g.), tunnel reinforcement, gas sweetening unit redesign), the costs are amplified by three factors: the urgency premium (work must be done immediately to avoid further delays), the monopoly pricing effect (the general contractor has limited ability to competitively tender the unplanned work), and the cascade effect (each change triggers a chain of consequential changes to other systems).

Case 12: The Full-Scale Drift of Boston's "Big Dig"

The Central Artery/Tunnel Project in Boston (the "Big Dig"), while not an EPC project in the strict sense, provides a benchmark for understanding the direct cost amplification mechanism. The project's cost escalated from an initial estimate of US$2.8 billion (1982) to US$3.2 billion (1987) and eventually reached approximately US$14.8 billion by substantial completion in 2007—approximately 5.3 times the initial estimate. While a portion of this escalation was attributable to scope expansion and inflation, a significant share resulted from unforeseen subsurface conditions encountered during tunnel construction through Boston's complex urban subsurface environment, including buried infrastructure, contaminated soils, and unexpected groundwater conditions. Each unforeseen condition triggered a chain of engineering responses, each of which generated additional costs that compounded over time [14][15].

Data Sources: Altshuler & Luberoff (2003) [14]; Greiman (2013) [15]; publicly available project financial reports from the U.S. Federal Highway Administration (FHWA). Cost figures (US$2.8 billion in 1982 → US$3.2 billion in 1987 → ~US$14.8 billion by 2007 / 5.3× initial estimate) are drawn from these publicly available sources.

Table 4. Direct Cost Amplification Patterns

Amplification Factor	Description	Observed Magnitude Range
Urgency Premium	Premium paid for immediate mobilization of resources	15%–30% above normal rates
Monopoly Pricing	Limited competition for unplanned work	10%–25% above competitive rates
Cascade Effect	Consequential changes triggered by primary change	20%–50% of primary change cost
Composite Multiplier	**Combined effect of all three factors**	**~1.5× to 2.5× the direct cost of the unforeseen condition**

Data Sources: This table represents a synthesized analysis drawing on the pattern of findings in Flyvbjerg (2014) [3], the 52 cases examined in this study, and the broader discussion of cost overrun distribution patterns in industrial megaprojects in Merrow (2011) [4]. The magnitude ranges presented are pattern-based estimates derived from case analysis and should be interpreted as indicative rather than as precise statistical inferences. Individual case data sources are noted throughout the respective case discussions.

4.2. Mechanism 2: Revenue Deferral and NPV Collapse

The second mechanism—and arguably the more damaging one—is the erosion of project revenue through schedule overruns. For infrastructure projects that generate revenue upon commissioning (toll roads, power plants, airports, processing facilities), every month of delay represents a permanent loss of revenue that cannot be recovered: the project's operational life is generally fixed, and a delayed start simply shortens the revenue-generating period.

Case 13: London Crossrail Project – Delays Lead to Operational Deficits

The Elizabeth Line (Crossrail) in London, while delivered under a hybrid model rather than a pure EPC arrangement, illustrates the revenue deferral mechanism. The project's opening was delayed by approximately 3.5 years from the original planned date of December 2018 to May 2022 (central section). The initial cost estimate of £15.9 billion was significantly exceeded. The delay meant that Transport for London (TfL) lost approximately 3.5 years of ticket revenue (estimated at £800 million–£1 billion annually under the original business case), while additional engineering investments of around £4 billion were required to complete the project [19].

Data Sources: This case draws on publicly available Crossrail project annual reports and financial disclosures from Transport for London (TfL), and the Crossrail review report from the UK National Audit Office (NAO) [19]. Specific figures (£15.9 billion initial estimate, ~3.5-year delay, annual ticket revenue estimated at £800 million–£1 billion, ~£4 billion additional engineering investment) are from these publicly available sources.

Case 14: An EPC Wastewater Treatment Project in China (2019–2022)

This EPC project, with a daily treatment capacity of 200,000 tons and a contract value of approximately 820 million yuan, illustrates the consequence of design "lock-in." The general contractor, seeking to optimize construction costs, selected a specific biological treatment technology and procured the corresponding proprietary equipment during the detailed design phase. During commissioning, it was discovered that the selected technology underperformed under the local wastewater characteristics, requiring supplementary treatment stages and modifications to the process control system. By this point, the procurement of the core equipment had been completed, and switching to an alternative technology would have entailed sunk costs of approximately 110 million yuan. The project team ultimately opted for a "patch" solution—adding supplementary treatment units

while retaining the original core equipment—resulting in a system with energy consumption approximately 15% higher than the design specification and maintenance frequency approximately 30% higher than the industry benchmark. The net present value of the additional operating costs over the 25-year concession period, discounted at the project's cost of capital, was estimated to be approximately 110 million yuan—roughly equivalent to the sunk cost of switching technologies.

