Strategies for Balanced Risk Flow-Down in International Nuclear Power Plant Construction under Localization Requirements

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1. Introduction

The execution of international energy and nuclear megaprojects is currently not driven solely by criteria of economic efficiency and technological superiority. A fundamental, non-negotiable condition for construction in the contemporary global market is strict compliance with Local Content Requirements (LCRs). Governments in emerging and transitioning economies progressively condition the issuance of construction licenses, operating permits, and sovereign state guarantees on the primary contractor's commitment to involving domestic industry at a predefined percentage volume [1]. Consequently, the supply chains for these multi-billion-dollar projects are no longer formed purely on the basis of open-market competence and historical track records, but are instead heavily dictated by localized political and macroeconomic mandates.

For primary Engineering, Procurement, and Construction (EPC) contractors, this political directive necessitates abandoning a fully optimized, globally sourced supply chain. The pressure for maximum localization inherently conflicts with the core principle of risk management utilized in complex infrastructure projects. The standard paradigm for managing risk relies on Lump-Sum Turnkey (LSTK) contracts, typically governed by standardized frameworks such as the FIDIC Silver Book [2]. Under this regime, the primary contractor commits to delivering a fully functional facility by a predetermined date and with guaranteed performance parameters. To protect its own liquidity and achieve project bankability, the contractor systematically mirrors all assumed risks—including cost overruns, delays, and defects—down to the lower tiers of the supply chain through a strict back-to-back flow-down mechanism [3].

In new nuclear builds, the application of this strict flow-down principle encounters critical, systemic limits. Conventional construction risks are compounded by extreme technical complexity, strict Quality Assurance (QA) requirements (e.g., ASME NQA-1 or RCC-M standards), nuclear third-party liability channeling, and risks associated with regulatory interventions and changes in law during long construction periods [4]. When international corporate legal standards, which implicitly assume the strict transfer of these monumental risks, are mechanically applied to local companies in transitioning markets, the contractual system frequently collapses. Local suppliers objectively lack the capitalization, institutional maturity, and access to international reinsurance required to absorb massive Delay Liquidated Damages (DLDs) or bear the brunt of cross-liability interfaces [5].

This friction creates a critical "perception gap" on localized projects between the theoretical legal ideal of back-to-back risk allocation and the engineering and financial reality of the domestic supply chain. If the primary contractor insists on uncompromising risk flow-down, local entities either price the risk with an untenable premium (escalating the overall Capital Expenditure) or sign the contract only to face rapid insolvency at the first occurrence of a critical path delay. The industry currently lacks an empirically supported framework that defines how to mathematically and legally resolve this contractual imbalance. Therefore, this work-in-progress paper outlines a rigorous methodological framework designed to empirically evaluate this friction and proposes a quantitative approach to achieving an "Equivalent Balance" in the subcontracts of localized nuclear megaprojects.

2. Methods and Results

Empirical research in nuclear project management and mega-infrastructure contract analysis standardly encounters the "small-N" problem. Traditional quantitative statistical tools, such as multiple linear regression, require vast, homogeneous datasets to ensure statistical significance [6]. Such datasets do not exist in the highly specialized and confidential environment of nuclear EPC contracts. Furthermore, standard statistical methods often rely on isolating individual variables, failing to capture the reality that contractual provisions (e.g., liability caps and penalty carve-outs) do not operate in a vacuum, but rather function as deeply interconnected configurations.

To overcome these epistemological and practical limitations, this study employs Fuzzy-Set Qualitative Comparative Analysis (fsQCA). Grounded in set theory and Boolean algebra, fsQCA enables the rigorous examination of complex, asymmetric causal relationships within medium and small-sized expert samples [7]. It directly addresses the concept of equifinality—the premise that multiple distinct contractual configurations can lead to the same

outcome, such as maintaining supplier liquidity or triggering a critical failure.

2.1 Research Design, Scope Condition, and Variable Operationalization

The unit of analysis for this study is explicitly defined as the contractual interface (a specific work package) between an international EPC contractor and a local subcontractor, rather than the individual respondent. Given that the empirical focus is exclusively on projects mandated by strict localization requirements, intense Local Content Pressure (LCP) is treated as the defining scope condition for the population under study, rather than a varying causal condition. This restricts the truth table to a robust 2^3 analytical space appropriate for the realistic sample size.

The fsQCA model relies on three core causal conditions and one outcome variable (SCB):

- Perception Gap (PGAP): Operationalized strictly as the divergence in risk assessment between the two parties during the contract negotiation phase. To ensure methodological consistency, this delta is populated using paired responses (one Tier 2 and one Tier 3 respondent evaluating the identical interface). Where strict paired sampling is constrained by confidentiality, data is triangulated utilizing a single boundary-spanning respondent who evaluates each perspective separately.

- Technological Maturity (TECH): The local firm's demonstrable capability to implement strict nuclear QA standards without incurring disproportionate First-Of-A-Kind (FOAK) costs.

- Strict Liability Flow-Down (LIAB): The rigidity of risk transfer, measured by the mechanical mirroring of Overall Liability Caps and specific carve-outs (e.g., gross negligence) from the prime contract.

- Supply Chain Bottleneck (SCB - Outcome): To ensure conceptual independence from PGAP, the outcome variable is anchored strictly to documented project events (e.g., formal dispute escalation, critical path stoppage) rather than perceptual assessments.

2.2 Fuzzy-Set Calibration Protocol

The fundamental analytical step in fsQCA is the transformation of qualitative and quantitative survey data into calibrated fuzzy sets. Variables cannot be reduced to a simple dichotomy (0 or 1) because contractual friction exists on a spectrum. Therefore, the direct method of calibration is applied, utilizing external expert criteria to establish three qualitative anchor points: full membership (1.0), full non-membership (0.0), and the crossover point of maximum ambiguity (0.5) [8]. Table I demonstrates the calibration logic.

