An Integrated Coordination Framework for Construction Procurement: Examining Early Supplier Involvement through Agent-Based Modeling

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A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2026

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Program Authorized to Offer Degree:
Construction Management

University of Washington

Abstract

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Construction projects rely on complex stakeholder networks, where coordination across design and construction phases is critical to performance. Despite decades of collaborative procurement frameworks, supplier expertise is integrated late in the design process, and the behavioral mechanisms linking procurement conditions to project outcomes remain poorly understood. This fragmentation generates coordination failures that manifest as rework, RFIs, constrained innovation, and declining workflow continuity. Existing literature examines procurement structures, stakeholder behavior, and project outcomes largely in isolation. Key drivers such as risk perception, supplier participation, and collaboration intensity are rarely formalized as measurable, dynamic variables throughout the project lifecycle. As a result, the mechanisms through which governance conditions and coordination timing jointly influence performance and innovation adoption remain unclear. This study examines how procurement structure, governance conditions, and stakeholder behavior interact within a dynamic system that shapes project performance. It develops and evaluates an Integrated Coordination Framework (ICF),

centered on a Central Coordination Agent (CCA), to structure early supplier engagement, compensation conditions, and coordination across the design lifecycle. A mixed-methods design integrates industry interviews with an agent-based simulation model in AnyLogic. Interview data were thematically coded and translated into agent decision rules through structured coding-to-model mapping. The model was evaluated using a four-stage validation framework: internal verification, expert-based mechanism validation, pattern validation, and quantitative benchmarking using the Wilcoxon signed-rank test. Four key findings emerge. First, procurement structure creates the conditions for improved performance, but governance influences whether those conditions translate into improved outcomes. Under ICF, projects achieved 75% innovation adoption, 80% fewer Requests for Information (RFIs), and stable capacity utilization (~88%), compared to 25% innovation adoption, full RFI accumulation, and declining capacity utilization (~75%) under fragmented procurement. Second, the Central Coordination Agent improves performance by shifting coordination and issue resolution upstream into the design phase, where conflicts can be addressed while decisions remain flexible. Under ICF, this earlier resolution process reduced RFI generation and stabilized construction workflow conditions. In contrast, low early redesign activity and limited RFI volume under typical procurement can create a false sense of effective coordination, as unresolved issues are deferred to later construction stages, where resolution becomes more disruptive, increases the volume of RFIs, and reduces available capacity. Third, GMP timing operates as a governance constraint rather than a coordination variable. Once GMP is established, behavior shifts from collaboration to cost protection, regardless of the quality of prior coordination. Fourth, the highest-impact lever lies in the middle governance layer, defined by three conditions: clear compensation for early engineering work, formalized supplier decision authority, and relational continuity across project portfolios. This study contributes to procurement governance and stakeholder coordination literature while providing foundational insights relevant to transaction cost economics in construction procurement. Methodologically, the study offers a replicable mixed-methods framework for examining procurement as a dynamic behavioral system. In practice, the simulation tool enables procurement managers to identify which governance parameters limit performance before coordination failures become visible, allowing targeted intervention at the root cause rather than a reactive response. More broadly, engaging supplier expertise early through structured coordination and supportive governance leads to more innovative outcomes and stronger long-term stakeholder relationships, and the Integrated Coordination Framework is designed to enable this opportunity.

This dissertation is dedicated to my parents, Dr. Snehal Fadnavis and Sunil Fadnavis, whose sacrifices, guidance, and unwavering belief in me made this journey possible.

It is also dedicated to my sister, Akanksha, for always standing by me and encouraging me to keep moving forward.

Finally, to my husband, Kaivalya, whose patience, strength, and calm reassurance carried me through every challenge.

Acknowledgements

I want to express my deepest gratitude to my Ph.D. advisor, Dr. Yong-Woo Kim, for his invaluable guidance, continuous support, and insightful feedback throughout this research. His mentorship has been instrumental in shaping my thinking and strengthening the quality of this work.

I am especially grateful to Prof. Giovanni Migliaccio, the Department Chair, for his mentorship in teaching and continued encouragement. I extend my sincere appreciation to my committee members, Dr. Shan Liu, Dr. Steve Muench, and Dr. Ken-Yu Lin. It has been a privilege to work with such a knowledgeable and supportive committee. I am especially grateful for your thoughtful feedback and for consistently challenging me to think more deeply, while always remaining approachable. I would also like to sincerely thank the staff and faculty in the Construction Management Department and the College of Built Environments for their support.

I want to acknowledge the organizations and industry partners who contributed to this research through case studies and valuable insights. Your collaboration and willingness to share practical knowledge greatly enhanced the work's real-world relevance.

I would also like to express my heartfelt gratitude to my family. I am grateful to my brother-in-law, Tejas, for always being supportive, and to my niece, Ruanshi, for bringing so much joy and lightness during this journey. I am deeply thankful to my father-in-law, Arun Deshpande, for his encouragement and constant presence throughout this journey. I also wish to honor and remember my late mother-in-law, Sarita Deshpande, whose blessings continue to guide me. To my friends in Seattle, who have become like family, thank you for your unwavering support and for the much-needed weekend parties that helped me pause, recharge, and keep going.

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Chapter 1 Introduction

This chapter presents the research background, the problem context, and the motivation for the study. Section 1.1 establishes the industry context and the persistent challenges in construction procurement. Section 1.2 identifies the specific coordination and integration challenges that motivate the research. Section 1.3 formalizes the problem statement, followed by the research gaps and questions in Section 1.4. Section 1.5 defines the research objectives, and Section 1.6 outlines the overall research approach. Section 1.7 describes the scope and limitations, and Section 1.8 presents the dissertation's organization.

1.1 Background and Industry Context

Construction projects rely on complex networks of stakeholders, including owners, designers, general contractors, specialty subcontractors, and material suppliers, whose decisions and interactions collectively shape project outcomes. Xue et al. (2010), Song et al. (2009), and, more recently, Evans and Farrell (2023) observe that, despite growing recognition of the importance of early integration, procurement practices in the construction industry have remained largely unchanged, with suppliers and specialty trades frequently engaged only after key design decisions have already been established.

While collaborative frameworks have advanced stakeholder integration in certain project contexts, gaps remain in how external supplier expertise is incorporated during early design stages, and in how compensation structures and cost commitment timing shape their willingness to engage, collaborate, and adopt innovative solutions (Chan et al., 2010; Ogundare et al., 2024). Recent research by Shehadeh and Alshboul (2025) and Zheng et al. (2025) further suggests that procurement structures increasingly influence not only contractual relationships but also broader coordination behaviors, risk allocation patterns, and project adaptability under uncertainty.

More broadly, the construction industry has increasingly shifted from fragmented, transaction-focused procurement approaches toward collaborative models that emphasize coordination, shared risk, digital integration, and early stakeholder involvement (Elghaish et al., 2022; Wang & Guo, 2022; Bühler et al., 2025). Despite these industry developments, many projects continue to face coordination and integration challenges that prevent early supplier expertise from being effectively used during design.

1.2 Construction Procurement Challenges

Persistent challenges in construction procurement stem from structural fragmentation and limited integration among project stakeholders and across phases. Construction procurement is typically organized across multiple independent participants, often resulting in fragmented decision-making (Bygballe et al., 2010; Koolwijk et al., 2018). Song et al. (2009), Xue et al. (2010), and Masood et al. (2024) note that suppliers engaged after major design decisions have a limited ability to influence system interfaces, sequencing, constructability, and coordination decisions during early design stages. This pattern of delayed engagement is often reinforced by procurement systems that prioritize cost certainty and price competition over long-term coordination, requiring near-complete designs before suppliers can be formally selected. As noted by Egan (1998) and later reinforced by Franz et al. (2020), these conditions persist within organizational structures, including contracting norms, accountability requirements, and budget approval processes, that sustain traditional procurement practices.

Low levels of early redesign activity and Request for Information (RFI) volume during the initial project phases are often interpreted as signs of effective coordination. Whether these early signals accurately reflect underlying coordination conditions or instead mask unresolved issues remains an open question that existing frameworks do not adequately address. Shen et al. (2022) and Mehta et al. (2022) argue that indicators such as rework frequency, RFIs, and workflow disruptions should be evaluated as interconnected outcomes of broader coordination systems rather than as isolated project metrics.

Construction projects also operate under high levels of uncertainty, requiring stakeholders to make decisions with incomplete information, which, in turn, influences coordination and risk-related behavior. Compensation structures and the timing of cost commitments further influence how stakeholders perceive risk and make decisions during the design process. Kim and Rhee (2026), Ogundare et al. (2024), and Shehadeh and Alshboul (2025) suggest that uncertainty about future cost responsibility can affect the willingness to pursue innovative or less conventional alternatives during the early design stages.

As a result, the mechanisms linking procurement decisions to coordination and performance outcomes remain insufficiently understood. Existing research also does not clearly explain why early supplier involvement (ESI) may improve coordination efficiency in some cases, while in others it enables meaningful design influence and innovation. Prior studies by Koolwijk et al. (2018) and Zheng et al. (2019, 2025) highlight the importance of both structural and behavioral conditions in shaping coordination dynamics; however, the ways these dimensions interact remain insufficiently understood. This study reviews existing research on collaborative procurement, stakeholder integration, coordination mechanisms, and behavioral dynamics in project delivery, particularly regarding timing, incentives, and coordination outcomes during early project phases.

1.3 Problem Statement

A. Procurement as a Static rather than Behavioral System: Existing literature often treats procurement as a relatively static, contract-driven process focused on cost control and risk minimization. Limited attention has been paid to how stakeholder behavior, feedback, and decision-making evolve over the project lifecycle in response to changing procurement conditions. Risk perception, participation, and collaboration intensity are not fixed at contract signing but shift continuously as governance conditions change, yet existing frameworks do not capture this dynamic dimension.

B. Structural Constraints on Supplier Integration: Although ESI is widely recognized as beneficial, existing procurement models do not provide effective mechanisms for integrating supplier expertise during early design stages. Supplier participation remains conditional and delayed, and even when suppliers enter the process early, they frequently remain in advisory roles without genuine decision authority. The value of early involvement depends not only on when suppliers enter the process, but on whether their input influences decisions while design flexibility still exists.