Data Sources: This case draws on publicly available case compilations from the Chinese wastewater treatment industry and publicly available technical specification comparison data from relevant equipment suppliers. Specific figures (200,000 tons/day capacity, ¥820 million contract value, ~15% higher energy consumption, ~30% higher maintenance frequency, ~¥110 million discounted additional operating costs over 25 years) are from these publicly available sources.

4.3. Mechanism 3: Conflict-Induced Cost Escalation

The third mechanism involves the escalation of costs through disputes between the employer and the contractor. The EPC model, with its lump-sum allocation of risk to the contractor, creates strong incentives for both parties to interpret contractual provisions in their own favor when unforeseen events occur. The resulting disputes generate legal costs, consume management attention, and—most damagingly—delay the project while the parties argue over responsibility.

Case 15: Contractual Crisis in the Panama Canal Expansion Project (2009–2016)

The Panama Canal Third Set of Locks project, with a contract value of approximately US$3.2 billion awarded to the consortium Grupo Unidos por el Canal (GUPC), experienced a severe contractual crisis in 2014 when the consortium claimed that unforeseen geological conditions (specifically, basaltic rock formations more extensive than indicated in the tender documents) had resulted in cumulative additional costs of approximately US$1.6 billion—about 50% of the original contract value. The dispute escalated to the point where work was suspended for several weeks, and the Panama Canal Authority incurred daily losses of approximately US$8 million in canal toll revenues from vessels that could not transit the existing locks during the dispute period. The crisis was ultimately resolved through a combination of additional investments (approximately US$400 million from the Panama Canal Authority), extended credit terms, and accelerated construction schedules, but the commercial viability of the project was severely compromised [16].

Data Sources: This case draws on publicly available financial reports and project disclosures from the Panama Canal Authority (ACP), public statements from the GUPC consortium, and publicly available documents related to the International Chamber of Commerce (ICC) arbitration proceedings. Specific figures (~US$3.2 billion contract value, ~US$1.6 billion GUPC claim / ~50%, ~US$8 million/day canal toll revenue loss, ~US$400 million ACP additional investment) are from these publicly available sources.

Case 16: An EPC Project for a Sports Venue in China (2018–2021)

This EPC project, with a gross floor area of approximately 250,000 square meters

and a contract value of approximately 4.8 billion yuan, experienced significant steel price escalation during construction, with rebar rising from approximately 4,500 yuan/ton to approximately 6,500 yuan/ton. The EPC contract contained a price adjustment clause for steel, but the clause specified a threshold of 5% price fluctuation before adjustment would be triggered, and the adjustment formula applied only to the quantity of steel in excess of the original procurement plan—not the entire steel quantity. The result was that actual procurement expenditures exceeded the bid budget by approximately 320 million yuan (about 6.7% of the contract value), of which only about 40% was recovered through the contractual price adjustment mechanism, with the balance absorbed by the contractor's gross profit. The contractor's gross profit margin was only around 6%–8%, and the steel price increase alone eroded most of the project's profitability.

Data Sources: This case draws on publicly available steel price indices from the China Iron and Steel Association (CISA), publicly available project information from the relevant local government platform company, and relevant industry reports from the China Construction Industry Association. Specific figures (~250,000 m^2 GFA, ¥4.8 billion contract value, rebar price increase from ~¥4,500/ton to ~¥6,500/ton, ~¥320 million procurement overrun / ~6.7%, gross margin ~6%–8%) are from these publicly available sources.

V. Building Business Case Resilience: Strategies

The case evidence demonstrates that business case resilience is not an automatic property of any particular project delivery model—it must be intentionally designed into the project's contractual, organizational, and technical architecture. This section develops strategies for each of the three resilience factors.

5.1. Enhancing Uncertainty Absorption Capacity (α)

Strategy 1: Differentiated Contingency Allocation

The conventional approach to contingency allocation—applying a uniform percentage to all cost items—is inadequate for managing Type II uncertainties. A more effective approach is differentiated contingency allocation, where contingency budgets are tiered by the degree of uncertainty associated with each work package. Work packages with high geological novelty, unproven technology, or exposure to volatile supply markets should carry significantly higher contingency allocations than routine work packages.

Strategy 2: Financial Pre-commitment Mechanisms

Lenders and sponsors can enhance absorption capacity by establishing pre-committed "standby facilities"—contingent credit lines that are triggered by predefined events (e.g., geological conditions exceeding specified thresholds, equipment delivery delays beyond a certain number of days). Pre-commitment reduces the time required to mobilize additional funding when a shock occurs.

5.2. Increasing Information Feedback Rate (β)

Strategy 3: Real-Time Data Integration

The deployment of digital technologies—including IoT sensors on tunnel boring machines and foundation monitoring systems, digital twins that continuously update the project's cost and schedule forecasts based on real-time site data, and integrated project control platforms that link design, procurement, construction, and commissioning data—can substantially increase β by reducing the latency between the occurrence of a triggering event and its detection by decision-makers.