Table I: Operationalization and Fuzzy-Set Calibration Anchors

Causal Condition	Full Non-Membership (0.0)	Crossover Point (0.5)	Full Membership (1.0)
PGAP	Exact alignment in risk assessment between EPC and local Subcontractor	Subcontractor requires risk premiums exceeding nominal profit margins	Fundamental divergence in risk assessment during negotiation; formal objection to risk allocation
LIAB	Liability capped dynamically based on subcontractor's contract value	Full flow-down applied, but with mutual exclusions for consequential damages	Mechanical 100% flow-down of Owner-level limits without carve-outs
TECH	Conventional industrial standards only; no nuclear QA experience	Possession of QA certificates, but high FOAK costs expected during execution	Full compliance with ASME NQA-1/RCC-M with established track record
SCB	Smooth interface handover; delays absorbed by local float	Dispute escalation requiring commercial settlement (Near-miss)	Documented interface failure: critical path stoppage or mandatory EPC step-in required

2.3 Boolean Minimization and Directional Expectations

Following data calibration, each of the three causal conditions will be tested in isolation for necessity. The data will then be transformed into a Truth Table comprising eight (2^3) logically possible configurations. Utilizing Boolean algebra, where $(*)$ denotes logical AND, $(+)$ denotes logical OR, $(\sim)$ denotes negation, and $(\rightarrow)$ denotes sufficiency for the outcome, we anticipate two primary causal pathways leading to a Supply Chain Bottleneck (SCB):

$$\text{LIAB} * \sim \text{TECH} \rightarrow \text{SCB} \qquad (1)$$

The first pathway posits that rigid back-to-back (LIAB) imposed on a supply chain lacking technological maturity ($\sim$ TECH) is sufficient to trigger a documented interface failure, independently of initial risk perception.

$$\text{PGAP} * \text{LIAB} * \text{TECH} \rightarrow \text{SCB} \qquad (2)$$

The second pathway isolates the unique contribution of the perception gap. It expects that even when a local subcontractor possesses adequate technological maturity (TECH), a massive divergence in risk assessment at negotiation (PGAP) combined with uncompromising liability flow-down (LIAB) creates an unsustainable financial architecture. The subcontractor assumes risks it cannot realistically insure, inevitably leading to dispute escalation (SCB) once risks materialize.

To construct the final parsimonious model, the Quine-McCluskey minimization algorithm will process the truth table based on the empirical survey data. These two expressions minimize to LIAB $*$ ($\sim$ TECH + PGAP), indicating that rigid liability flow-down is the common denominator in both expected failure pathways. Given the asymmetric nature of set-theoretic causation, sufficiency will be analysed separately for SCB and for its negation ($\sim$ SCB); the latter defines the Equivalent Balance configurations sought by this study. Table II outlines all eight logically possible configurations representing these pathways.

Table II: Truth Table Directional Expectations

LIAB	PGAP	TECH	Expected SCB	Pathway Logic
1	1	0	1 (Fail)	Captures Expression (1)
1	1	1	1 (Fail)	Captures Expression (2)
1	0	0	1 (Fail)	Captures Expression (1)
1	0	1	0 (Pass)	Contrast against 1,1,1; shows independent contribution of PGAP
0	1	0	0 (Pass)	Relaxed liability acts as safety valve
0	1	1	0 (Pass)	Relaxed liability accommodates perception gap
0	0	0	0 (Pass)	Relaxed liability absorbs low technological maturity
0	0	1	0 (Pass)	Balanced flow-down, aligned perception

2.4 Methodological Limitations and Analytical Parameters

The reliance on a highly specialized expert sample inherently introduces limited diversity, resulting in logical remainders within the truth table. Given the anticipated small sample size ($N \approx 10 - 15$), the model enforces a strict frequency cutoff of 1. To mitigate common method bias, where cause and outcome might be reported by the same respondent, the calibration of the outcome (SCB) is strictly anchored to documented project events rather than subjective assessments.

The fsQCA minimization will be executed using the QCA package in the R environment. Robustness will be ensured by applying a consistency threshold of 0.85 and a Proportional Reduction in Inconsistency (PRI) of at least 0.75. Necessity will be evaluated using a

consistency threshold of 0.90, and the Relevance of Necessity (RON) metric will be utilized to filter out trivial necessary conditions [9]. In accordance with set-theoretic best practices, the study will report the conservative, intermediate, and parsimonious solutions to transparently display the treatment of counterfactuals.

3. Conclusions

Integrating a politically protected local market into the highly regulated environment of a nuclear megaproject encounters profound, systemic financial and capacity barriers. As argued in the preceding framework, the mechanical application of LSTK flow-down principles in such transitional environments does not result in the transfer of risk, but merely the illusion of it. Enforcing agreed-upon Liquidated Damages in a scenario where the local subcontractor lacks intrinsic liquidity and insurance coverage is functionally futile; the replacement costs, arbitration delays, and schedule acceleration efforts inevitably revert to the primary EPC contractor.

By utilizing fsQCA to structure qualitative legal contract analysis alongside quantitative engineering risk assessments, this ongoing research establishes an empirical baseline for defining "Equivalent Balance". The forthcoming finalized Boolean models will provide project owners and prime contractors with actionable, mathematically supported parameters for recalibrating subcontracts. This shift from rigid, dogmatic back-to-back contracting toward sustainable, context-aware risk governance is essential for securing the critical path and ensuring the successful delivery of localized nuclear megaprojects.

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