C. Compensation Structures and GMP Timing as Behavioral Mechanisms: Compensation structures and Guaranteed Maximum Price (GMP) timing are predominantly treated as cost and risk management decisions rather than as governance mechanisms that shape stakeholder behavior. The timing of cost commitments influences willingness to engage early, risk perception, and openness to innovation. However, existing studies do not examine how compensation structures operate to balance cost certainty, design flexibility, supplier integration, and innovation potential. This gap is particularly important because owner governance, including statutory requirements and audit accountability structures, frequently determines when GMP can occur regardless of coordination readiness.

D. Missing links between coordination failures and project outcomes: While RFIs, rework, and coordination failures are well studied as indicators of design and information gaps, their translation into measurable outcomes such as workflow stability remains insufficiently explored. Design performance is often measured through separate indicators rather than as a single, clearly defined concept. Innovation adoption, despite being widely recognized as beneficial, has not been examined as an outcome of procurement timing, supplier participation, and design-stage information quality.

1.4 Research Gap and Research Questions

Building on the problem identified above, this study is motivated by a broader gap in existing research: construction procurement is still primarily examined through fragmented perspectives that do not fully capture the dynamic interactions between governance conditions, stakeholder behavior, and project performance. Behavioral drivers such as risk perception, participation, and collaboration intensity are rarely formalized as measurable variables or explicitly modeled. The link between coordination failures and measurable outcomes remains underexplored. Moreover, existing research treats innovation adoption as a technology-driven phenomenon rather than examining how procurement timing and supplier participation influence the likelihood of integrating innovation during the design process.

The following overarching research question guides the research: How does early supplier engagement within structured procurement shape stakeholder behavior, innovation adoption, and project performance across the design and construction lifecycle?

To address this question, the following research questions are investigated:

RQ1: How do procurement coordination structures influence stakeholder behavior, including supplier participation, collaboration intensity, and risk perception?

RQ2: How do governance conditions, particularly GMP timing, shape stakeholder engagement, innovation adoption, and the extent to which ESI influences design outcomes?

RQ3: How do coordination failures in the design phase, reflected through fragmented participation, low collaboration intensity, and reduced design clarity, propagate into measurable construction-phase outcomes, including RFI generation and capacity utilization?

RQ4: How can an integrated agent-based framework be developed to capture the behavioral dynamics through which procurement conditions produce system-level outcomes?

To address these questions, this study defines the following research objectives.

1.5 Research Objectives

This study aims to develop and evaluate an Integrated Coordination Framework that examines how procurement structure, governance conditions, and stakeholder behavior interact to shape innovation adoption and project performance across the design and construction lifecycle. This study pursues four objectives that together address the research gaps and questions identified above:

1. To develop the Integrated Coordination Framework (ICF) with a Central Coordination Agent (CCA), and implement it as an agent-based simulation tool that allows practitioners to analyze how procurement coordination and governance conditions shape system-level outcomes.

2. To translate interview-derived behavioral constructs into a validated agent-based model that captures how stakeholder behavior, participation, collaboration intensity, and risk perception respond to procurement conditions and collectively shape system-level outcomes.

3. To evaluate how coordination structure and GMP timing influence innovation adoption, design rework, RFI generation, and capacity utilization across the integrated framework and typical procurement environments.

4. To examine the governance conditions that determine whether ESI produces meaningful design influence or remains advisory.

1.6 Research Approach Overview

These objectives require an approach that can capture both the contextual complexity of real-world decision-making and the dynamic interactions that drive system-level outcomes. This study, therefore, adopts a mixed-methods design that integrates qualitative industry interviews with agent-based modeling (ABM) to examine how procurement structures and coordination conditions shape stakeholder behavior and project outcomes.

The research begins with a literature review and exploratory industry interviews. These interviews involve experienced professionals across owners, general contractors, central coordinating agents, and suppliers, ensuring that the data reflects practical, decision-driven insights. The qualitative data is systematically analyzed using a structured thematic coding process to extract recurring behavioral patterns, including collaboration dynamics, risk perception, compensation structures, and ESI.

These empirically grounded insights are then translated into an agent-based framework. A structured mapping process converts qualitative themes into model components, including agent attributes, decision rules, and interaction mechanisms. The ABM represents key stakeholders as interacting agents whose decisions evolve in response to project conditions, coordination structures, and behavioral factors. Simulation experiments are conducted to compare different procurement scenarios, particularly the Integrated Coordination Framework (ICF) and typical approaches. The model generates time-based outputs across key metrics spanning the design and construction phases. This enables examination of how changes in coordination conditions produce different system-level performance outcomes.

To strengthen model credibility, the study incorporates a structured validation framework that evaluates both the model's internal logic and the alignment of emergent outputs with real-world construction practices.

1.7 Scope and Limitations of the Study

This study focuses on the design coordination phase during which key decisions regarding supplier engagement, GMP timing, and coordination structure are made. The simulation model is scoped to this phase, with downstream construction execution, bidding behavior, and detailed financial flows excluded to isolate procurement-driven effects on performance. The supplier agents represented in the model reflect key specialty trades and material suppliers, such as curtain wall fabricators and switchgear providers, whose technical expertise and long lead times make early design engagement particularly consequential.

The findings are most directly applicable to mid- to large-scale commercial, institutional, and infrastructural construction projects operating under GMP-based delivery in the United States, consistent with the project contexts represented in the interview sample. The framework is particularly relevant to project delivery methods that involve early engagement with contractors and suppliers, including Integrated Project Delivery (IPD), Design-Build, and GC/CM. The study does not claim generalizability across all delivery methods, project scales, or regulatory environments without adaptation.

The ABM represents stakeholder behavior through simplified, calibrated parameters derived from industry interviews. While this produces validated performance differentiation, it does not fully capture the social, relational, and organizational complexity that shapes procurement decisions in practice. The model is intended as a behavioral representation rather than a precise predictive tool, and its outputs are to be interpreted as directional rather than precise.

1.8 Organization of the Dissertation

This dissertation is organized into eight chapters:

Chapter 1. Introduction: Presents the research background, problem context, and the persistent coordination challenges in construction procurement. Identifies the research gaps, formulates the research questions and objectives, and outlines the mixed-methods approach adopted in this study.

Chapter 2. Literature Review: Reviews existing research on construction procurement systems, collaborative procurement models, ESI, compensation structures, GMP timing, coordination failures, and their performance outcomes, and innovation adoption. Identifies detailed research gaps from the literature.

Chapter 3. Research Strategy and Methodology: Introduces the Integrated Coordination Framework and the CCA as the core coordination mechanism. Defines the key behavioral constructs and conceptual relationships linking procurement conditions to project outcomes. Describes the mixed-methods approach, including industry interviews, thematic coding, the rationale for ABM, and the multi-stage validation strategy.

Chapter 4. Agent-Based Model Development: Presents the full development of the simulation model, including interview-to-parameter mapping, agent definitions, and behavioral structures, mathematical representation of decision relationships, performance metric formulation, model assumptions and system boundaries, and implementation in AnyLogic.

Chapter 5. Results: Presents the simulation outputs across four key performance metrics, innovation adoption, design rework, RFI generation, and capacity utilization, comparing ICF and typical environments across the design and construction lifecycle. Examines system-level behavior and project stability patterns that emerge from differences in coordination timing and structure.

Chapter 6. Model Validation: Presents a four-stage validation framework covering model verification, mechanism validation through expert walkthroughs, and pattern validation by comparing simulation output trajectories against expert expectations, and quantitative benchmarking against industry-informed ranges.

Chapter 7. Discussion: Interprets the simulation results in relation to the research propositions and situates the findings within pull planning theory, supplier participation and governance literature, and the role of GMP timing in shaping coordination and stakeholder behavior.

Chapter 8. Conclusions: Summarize the key research findings, outline theoretical, methodological, and practical contributions, discuss study limitations, and identify directions for future research.

This study addresses persistent coordination and integration challenges in construction procurement by examining how stakeholder engagement structures and compensation mechanisms influence coordination outcomes during early project phases. GMP timing is examined as a procurement condition that shapes stakeholder behavior, decision-making flexibility, and opportunities for collaborative design influence. The following chapter reviews the relevant literature on construction procurement systems, collaborative procurement models, ESI, compensation structures, the impact of coordination failures on performance measures, and innovation adoption to establish the study's theoretical and conceptual foundation.

Chapter 2 Literature Review

This chapter reviews the literature on construction procurement and coordination to establish the theoretical foundation for this study. It examines how procurement structures, stakeholder interactions, and decision-making mechanisms influence coordination and project performance. The literature review is organized to examine procurement structures and coordination mechanisms (Sections 2.1–2.2), followed by early supplier involvement (Section 2.3), compensation mechanisms and GMP timing (Section 2.4), coordination outcomes (Section 2.5), innovation adoption (Section 2.6), and concludes by identifying key research gaps (Section 2.7).

2.1 Construction Procurement Systems and Coordination Mechanisms

Construction procurement is defined in this study as the coordination of inter-organizational decision-making and integration of key stakeholders, including owners, designers, contractors, and suppliers, across project phases. It reflects how firms utilize supplier capabilities, technologies, and processes to enhance project performance while fostering long-term, cooperative relationships among stakeholders. In this paper, the Typical Construction Procurement process is considered from the owner's demands through the design phase to construction handover, as illustrated in Figure 1. Although several researchers have provided definitions of the Construction Procurement system, this research defines it as the coordination of inter-organizational decision-making and the integration of key construction business processes and key agents involved, including the client/owner, designer, General Contractor (GC), subcontractors, suppliers, etc. The procurement process begins with design development, which involves organizations at the design stages, such as the client/owner, designer, GC, A/E consultants, subcontractors, and suppliers. In this model, GC is the core, and the owner and A/E Consultants are the other two main partners. In addition to direct suppliers of GC, subcontractors are also regarded as suppliers of GC; meanwhile, subcontractors have their own suppliers (Xue et al., 2005).

Despite significant technological and cultural advancements in the construction industry in recent decades, procurement practices for external suppliers with expertise in materials and technology remain largely unchanged, and persistent problems continue to impede efficiency and innovation. Several researchers attribute these issues to fragmented interfaces among participants and stages, leading to independent control and a lack of integration (Xue et al., 2010). This fragmentation, particularly the separation of design and construction and limited integration across functional disciplines, contributes to low productivity, cost and time overruns, and frequent conflicts.