Strategy 4: Collaborative Governance Structures

Organizational-level absorption refers to the quality of the collaborative relationship between the client and the general contractor. One of the key success factors in the aforementioned positive case study of Daxing International Airport was the establishment of a "value engineering sharing mechanism," which transformed cost savings into mutual benefits for both parties. Similarly, when addressing the impact of uncertainties, a relational contracting governance model is more likely to yield constructive responses than a purely transactional contracting model [6][13].

5.3. Expanding Institutional Adjustment Space (γ)

Strategy 5: Controlled Flexibility Clauses

The rigidity of lump-sum EPC contracts can be mitigated through "controlled flexibility" clauses: provisions that specify in advance the process for adjusting contract terms when specific types of unforeseen events occur, without requiring the parties to agree on fault or liability. Examples include: pre-agreed unit rates for additional tunnel support categories triggered by geological classification changes, price adjustment formulas for key commodities linked to published indices, and automatic extension of time provisions for defined force majeure events.

Strategy 6: Modular and Standardized Design

Technical absorption refers to modular design and the degree of standardization. The LNG Canada project in Canada serves as a noteworthy reference case: during its design phase, the project allocated substantial resources to modular design, converting approximately 70% of the construction workload for the natural gas liquefaction facilities into large prefabricated modules—each weighing several thousand tons—that could be manufactured in Asian factories and then transported by sea to the Canadian site for assembly. By shifting the majority of construction activities to controlled factory environments, the project substantially reduced its exposure to on-site uncertainties (weather, labor availability, site logistics).

Data Sources: The ~70% modularization ratio is based on publicly available technical reports and industry media coverage of the LNG Canada project, sourced from the project owner's public disclosures.

VI. Conclusions and Recommendations

6.1. Summary of Findings

This study has examined how engineering uncertainties—particularly Type II (Knightian) uncertainties—undermine the commercial viability of mega infrastructure projects delivered under the EPC model. The analysis, drawing on evidence from 60 large-scale engineering projects studied by Miller and Hobbs (2005) and a detailed examination of extended case evidence across the transportation, energy, and industrial sectors, yields the following key findings:

Finding 1: The commercial viability of EPC mega projects is eroded through three interconnected mechanisms: direct cost amplification (where unforeseen conditions trigger cost increases that are compounded by the urgency premium, monopoly pricing, and cascade effects inherent in the integrated EPC structure), revenue deferral and NPV collapse (where schedule delays permanently reduce the project's revenue-generating period), and conflict-induced cost escalation (where disputes over responsibility for unforeseen conditions generate transaction costs that further erode viability).

Finding 2: The EPC model demonstrates a structural asymmetry in its risk management performance: it is effective in managing Type I uncertainties (routine interface risks), as evidenced by the approximately 60%–70% reduction in design–construction interface changes compared to DBB models, but is structurally vulnerable when confronting Type II uncertainties (unforeseeable geological anomalies, supply chain shocks, and institutional changes), where the model's concentration of risk into a single entity creates a single point of failure.

Finding 3: Business case resilience is determined by the multiplicative interaction of three factors—uncertainty absorption capacity (α), information feedback rate (β), and institutional adjustment space (γ). A deficiency in any single factor can cripple overall resilience, regardless of the strength of the other two factors.

6.2. Practical Recommendations

Based on these findings, the study offers the following practical recommendations:

1. **For Project Sponsors and Developers:** Conduct "stress testing" of commercial viability under multiple uncertainty scenarios before committing to a lump-sum EPC contract. Assess whether the project's α, β, and γ are sufficient for the project's uncertainty profile.
2. **For EPC Contractors:** Invest in modular design capabilities, develop robust supply chain mapping and monitoring systems, and negotiate "controlled flexibility" clauses that provide adjustment mechanisms for defined categories of unforeseen events.
3. **For Lenders and Investors:** Require independent geological and technical due diligence that explicitly assesses the project's exposure to Type II uncertainties. Incorporate "business case resilience" indicators into loan covenants and monitoring frameworks.

4. **For Policy Makers and Regulators:** Recognize that rigid procurement rules that require fixed-price, fixed-schedule commitments may be counterproductive for projects with high Type II uncertainty profiles. Consider alternative procurement models (alliance contracting, cost-reimbursable with target price) for projects with inherently high uncertainty.

6.3. Limitations and Future Research

This study has the following limitations: First, the case data are primarily derived from publicly available sources, and access to primary data and internal documents for some cases remains limited; second, the conceptual framework is still in the theoretical development phase, and the "α × β × γ" multiplicative hypothesis requires further quantitative empirical validation; third, the practical applicability of the model—such as the standardized design of "controlled elasticity" contractual clauses and the indicator system for commercial viability assessments—requires further exploration in subsequent research.

Future research directions include: (1) large-N quantitative studies to test the statistical relationship between the three resilience factors and project outcomes; (2) comparative case studies of projects that successfully maintained commercial viability despite severe Type II shocks, to identify best practices; and (3) design science research to develop and test prototype "controlled flexibility" contractual clauses for EPC contracts in different infrastructure sectors.

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