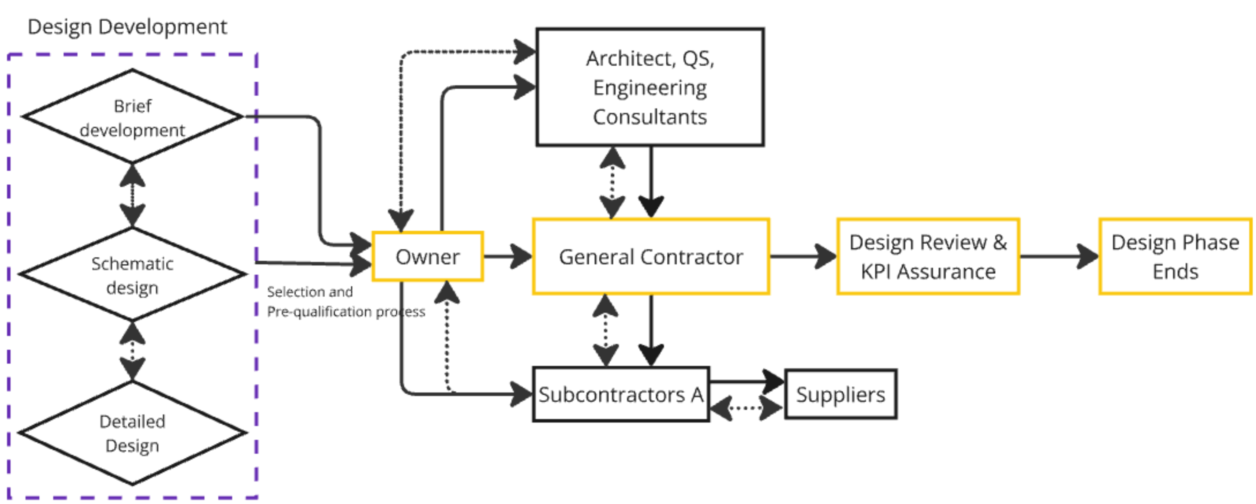


Figure 1. Typical Construction Procurement Model

A substantial body of literature exists on lean construction theory, procurement approaches, collaboration, and its applications, emphasizing the elimination of waste, continuous improvement, and process optimization to enhance value delivery (Ballard & Tommelein, 2021). Although design management research emphasizes shifting from purely transformational to value-generation approaches, and lean practices promote early stakeholder involvement (Tommelein, 1998), key suppliers are often not engaged early enough to significantly influence materials and methods. Traditional procurement models often miss opportunities to integrate specialized supplier expertise early in the design phase, largely due to rigid contracts, fragmented decision-making, and lowest-bid selection methods (Pan et al., 2011). The undesirable outcomes of the existing procurement system include adversarial relationships between agents, “win/lose” attitudes, and a makeshift focus. These issues lead to unclear communication, hinder long-term relationships, and force agents to operate in silos with minimal collaboration, thereby negatively impacting coordinated decision-making (Simonsen et al., 2023; Xue et al., 2005; Raoufi & Fayek, 2018). Furthermore, risks are often disproportionately allocated, discouraging agents from adopting innovative solutions. Collaborative procurement approaches such as IPD, Target Value Design (TVD), and Early Contractor Involvement aim to enhance integration but often overlook explicit mechanisms for involving external suppliers (Taggart et al., 2014; Song et al., 2009). Collaborative procurement models limit early supplier involvement because of rigid contracts and cost-driven selection, which require near-complete designs. Without clear incentives, suppliers have less motivation to contribute expertise early, leading to missed opportunities for innovation. To address these shortcomings, the following sections of the literature review are organized into thematic areas that broaden the theoretical grounding and deepen the analysis of current practices in collaborative procurement.

2.2. Critical Review of Collaborative Procurement Models

Existing lean construction studies predominantly focus on on-site activities and workflow, often placing less emphasis on the procurement phase, where adversarial relationships and inefficiencies are more apparent (Kim, 2019; Sarhan et al., 2018). While lean practices have been shown to improve efficiency and foster collaboration among project stakeholders (Xue et al., 2010; Zhang & Chen, 2016), critical gaps remain in extending these principles to include external supply chain actors during the design phase. Industry-driven procurement initiatives in the UK, exemplified by Rethinking Construction (Egan, 1998; Department of Trade and Industry, 1998) and the Procure 21+ (P21+) Guide, a public-sector response, have challenged the construction sector to adopt earlier supplier engagement. According to Egan (1998), the rationale for an integrated process is the inefficiency of project delivery, constrained by the largely separate processes through which projects are generally planned, reflecting a fragmented and confrontational culture. Although effective, this predetermined contractual arrangement may limit flexibility in current collaborative procurement approaches. Building on these insights, a critical review of existing collaborative models further identifies areas for improvement.

Collaborative procurement frameworks, such as IPD, TVD, and P21+, have emerged to foster early stakeholder involvement and address longstanding procurement inefficiencies. IPD integrates owners, architects, and contractors (both general and specialty) into a single contractual framework, improving risk management, innovation, and efficiency (Kim & Dossick, 2011; El Asmar et al., 2013). A key advantage of IPD is early involvement of specialty trades, which reduces design conflicts and enhances constructability (Azari et al., 2011; Mesa et al., 2016; Evans & Farrell, 2023). However, challenges such as complex multi-party contracts and difficulties with risk sharing in IPD have hindered its broader adoption. A critical limitation of TVD within IPD is the absence of clearly defined contractual incentives to integrate external supplier expertise early, which discourages innovation precisely when it is most beneficial. Furthermore, to leverage price competition, owners or general contractors (acting as contractees) typically require near-complete designs before selecting suppliers, prioritizing cost savings over early integration of key supplier expertise. Nevertheless, since external suppliers in key areas (façade, MEP) possess significant expertise in new materials and methods, their inclusion in early design remains essential (Akintoye et al, 2000). Additionally, the compensation structures in current collaborative procurement models often lack clear incentive alignment, fostering competition and further exacerbating inefficiencies (Chan et al., 2010; Kim & Rhee, 2024). Therefore, a gap remains in existing collaborative procurement frameworks that prioritize cost savings over early supplier integration. The relationships in P21+ are structured primarily between Owners and Principal Supply Chain Partners under a long-term framework agreement. Building on the foundational principles that structure procurement relationships between owners and suppliers, this study proposes a framework that enables dynamic interactions among stakeholders and supports a more flexible, adaptive model applicable to other collaborative procurement models.

Current collaborative procurement approaches have demonstrated improvements in efficiency, cost reduction, and stakeholder collaboration. Industry-driven collaborative procurement initiatives have encouraged the sector to adopt earlier supplier engagement. However, gaps remain in the effective integration of supplier expertise during early design stages.

2.3 Early Supplier Involvement in Construction Projects

Effective information sharing is essential to an efficient procurement process, as it enhances coordination among agents and deepens the owner's understanding of their needs (Sahin & Robinson, 2005; Li & Lin, 2006; Leuschner et al., 2013). Inclusive decision-making is crucial, ensuring that key partners are actively involved and given opportunities to express their concerns and opinions (Eriksson, 2015). Without this inclusivity, the supply chain risks sub-optimization, leading to inefficiencies and fragmentation (Arshinder et al., 2011).

In this context, collaboration extends beyond process alignment to include trust and commitment, which are fundamental to relational integration and the development of mutually beneficial relationships. Furthermore, supply chain integration improves performance by aligning activities between upstream and downstream stakeholders (Carter et al., 2009; Barratt, 2004).

Within the construction industry, these approaches are recognized as vital for enhancing the efficiency and quality of design processes (Akintoye et al., 2000; Bygballe et al., 2010). Recent research increasingly focuses on integration and collaboration at the project level (Meng, 2012), with studies suggesting that IPD methods encourage a culture of cooperation (Lahdenperä, 2012). While traditional procurement methods often lack these integrative activities, their absence in conventionally procured projects can undermine long-term relationships and project outcomes (Carter et al., 2009). Early supplier involvement enables the integration of specialized knowledge into design decisions, improving constructability, reducing design conflicts, and supporting more informed material selection. Suppliers and specialty contractors possess expertise in construction methods, materials, and emerging technologies that can significantly enhance design outcomes when engaged early. However, in many procurement systems, supplier participation remains conditional and often occurs after key design decisions have been established. This delayed involvement limits the ability to leverage supplier expertise during critical design stages, reducing opportunities for improved coordination and innovation.

Early supplier involvement improves coordination and can enhance design outcomes; however, its impact depends on how effectively supplier knowledge is integrated into decision-making processes. In practice, supplier participation often remains advisory, with limited influence on core design decisions. As a result, early involvement may improve coordination without significantly affecting design performance or innovation. This highlights that the value of early supplier involvement depends on how effectively supplier knowledge is incorporated into decision-making processes, rather than on the timing of participation alone. While early supplier involvement highlights the importance of integrating expertise during design, its effectiveness ultimately depends on how procurement structures and compensation mechanisms shape stakeholder behavior.

2.4 Compensation Structures, GMP Timing, and Risk Allocation

2.4.1 Agreeing on the GMP

The GMP model is widely recognized as a strategy that provides clients with cost certainty while incentivizing contractors to optimize project costs. However, its effectiveness depends heavily on the timing of GMP finalization during the design phases. The literature highlights that one of the fundamental challenges of GMP contracts is the risk of finalizing the contract price before the design is fully developed (Perry & Barnes, 2000). Effective risk management in construction projects begins with identifying and allocating risks to mitigate uncertainties. Contract types not only define the parties' obligations but also determine how risks are distributed among stakeholders. In response to the limitations of the traditional design-bid-build approach, the construction industry has been shifting toward alternative project delivery methods. These methods often involve engaging the prime contractor for preconstruction services, including estimating construction material costs and work packages before the design is fully completed (Gransberg et al., 2011). Boukendour and Bah (2001) describe GMP as a hybrid contract that combines cost reimbursement with a call option in a fixed-price arrangement. The absence of a fully defined design at the time of the GMP agreement often shifts considerable risk onto the contractor, who is then responsible for absorbing cost overruns due to unforeseen design developments.

Compared to conventional fixed-price lump-sum contracts, the GMP strategy establishes a clear price ceiling or target cost, reducing financial uncertainties for the client (Perry & Barnes, 2000).

Under this contract type, the owner's financial liability cannot exceed the guaranteed cap unless client-approved additional work is introduced (Mills & Harris, 1995). This arrangement strengthens cost control and minimizes the risk of overspending. Additionally, GMP contracts incorporate gain-share provisions that further motivate contractors to pursue cost-effective methods and achieve savings (Perry & Barnes, 2000; Boukendour & Bah, 2001; Fan & Greenwood, 2004). A notable strategy observed in practice is using multiple GMPs throughout a project's lifecycle rather than a single comprehensive GMP. Some projects implement phased GMP agreements, where work is divided into separate packages, each with its own GMP. This phased approach allows for greater cost control and enables the early procurement of long-lead materials, which is particularly useful in volatile market conditions (Ogundare et al., 2024).

GMP contracts enable construction to commence before design completion, expediting site work and improving logistics planning. Pre-agreed change mechanisms reduce disputes, leading to faster finalization of project accounts than traditional contracting approaches. GMP's open-book accounting further facilitates the transparent handling of design modifications, minimizing the time required for variation assessments (Mills & Harris, 1995). Studies indicate that GMP schemes can enhance construction quality by reducing rework and improving quality performance compared to fixed-price lump-sum arrangements. Key contributing factors include improved design buildability, ongoing client involvement, and robust communication channels. GMP fosters cooperative and productive working relationships through its incentive-driven and transparent approach. By sharing both gains and risks, contractors are encouraged to achieve cost efficiencies while maximizing project value (Choi et al., 2016). The open-book accounting principle and the collaborative environment encouraged by GMP replace adversarial mindsets with a team-focused culture, which has proven effective. While these characteristics highlight the benefits of GMP, its effectiveness is strongly influenced by the timing of its finalization.

2.4.2 Impact of GMP Timing

The timing of GMP finalization plays a crucial role in determining the project's flexibility for design modifications. Once the GMP is set, clients face significant constraints in making changes without incurring additional costs (Perry & Barnes, 2000). Variations in design development may fall within the contractor's scope or be classified as formal changes that require additional compensation, often leading to disputes (Fan and Greenwood, 2004). P21+ strongly advocates for finalizing the GMP after substantial design completion, ensuring that client requirements are finalized, subcontractor pricing is fully market-tested, and risk allocation is clearly defined before contractual commitments are made. This approach prioritizes financial predictability by minimizing exposure to cost overruns due to design modifications or unforeseen risks. Figure 2 illustrates the trade-off observed, in which early GMP finalization introduces risks from the owner's perspective, including cost uncertainty and concerns about contractor pricing. In contrast, Ogundare et al. (2024) identify a range of GMP timing strategies, including phased GMPs, where cost agreements are progressively established at different stages of design and procurement.

This alternative approach offers greater flexibility in securing material prices early, particularly in volatile markets, but also introduces risks related to incomplete design information and risk allocation. From an innovation standpoint, early GMP facilitates the integration of suppliers and trade partners during the early design phases, enabling informed decision-making and adoption of new technologies or materials.

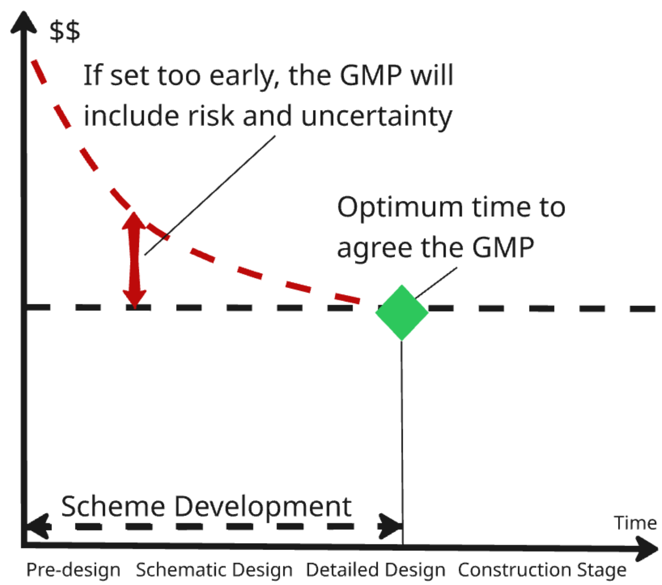


Figure 2. Trade-off between GMP timing and innovation across design development stages

While late GMP finalization prioritizes cost certainty for owners by minimizing exposure to unforeseen expenses, it can limit the project's adaptability to incorporate design changes and innovations. These timing decisions are shaped by what this study terms procurement governance, which refers to the formal and informal mechanisms through which owners control cost commitments, risk distribution, and conditions for stakeholder engagement (Yan & Zhang, 2020; Hwang et al. 2026). In construction, governance operates at multiple levels: at the owner level, through approval procedures, accountability structures, and procurement controls that determine when cost and contractual commitments can be made (Guo et al., 2014); and at the project level, through compensation arrangements, relational governance, and decision authority that determine whether early supplier involvement translates into meaningful design influence (Hua et al., 2026; Hwang et al., 2026). Zheng et al. (2025) demonstrate that the configuration of such governance mechanisms significantly mediates project performance, while Zheng et al. (2019) show that asymmetric risk allocation as a governance condition produces risk-averse contractor behavior that suppresses early engagement regardless of procurement intent. Understanding how these conditions operate upstream of any coordination structure is therefore essential to evaluating why similar procurement arrangements produce different outcomes in practice. Conversely, early GMP finalization offers greater flexibility and can expedite project timelines, but it introduces risks of incomplete design information and potential cost overruns. Research indicates that early GMP agreements can facilitate faster project delivery by allowing construction to begin before the design is fully complete. This approach, often associated with fast-track construction methods, can be beneficial in time-sensitive projects where schedule acceleration is critical. However, proceeding with incomplete designs may lead to more change orders and disputes. Moreover, the success of early GMP finalization depends heavily on collaboration among project stakeholders. Effective communication and trust among owners, contractors, and designers are essential for managing uncertainties. In such scenarios, contractors may include higher contingencies in their pricing to account for uncertainties, thereby affecting the overall project budget. Kim and Rhee (2026) demonstrate that under conventional GMP structures, contractors avoid adopting innovative technologies because they bear the cost uncertainty while owners retain cost savings, leading to risk-averse behavior unless incentive mechanisms are introduced.

This highlights that GMP timing decisions are inherently linked to how risk is perceived, distributed, and managed among project participants. As the level of design completeness and certainty varies, so does the allocation of financial and performance risk among stakeholders, making risk allocation a critical mechanism shaping the implications of GMP timing in practice.

2.4.3 Risk Allocation

GMP contracts are designed to distribute risk among owners, contractors, and suppliers. Unlike traditional lump-sum contracts, GMP agreements require contractors to provide cost estimates early in the design phase, enabling more accurate budgeting and greater financial transparency

(Chan et al., 2010). However, risk allocation remains a key challenge, particularly during supply chain disruptions and material price fluctuations. Research indicates that contractors often bear the risk of cost escalation, relying on pricing data from subcontractors and trade partners. In some cases, risk is shared between prime contractors and subcontractors, reducing the likelihood of excessive bid inflation (Ballard et al., 2015). Additionally, owners may hesitate to commit to early GMP agreements, fearing that premature cost commitments might introduce unnecessary financial exposure if designs evolve significantly.

P21+ employs a structured joint risk management framework that systematically assesses, allocates, and mitigates risks before GMP finalization. By delaying GMP finalization until substantial design completion, P21+ ensures that approximately 80% of the GMP is based on firm-subcontracted work packages, reducing uncertainty in cost estimation and supplier commitments. However, Ogundare et al. (2024) note that some projects deviate from this risk-averse methodology and instead adopt flexible risk-sharing mechanisms in which contingencies are adjusted across phases. In projects implementing phased GMPs, contractors and subcontractors often share the burden of cost escalation, with risks shifting dynamically in response to procurement trends and price fluctuations. While this flexibility allows for early supplier involvement and proactive material procurement, it also exposes projects to financial uncertainties if initial cost assumptions prove inaccurate.

While compensation structures shape stakeholder incentives and decision-making, their impact extends beyond financial outcomes, influencing how coordination unfolds during the design phase. In particular, the timing of GMP finalization and associated risk-sharing mechanisms affects stakeholders' willingness to engage early, share information, and align decisions. When these mechanisms discourage early participation or increase perceived risk, coordination becomes fragmented, leading to misaligned design and procurement processes.

2.5 Integration Failures in Design Phase: RFIs, Rework, and Design Performance

Several studies highlight that coordination failures are not merely isolated issues but systemic outcomes of fragmented decision-making, delayed stakeholder integration, and misaligned information flows during the design phase. These failures manifest as rework, Requests for Information (RFIs), and reduced design performance, each reflecting distinct dimensions. Rather than acting independently, these outcomes are interconnected, where deficiencies in design clarity, supplier integration, and information exchange propagate across project stages, leading to cumulative inefficiencies. As such, rework, RFIs, and design performance can be interpreted as indicators of the effectiveness of procurement coordination.

2.5.1. Design Rework

Rework is widely recognized as a major contributor to cost overruns and schedule delays in construction projects. It often arises from procurement inefficiencies such as late material deliveries, misaligned specifications, and inadequate communication between suppliers and contractors. Studies indicate that early supplier involvement and alignment between procurement and design activities can significantly reduce material mismatches and construction defects (Gil et al., 2006). In prefabricated construction, where design and procurement are highly interdependent, misalignment and late design changes significantly increase rework and reduce efficiency (Shen et al., 2022; Hyun et al., 2020; Luo et al., 2020). Procurement failures such as incorrect material orders, unclear specifications, and delayed approvals contribute to higher rework rates and reflect coordination inefficiencies (Luo et al., 2020). Rework time is widely recognized as an indicator of project performance and coordination quality (Love et al., 2004). Rework in construction projects is not viewed solely as an operational inefficiency, but as an indicator of upstream coordination failures. In this sense, rework not only reflects misalignment in design and procurement decisions but also complements other indicators, such as RFIs and design performance, in evaluating the overall effectiveness of coordination.

2.5.2. RFIs and Workflow Disruption

RFIs have been increasingly conceptualized as a measurable indicator of coordination quality across project interfaces. Empirical studies demonstrate that RFIs primarily arise from design errors, omissions, and inconsistencies in documentation, reflecting fragmented information flows and inadequate stakeholder integration (Hanna et al., 2012). High RFI frequencies are, therefore, not merely procedural items but signals of systemic coordination deficiencies that necessitate reactive problem-solving during project execution. Critically, Love et al. (2013) highlight that the generation and processing of RFIs disrupt workflow continuity, often triggering rework, delays, and decision bottlenecks.

RFI-related disruptions interrupt workflows, create idle time, and disrupt task sequencing, leading to productivity loss and project delays (Love et al., 2013; Han et al., 2013). Such disruptions implicitly affect resource utilization, as the construction phase is often forced to wait or reassigned inefficiently while information is pending resolution. However, despite this clear operational impact, existing literature has largely examined RFIs through the lens of information management and coordination quality, with limited attention to their implications for capacity utilization as a measurable outcome. While studies show that poor coordination leads to inefficient resource use (Hwang et al., 2009), the direct link between RFIs and capacity utilization remains underexplored. In this sense, RFIs function not only as indicators of information and coordination breakdowns but also as causes of broader disruptions in workflow and project performance. These disruptions are strongly linked to design clarity and reliability, underscoring the key role clarity plays in coordination**.**

2.5.3. Design Performance and Coordination Quality

Design performance in construction is increasingly recognized as a multidimensional concept that extends beyond traditional productivity metrics, reflecting the iterative and coordination-intensive nature of design processes. Rather than being captured solely by output-based measures, design performance is often reflected in qualitative dimensions such as design completeness, coordination effectiveness, information clarity, and the ability to minimize errors and downstream rework (Love et al., 2013; Alves et al., 2016). In this context, design productivity is typically understood in terms of efficiency or output, which represents only a partial view, as it does not fully capture the quality and reliability of design clarity or the effectiveness of coordination processes. Existing studies show that incomplete documentation or poor coordination during project execution cause RFIs, redesigns, and workflow disruptions, indicating shortcomings in design performance rather than merely operational inefficiencies (Love et al., 2014). Research shows that early supplier involvement improves design reliability and reduces the need for repeated clarifications, highlighting the importance of good coordination in design performance (Nguyen & Akhavian, 2019; Song et al., 2009). However, despite widespread acknowledgment of these qualitative attributes, the literature remains fragmented in how design performance is conceptualized and assessed (Wang et al., 2016), with many studies treating its indicators indirectly rather than as part of a coherent performance construct. As a result, it is still unclear how improvements in design quality lead to measurable gains in productivity and project outcomes.

These performance outcomes are interconnected, and their interaction shows how failures lead to measurable inefficiencies, providing a basis for evaluating performance and identifying opportunities to leverage supplier expertise at early stages. While these outcomes reflect inefficiencies, they also point to missed opportunities for innovation and the adoption of new technologies.

2.6 Innovation Adoption in Construction Projects

Innovation adoption cannot be understood merely as the introduction of new materials or digital tools, but as a procurement and integration-dependent process shaped by risk allocation, information quality, and the timing of key supplier involvement. Innovations such as BIM-enabled workflows, Industry 4.0 technologies, and digitally integrated supply chains improve transparency, coordination, and decision quality across project delivery systems (Elghaish et al., 2022; Wang & Guo, 2022). However, adoption remains uneven because procurement systems often prioritize cost certainty, contractual defensibility, and short-term risk control over experimentation and learning. In such environments, innovative materials, specialist services, and digital tools are treated as sources of uncertainty rather than as mechanisms for improving project performance.

Suppliers and specialty contractors possess the practical knowledge required to evaluate constructability, material suitability, and implementation feasibility. However, their involvement typically occurs only after major design and procurement decisions have been fixed (Song et al., 2009; Wang et al., 2016). As a result, innovation is constrained by the delay in knowledge integration. Fragmented design information and weak inter-organizational coordination further increase perceived risk, reducing stakeholders' willingness to adopt unfamiliar solutions, particularly under arrangements where early cost commitments are expected before uncertainty is resolved (Love et al., 2014). This creates a situation where decisions are made without fully leveraging expertise, even when better solutions exist. Low innovation adoption is not just due to resistance to change; it often results from procurement environments that separate design, supply chain knowledge, and decision-making. Although prior studies document the benefits of digitalization and integration, fewer examine innovation adoption as an outcome of procurement timing, supplier participation, and design-stage information quality.

These limitations highlight the need to examine how procurement structures influence stakeholder behavior, coordination, and innovation, forming the basis for the research gaps identified in the following section.

2.7 Research Gaps/ Key Findings from Literature Review

The literature demonstrates that early supplier involvement is necessary because critical technical decisions affecting constructability, fabrication, and system integration are made during schematic design and design development, when design flexibility remains high. When suppliers are engaged after these decisions are finalized, their ability to influence interfaces, sequencing, and fabrication constraints is significantly reduced, leading to inefficiencies in redesign and coordination. However, evidence also shows that early involvement alone is insufficient, as suppliers often remain in advisory roles unless supported by clear decision authority, predictable compensation, and aligned risk–reward structures. This indicates that early supplier involvement is not a timing-based coordination strategy, but a structural and behavioral requirement for enabling decision-relevant participation and effective integration of supplier knowledge during early design. Although collaborative approaches aim to improve stakeholder integration, they often do not fully incorporate key external suppliers into early-stage decision-making. As a result, opportunities to leverage supplier expertise to improve constructability and support innovation remain limited. In parallel, research on compensation structures highlights the role of cost mechanisms in shaping stakeholder incentives, where the timing of cost commitments influences willingness to engage early. Coordination failures, reflected in RFIs, design revisions, and construction disruptions, are widely recognized as outcomes of these fragmented processes. However, existing literature largely examines these elements in isolation, with limited integration among procurement structure, stakeholder behavior, and project outcomes. Building on these gaps, the following key research directions are identified:

1. Procurement as a dynamic behavioral system: Existing literature largely treats procurement as a static, contract-driven process focused on cost control and risk minimization. Limited attention has been paid to a dynamic system in which stakeholder behavior, feedback, and decision-making evolve over the project lifecycle.

2. Behavioral modeling of procurement decisions: Existing literature discusses stakeholder behavior such as risk perception and participation, but these are rarely formalized into measurable decision variables or modeled explicitly. There is limited work translating behavioral drivers into structured decision-making mechanisms that can be systematically represented and analyzed.

3. Supplier integration is structurally constrained: Although early supplier involvement is widely recognized as beneficial, existing procurement models do not provide effective mechanisms for integrating supplier expertise during early design stages. Supplier participation remains conditional and delayed, limiting opportunities for improved coordination, constructability, and innovation.

4. Lack of strategic understanding of compensation structures: Compensation structures play a key role in shaping how stakeholders make decisions, manage risk, and engage in early collaboration. However, the timing of cost Commitments (GMP) is predominantly treated as a risk management decision rather than a strategic mechanism. Existing studies do not adequately examine how compensation structures and GMP timing can be used together to balance cost certainty, design flexibility, supplier integration, and innovation potential.

5. Missing link between coordination failures and outcomes: While RFIs, rework, and coordination failures are well studied as indicators of design and information deficiencies, their translation into measurable or model-based outcomes such as capacity utilization and workflow stability remains insufficiently explored.

6. Design performance vs productivity: Existing literature evaluates design-related outcomes through fragmented indicators such as quality, coordination, and error reduction, but lacks a clear conceptualization of design performance as a unified construct. Design performance is often discussed separately from productivity, with limited clarity on how these concepts relate within procurement-driven coordination contexts.

7. Innovation adoption as a procurement outcome: Although the benefits of innovation are widely recognized, limited research examines how procurement structures and design-stage conditions jointly influence innovation adoption levels.

8. Lack of integrated system-level analysis: Existing studies examine procurement structures, stakeholder behavior, and project outcomes separately, but do not capture how these elements interact within a system. There is limited understanding of how changes in key procurement conditions (e.g., GMP timing or supplier participation) influence other variables and overall project performance.

Chapter Summary

The literature reviewed in this chapter demonstrates that persistent coordination failures in construction procurement are not isolated operational problems, but systemic outcomes of fragmented procurement structures, delayed stakeholder integration, and misaligned governance conditions. Although collaborative procurement models have improved stakeholder coordination in some contexts, significant limitations remain in integrating supplier expertise into early design decision-making and in understanding how compensation structures influence stakeholder behavior under uncertainty.

The review further shows that early supplier involvement alone does not guarantee improved outcomes. Its effectiveness depends on whether suppliers are granted meaningful influence over decisions during stages when design flexibility remains high, and whether governance conditions support early collaboration, shared risk management, and coordinated decision-making. Existing literature also indicates that compensation structures and GMP timing influence stakeholder risk perception, participation, and openness to innovation. However, these mechanisms are rarely examined as dynamic behavioral drivers within procurement systems.

In addition, the literature establishes that RFIs, rework, workflow disruption, and reduced design performance are interconnected outcomes of fragmented coordination processes rather than isolated project-level issues. However, limited research captures how these elements interact dynamically across project phases.

Collectively, the identified gaps reveal the need for an integrated framework that represents procurement as a dynamic behavioral system in which governance conditions, stakeholder interactions, and coordination mechanisms jointly shape innovation adoption and project performance. In response to these gaps, the following chapter presents the research strategy, conceptual framework, and methodological approach adopted in this study.

Chapter 3 Research Strategy

This chapter presents the research strategy and methodological development adopted to examine procurement coordination and stakeholder behavior. Section 3.1 presents the overall research design, followed by Section 3.2, which introduces the mixed-methods approach integrating qualitative interviews with ABM. Section 3.3 establishes the theoretical foundation of the study, and Section 3.4 introduces the ICF with the CCA as the core coordination mechanism. Section 3.5 defines the key behavioral constructs, including participation, collaboration, design clarity, and risk perception, which form the basis of stakeholder decision-making. Building on these constructs, Section 3.6 presents the conceptual relationships and research hypotheses linking procurement conditions to project outcomes. Section 3.7 details the industry interview process, including case study design, participant selection, data collection, and thematic coding. Section 3.8 then introduces the ABM approach, including its rationale and the translation of qualitative insights into simulation components. Finally, Section 3.9 outlines the validation strategy, including triangulation, mechanism validation, pattern validation, and benchmarking, to ensure the credibility and robustness of the model and findings.

3.1 Overall Research Design

This study investigates how procurement structures, coordination mechanisms, and stakeholder decision-making influence project performance in construction systems. To address this objective, a mixed-methods research design is adopted, integrating qualitative industry insights with agent-based simulation to capture both behavioral complexity and system-level dynamics. The research follows an iterative, integrative workflow that combines qualitative data collection, conceptual model development, simulation modeling, and validation. As illustrated in Figure 3, the process begins with exploratory industry interviews and a literature review to establish the research context, define key constructs, and identify relevant performance metrics. These insights inform the development of a conceptual representation of procurement coordination and stakeholder interactions.

Subsequently, the data collected are systematically analyzed to extract recurring behavioral patterns and decision-making factors. These empirically grounded insights are then used to inform the structure of the ABM, including agent attributes, interaction mechanisms, and decision rules.

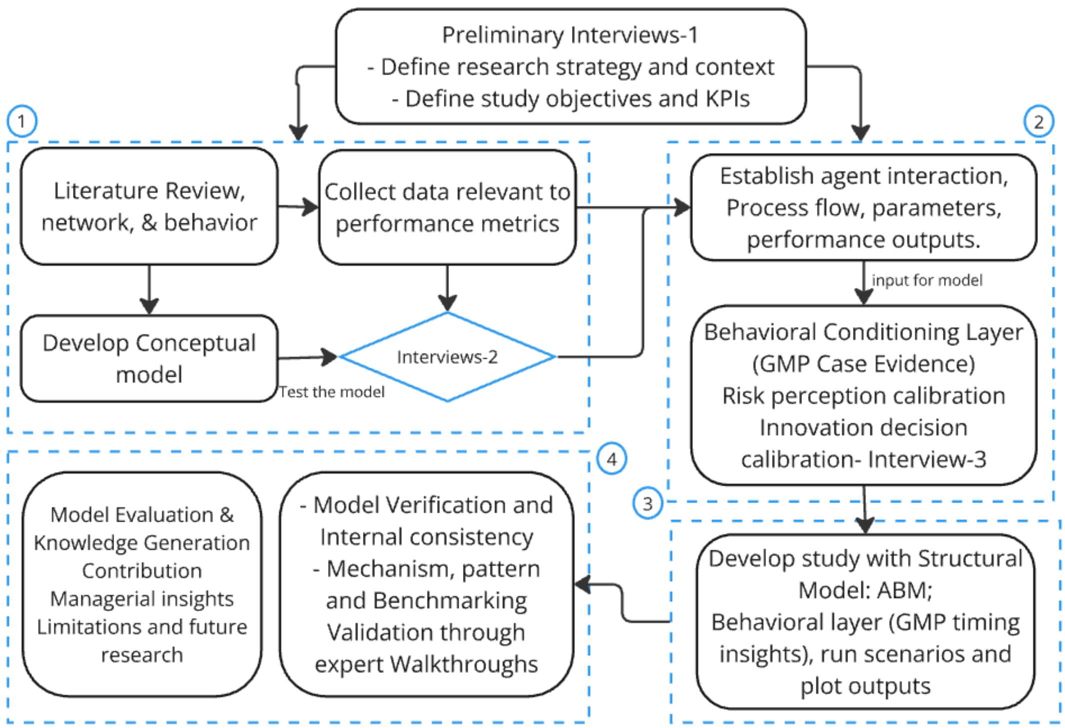


Figure 3. Data Collection Workflow

Following model development, simulation experiments are conducted to evaluate the impact of different procurement structures, particularly comparing the ICF with traditional approaches. The model generates time-based performance outputs, enabling analysis of key outcomes such as collaboration, rework, and technology adoption. This integrated research design enables empirical grounding of the simulation while supporting analytical exploration of complex procurement dynamics.

Building on the research gaps identified in Chapter 2, this chapter operationalizes the study's objectives through a mixed-methods strategy integrating qualitative interviews and agent-based modeling. The research is structured around four objectives: (1) developing an Integrated Coordination Framework with a CCA, (2) translating behavioral constructs into a simulation-based representation of stakeholder decision-making, (3) evaluating how procurement structure and GMP timing influence project outcomes, and (4) examining the governance conditions that determine whether early supplier involvement produces meaningful design influence. These objectives collectively guide the framework development, simulation design, and validation process presented in this chapter.

3.2 Mixed-Methods Strategy

Case study interviews provide in-depth, context-specific insights into core aspects of the procurement process, such as contractor-supplier relationships and collaborative decision-making that computational approaches alone might not fully capture. ABM complements these qualitative findings by quantitatively simulating the interactions among multiple stakeholders, illuminating emergent patterns, and cause-and-effect relationships within complex construction projects.

A key methodological challenge is the inconsistency in applying the case study research method, ensuring validity control, reliability assurance, and sufficient data collection (Taylor et al., 2011). This inconsistency raises concerns about accepting theoretical arguments without substantial evidence, potentially causing criticisms. Construct validity is vulnerable in case-study research and requires multiple sources of evidence, a chain of evidence, and the review of draft case results with key participants to ensure credibility. Meeting the burden of production can be challenging in Phase I of this research, in which describing the case-study research setting and providing descriptive information about cases are often neglected. One of the challenges in statistical studies is the number of variables that determine project success or failure, given the unique nature of construction activities (Taylor et al., 2011). Researchers sometimes merely hypothesize associations rather than causal relationships due to these complexities and treat variables independently, which could pose a key challenge in Phase I of this study when developing a conceptual model.

This mixed-methods strategy offers a comprehensive view by uniting the rich evidence from case-study interviews with the systematic analysis of agent-based simulation. As a result, contradictions and nuances that may be overlooked by a single method are more readily identified and explored. This study leverages the strengths of both qualitative and computational approaches to strengthen the analytical rigor of the research findings. Validation is supported through structured techniques and iterative expert feedback to ensure model credibility, enhance reliability, and maximize the generalizability of results. Together, these integrated methods combine qualitative depth with quantitative rigor, significantly enriching the procurement literature, connecting theory with practice, and demonstrating clear practical benefits.

3.3 Theoretical Foundation of the Framework

Construction projects operate under complex procurement environments where stakeholders must balance cost commitments, risk exposure, and evolving design information. In such settings, stakeholder behavior becomes a critical driver of coordination outcomes, influencing participation, collaboration, and the integration of technical expertise during project development.

To address this, this chapter introduces an ICF that restructures stakeholder interactions and supplier engagement during project development, linking procurement conditions, stakeholder behavior, and project outcomes. The framework positions procurement as a behavior-driven system in which coordination is actively managed through structured mechanisms rather than being determined solely by contractual arrangements. The ICF establishes an environment in which key project participants are connected through a central coordination mechanism, enabling early supplier input to influence design decisions and improving alignment between design and construction.

A key component of the framework is the role of coordination mechanisms that shape stakeholder behavior. In particular, compensation structures influence how stakeholders perceive risk, make early commitments, and participate. By incorporating early GMP timing and enabling early engagement on critical work packages, the framework creates conditions that support both cost control and collaborative decision-making. The framework, operationalized through a CCA, is treated as a dynamic, feedback-driven system in which stakeholder behavior evolves in response to changing project conditions and uncertainty.

3.4 Integrated Coordination Framework with a Central Coordination Agent

The framework enables early engagement of downstream stakeholders through structured coordination and aligned compensation strategies. As illustrated in Figure 4, the framework establishes coordinated linkages across key project phases. During the Design Development phase, the Owner and A/E consultants focus on design refinement and compensation structuring, which influence subsequent stakeholder behavior and decision-making. The model then transitions to the Primary Design Assist phase, where the GC engages with the CCA to ensure the availability and alignment of required resources. At the same time, subcontractors and consultants contribute based on their technical roles. In the Secondary Design Assist phase, the CCA brings together a pool of specialist suppliers to provide targeted expertise that supports innovation and technical optimization. This phased structure allows supplier expertise to be incorporated at critical decision points rather than after design completion. At the center of this framework is the CCA, a dedicated intermediary responsible for managing stakeholder interactions, facilitating supplier integration, and maintaining alignment between design and procurement processes. In governance terms, the CCA operates at the middle layer of the procurement system, structuring the compensation conditions, decision authority, and relational continuity that determine whether early supplier involvement produces genuine design influence rather than remaining advisory.

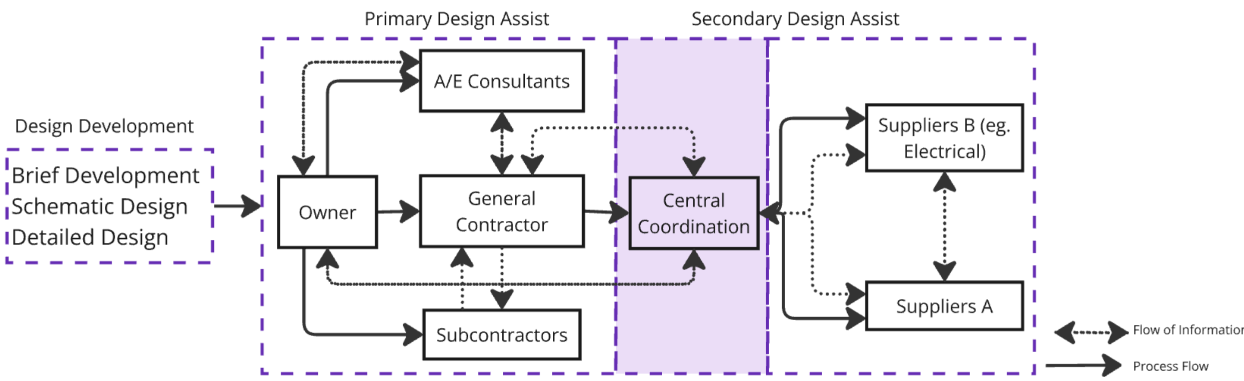


Figure 4. Proposed Integrated Coordination Framework with Central Coordination

The following key characteristics define CCA: (1) Strategic supply chain connector: maintains a structured network of suppliers with documented capabilities, capacities, lead times, and technical expertise, enabling informed and project-specific supplier identification and early technical input based on project needs.

(2) Coordination and decision integrator: facilitates alignment among the owner, GC, design team, and subcontractors by structuring communication, synchronizing decision timelines, and ensuring that technical inputs are integrated into design and procurement decisions across project phases.

(3) Information and feedback repository: maintains and organizes project-related data, including supplier performance, coordination outcomes, and lessons learned, enabling feedback-driven improvement in decision-making

(4) Optimization and innovation enabler: supports coordination mechanisms such as GMP timing and incentive structures, facilitates early supplier involvement to enhance innovation, and improves decision-making related to resource allocation and technology adoption

(5) Lean-aligned facilitator: promotes value-driven integration consistent with lean construction principles by leveraging the expertise of the suppliers and enabling early standardization of components.

The CCA can be implemented in multiple formats depending on the project context. It may exist as an individual role (e.g., supply chain coordinator), an organizational entity (e.g., a centralized procurement firm), or a technology-enabled system, including digital or AI-based agents that support data-driven integration and decision-making. This flexibility allows the framework to be adapted across different procurement environments while maintaining its core integration function.

Within this framework, procurement conditions define the environment in which agents operate and interact. These conditions include the timing of cost commitments (e.g., GMP timing), coordination structure, and the level of uncertainty during early design. The environment shapes the constraints and incentives faced by stakeholders, influencing their risk perception, participation decisions, and interaction patterns. As a result, agent behavior is continuously influenced by the procurement environment rather than being fixed or independent.

3.5 Key Behavioral Constructs

Within the ICF, procurement outcomes are driven by a set of interrelated behavioral drivers that capture how stakeholders respond to coordination structures, uncertainty, and early decision-making conditions. These variables represent the underlying mechanisms and form the basis for model development. Within the structure, supplier participation reflects the extent to which suppliers and specialty trades engage in early design activities, enabling the integration of domain-specific expertise into decision-making and improving constructability. The level of participation is closely linked to collaboration intensity, which reflects the degree of interaction, communication, and joint problem-solving among project stakeholders, thereby supporting better information flow and decision alignment (Sacks et al., 2010). These interactions directly influence design clarity, defined as the completeness, consistency, and reliability of design information, which reduces uncertainty and minimizes downstream conflicts and rework (Shehadeh & Alshboul, 2025).

In addition, this framework highlights that stakeholder behavior is also shaped by risk perception, which captures the perceived financial, lead-time, and schedule-related uncertainty associated with early commitments under different procurement and compensation structures (Mehta et al., 2022). In response to such uncertainty, suppliers may adopt risk buffering strategies, incorporating additional cost or time allowances to manage potential variability, particularly under conditions of early risk transfer and incomplete design information. These behavioral drivers are treated as distinct decision-making variables representing different dimensions of stakeholder response.

3.6 Conceptual Relationships and Research Propositions

The framework establishes a set of causal and logic-based relationships linking procurement conditions, stakeholder behavior, and project outcomes. Unlike static models, the ICF recognizes that agent-level decision thresholds govern transitions between states (e.g., from non-participation to active collaboration). These thresholds are defined by the balance between perceived risk and expected benefits under the given procurement conditions, reflecting decision-making under uncertainty. Agents participate in early coordination only when the expected benefits exceed the perceived risks, thereby linking procurement conditions directly to stakeholder decision-making and interaction patterns, as illustrated in Figure 5.

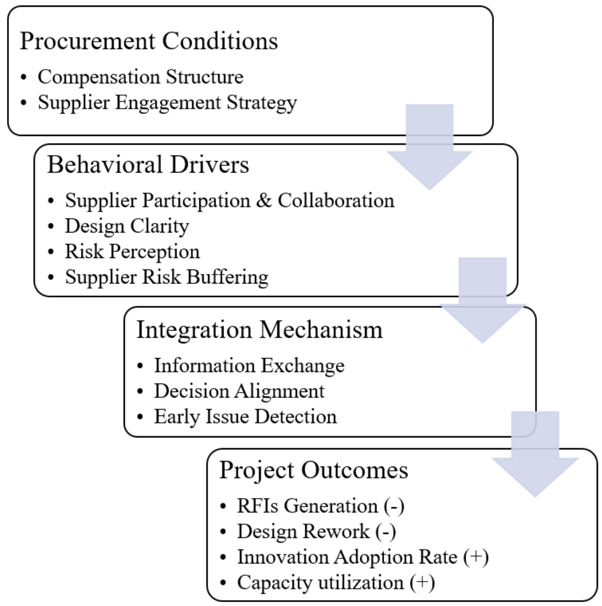


Figure 5. Conceptual representation of behavioral drivers and their influence on project outcomes through interaction mechanisms.

Table 1 summarizes the key conceptual relationships between behavioral drivers and project outcomes within the Integrated Coordination Framework. The relationships represent the causal pathways through which procurement conditions influence stakeholder behavior and, in turn, affect coordination and performance outcomes. The table captures both direct and combined effects of behavioral variables. These relationships directly influence coordination outcomes and project performance. Higher design clarity and stronger collaboration are associated with fewer RFIs, while fragmented information and delayed participation increase formal information exchanges. Increased RFIs disrupt coordination, reduce workflow stability, and negatively affect overall project performance. These relationships form the structural basis of the conceptual model and guide the development of hypotheses and simulation logic by defining how behavioral mechanisms translate into measurable project outcomes.

Table 1. Conceptual Relationships Linking Behavioral Drivers to Project Outcomes in the ICF

Relationship Type	From (Driver)	To (Outcome)	Description
Participation → Collaboration	Supplier Participation	Collaboration Intensity	Higher supplier participation increases interaction, communication, and joint problem-solving among stakeholders.
Collaboration → Design Clarity	Collaboration Intensity	Design Clarity	Increased collaboration improves information flow and decision alignment, enhancing design clarity and reducing uncertainty.
Design Clarity → Rework/RFI	Design Clarity	RFI / Rework	Improved design clarity reduces design conflicts, rework, and the frequency of RFIs.
Risk → Participation	Risk Perception	Supplier Participation	Higher perceived risk reduces willingness to engage early, limiting supplier participation.
Behavior → Design Performance	Participation + Collaboration + Design Clarity	Design Performance	Strong participation, collaboration, and clear design improve overall design performance.
Behavior → Innovation	Participation + Design Clarity	Innovation Adoption	Early supplier involvement and better design conditions increase the likelihood of innovation adoption.
Coordination → Capacity	RFI / Rework	Capacity Utilization	Increased RFIs and rework disrupt workflow and reduce effective capacity utilization.

These relationships capture both direct and combined effects of behavioral variables. The outcomes are presented and interpreted in both absolute and normalized terms (Table 2). Outputs such as RFIs and rework are generated as counts and additionally normalized relative to their respective maximum or baseline values for comparison across scenarios. In contrast, RFIs and rework are represented as counts and corresponding normalized percentages. This dual representation allows the model to capture both the absolute intensity of coordination effects and their relative impact on project performance.

Table 2. Measurement scales for construction performance measures

Example of Measures	Scale of measure	Data Type	Project Stage
Innovation Adoption Level	Number, Percentage	Quantitative	Design
Capacity Utilization	Percentage	Quantitative	Construction
RFIs	Number, Percentage	Quantitative	Construction
Rework	Number, Percentage	Quantitative	Design
Design Performance	Satisfaction	Qualitative	Design

Within this structure, procurement conditions define the system environment; behavioral drivers represent agent-level decision variables while outcomes such as RFIs, rework, capacity utilization, design performance, and innovation adoption reflect system performance. These effects do not occur in isolation but evolve through reinforcing and constraining feedback mechanisms within the system. For example, greater collaboration improves design clarity, reduces uncertainty, and encourages greater participation, thereby further strengthening coordination. Conversely, high perceived risk and low participation reinforce fragmented coordination patterns, limiting coordination effectiveness over time. This mapping enables the framework to be translated into a dynamic model in which stakeholder interactions and coordination outcomes can be evaluated across different procurement scenarios. These reinforcing dynamics establish the framework's structural logic and provide a basis for systematic evaluation. Building on the conceptual framework, the following hypotheses are formulated to test the proposed relationships.

3.6.1 Strategic (System-level) Propositions

To evaluate the effectiveness of the proposed ICF, this study formulates strategic, system-level propositions that examine how alternative procurement structures influence project performance under conditions of early design uncertainty and coordination complexity. These hypotheses explicitly compare coordinated and fragmented procurement environments, focusing on how governance mechanisms, particularly the introduction of a CCA and the structuring of early compensation, affect system-level outcomes.

P1: Projects operating under the ICF will outperform traditional procurement environments in terms of innovation adoption and overall design performance.

P2: The integration of a CCA will outperform a typical model by reducing coordination-related inefficiencies, resulting in lower levels of RFIs and cumulative redesign.

P3: Earlier GMP timing within coordinated procurement environments will enhance stakeholder engagement and increase innovation adoption, particularly when design information is incomplete and risk perception is high.

P4: ICF will outperform fragmented procurement environments by maintaining higher and more stable capacity utilization under coordination-intensive project conditions.

P5: The performance advantages of coordinated procurement structures are mediated through changes in stakeholder behavior, particularly participation, collaboration intensity, and risk perception.

3.6.2 Secondary Propositions: Behavioral Mechanisms

To operationalize the conceptual framework, a set of supporting behavioral relationships is defined to represent the underlying mechanisms through which procurement conditions influence stakeholder interactions and project outcomes. These relationships are not treated as primary research propositions; rather, they provide a structured representation of empirically observed patterns derived from industry interviews and literature. They serve as the behavioral foundation of the model, capturing how variables such as risk perception, participation, collaboration, and design clarity interact within the system.

Table 3. Supporting Behavioral Relationships Derived from Conceptual Framework

From (Driver)	To (Outcome)	Description
Procurement Conditions	Risk Perception / Participation	Procurement conditions shape stakeholders' risk perceptions and influence their willingness to participate in early coordination.
Supplier Participation	Collaboration Intensity	Higher supplier participation increases interaction, communication, and joint problem-solving among stakeholders.
Collaboration Intensity	Design Clarity	Increased collaboration improves information flow and decision alignment, enhancing design clarity.
Design Clarity	RFI / Redesign	Improved design clarity reduces design conflicts, RFIs, and downstream redesign.
Risk Perception	Supplier Participation	Higher perceived risk reduces willingness to engage early, limiting supplier participation.
Participation + Design Clarity	Innovation Adoption	Early participation and improved design conditions increase the likelihood of innovation adoption.
RFI / Redesign	Capacity Utilization	Increased RFIs and redesign disrupt workflow and reduce effective capacity utilization.

These relationships (Table 3) provide a structured representation of the behavioral mechanisms embedded within the proposed framework. They support translating procurement conditions into stakeholder interactions and coordination dynamics within the model. Rather than serving as testable propositions, these relationships guide the interpretation of how procurement decisions influence behavioral responses and, in turn, affect project performance outcomes.

3.7 Industry Interviews and Data Collection

3.7.1. Case Study Approach and Rationale

This study adopts a case study approach to examine the complex, context-dependent dynamics of construction procurement and stakeholder coordination. The case study method involves data collection to understand how and why individuals, organizations, and markets behave as they do. Case study research has long been recognized as a powerful method for investigating contemporary phenomena (Yin, 2018; Creswell, 2007; Miles & Huberman, 1994; Swanborn, 2010). Its strength lies in its holistic focus, allowing researchers to immerse themselves in complex environments and capture the nuanced interplay of multiple factors. This approach explores the intricacies of construction procurement systems and innovative organizational structures. Taylor et al. (2011) highlight that case studies allow researchers to answer questions of how and why, observe and document causal factors, quantify the impact of new technologies, and capture participants' observations about how the case in question is similar to or different from other projects. Yin (2018) defines the case study method as an empirical inquiry into a contemporary phenomenon, particularly when the boundaries between the phenomenon and its context are unclear. Such inquiries often require both qualitative and quantitative methods to gain comprehensive insights into organizational dynamics and decision-making processes in the construction industry. Bemelmans et al. (2012) conducted case studies to address gaps in the relationship between suppliers and contractors and identified criteria for efficient contractor-supplier relations. Similarly, Autry and Golicic (2010) and Koolwijk et al. (2018) conducted case studies to examine the impact of collaborative or development practices on the efficiency and quality of supply chain performance. Drawing on these several research case studies and Yin's definition of case studies, which emphasizes the investigation of contemporary phenomena, this study will delve deeply into the intricate dynamics of these relationships. To explore the impacts of performance measures, this study conducts interviews, analyzes documents, and gathers rich data on strategies, communication channels, trust-building mechanisms, and risk management processes.

This approach is particularly appropriate for this study because procurement coordination, early supplier involvement, and compensation structures are context-dependent and shaped by organizational behavior that cannot be isolated through purely quantitative methods. The case study method enables the capture of these embedded decision-making processes and their translation into behavioral rules and parameters for the simulation model.

3.7.2 Sample and Participants

A purposive sampling strategy is used to identify industry professionals with relevant experience in construction procurement and supply chain practices. The participants are selected from a professional network of experts representing key stakeholder groups, including owners, general contractors, and suppliers. The proposed list of relevant stakeholders is presented in Table 4. The selected organizations include major industry participants such as Turner Construction, Hensel Phelps, McKinstry, Abbott Construction, and Sequoyah Electric, as well as institutional owners such as the University of Washington and Microsoft. These organizations are actively involved in complex construction projects and represent a range of procurement practices, from traditional approaches to more integrated and supply chain-oriented models. In particular, SourceBlue is included to represent a centralized procurement and coordination entity, aligning directly with the concept of the CCA examined in this study.

Table 4. List of Relevant Organizations and Experts to Interview

Organizations	Position	Stakeholder Type
SourceBlue	Senior Design Manager	CCA
McKinstry	Director of Supply Chain	Supplier
Sequoyah Electric	Project Executive	Supplier
Sequoyah Electric	Director of Purchasing	Supplier
Turner Construction	Procurement Manager	General Contractors

North Coast Electric	Account Manager	Supplier
Hensel Phelps	Project Manager	General Contractors
Hensel Phelps	Project Manager	General Contractors
University of Washington, Tacoma	Senior Director, UW Facilities	Owner
University of Washington	Director, Project Delivery Group	Owner
University of Washington	Director of Major Projects	Owner
Microsoft	Senior Project Controls and Capital Program Leader	Owner
Abbott Construction	Project Executive	General Contractors

All participants hold mid- to senior-level positions and possess substantial industry experience in project delivery and supply chain management. Their positions, including project managers, procurement managers, supply chain directors, and owner representatives, ensure that the data reflects practical insights from individuals directly involved in decision-making, coordination, and supplier engagement across different project phases. Their roles involve direct engagement in decision-making, coordination, and supplier interactions, making them well-suited to provide insights relevant to this study.

3.7.3. Data Collection

The data collection is conducted in two sequential phases. The first phase extends a preliminary survey conducted with organizations including Sequoyah Electric, SourceBlue, Turner Construction, and McKinstry, focusing on supplier–contractor relationships and ESI. The second phase consists of detailed interviews that expand the scope to include central coordination, technology adoption, compensation structures, and risk-sharing attitudes. These phases collectively support the investigation of the ICF and its potential to improve collaboration and enable early integration of technology and material expertise. The objective of the interviews is to: a) establish a shared understanding of integrated procurement approaches, including challenges and benefits; b) capture stakeholder perspectives on technology adoption, risk-sharing attitudes, and performance outputs; c) analyze the impact of compensation structures on agent behavior and decision-making; and d) inform the development and validation of the process model, including triggering conditions, state transitions, agent interactions, and parameter values. Building on these objectives, the second round of interviews is designed to explore key mechanisms underlying procurement decision-making and coordination practices in greater depth, as attached in Appendix 10.1. The first theme focuses on central coordination and early supplier involvement, comparing conventional procurement approaches with the ICF and examining the challenges of engaging specialized suppliers in the early design stages.

The second theme examines technology adoption and risk attitude, including how individual and organizational risk tolerance influences decision-making, how cost variability affects adoption choices, and the role of structured coordination in facilitating the implementation of high-risk technologies. The third theme addresses risk management within the framework, with particular attention to mitigation strategies for new technologies, approaches to equitable risk allocation, and the role of transparency and accountability in reducing conflicts. The fourth theme focuses on performance measurement, including how outcomes such as innovation adoption, design productivity and performance, rework, RFIs, and capacity utilization are tracked, as well as how coordination mechanisms and external factors influence these performance indicators. The final theme examines compensation and payment structures, specifically the timing of GMP finalization, its influence on collaboration and risk attitudes, and the effects of trust, fairness, and payment clarity on procurement decisions. Before conducting the interviews, a draft questionnaire is distributed to selected academic and industry experts to evaluate clarity, relevance, and completeness. Based on the feedback received, the questionnaire is refined and finalized to ensure robustness and alignment with the research objectives. The data collected through these interviews form the basis for the qualitative analysis and thematic coding process described in the following section.

3.7.4 Qualitative Data Analysis and Thematic Coding

The qualitative data collected from industry interviews were analyzed using a structured thematic coding approach to identify coordination patterns, behavioral drivers, and decision-making factors specific to construction procurement systems. The coding process was conducted using NVivo software to ensure systematic organization, consistency, and traceability of themes across the interview data. An inductive coding strategy was adopted, whereby interview transcripts were iteratively reviewed and segmented into meaningful analytical units. Initial codes were assigned to capture recurring concepts such as early supplier involvement, central coordination, risk-sharing attitudes, compensation structures, and technology adoption. A color-coding scheme was used during this process to differentiate emerging themes and maintain consistency across multiple interviews visually. Through an iterative process of constant comparison, similar codes were grouped into higher-level themes representing broader conceptual categories. These themes were further organized into overarching dimensions, including coordination mechanisms, risk behavior, contract structures, and performance outcomes, enabling the identification of relationships across stakeholder perspectives.

The analysis focused on identifying recurring patterns among stakeholders, particularly differences in how owners, contractors, and suppliers perceive risk, collaboration, and decision-making across varying procurement structures. The frequency and consistency of themes were examined to determine dominant coordination dynamics and key influencing factors. Special attention was given to identifying causal relationships, such as how GMP timing influences risk perception, and how early supplier involvement affects collaboration and redesign. This process resulted in a refined set of empirically grounded constructs representing key behavioral and coordination dynamics in construction procurement systems. These include collaboration intensity, trust, risk perception, technology adoption behavior, and contract timing, all of which are derived directly from interview evidence and reflect real-world industry practices. These constructs provide the analytical foundation for subsequent model development.

3.8 Agent-Based Modeling Approach

3.8.1 Rationale for ABM

This study adopts an ABM approach to capture the dynamic and behavior-driven nature of coordination and decision-making in construction procurement systems. ABM differs from other computational models by enabling agent-to-agent interactions, making it particularly suitable for studying dynamic systems (Awwad et al., 2017). Bibliometric techniques help identify the most frequent keywords, co-citation patterns, and emerging research directions, offering insights into how simulation techniques have been applied in construction management and procurement processes. Figure 6 shows the co-occurrence network of keywords with VOSviewer 8.9.8, consisting of nodes and links, which represent the co-occurrence strength between them, respectively. The thickness of a link between keywords indicates the strength of their co-occurrence. The top 10 frequently used keywords determined by the analysis were simulation, ABM, construction, management, performance, framework, model, system, design, and behavior. Prior studies have used ABM to model construction supply chain coordination (Xue et al., 2005; Tah et al., 2001) and to optimize design collaboration (Min & Bjornsson, 2008). They developed a framework for construction supply chain coordination, in which the agents were members of the designer, owner, and GC firms, and agent interactions were the flow of information or funds. Several ABM tools have been developed to support collaborative design processes (Tang, 2004). An ABM-CAD system that uses the internet and web technologies was developed, allowing multiple users to view the design and make modifications synchronously and dynamically (Rosenman & Wang, 2001). Anumba et al. (2002) applied ABM at the design stage to support collaborative design through negotiations among intelligent agents to facilitate the design process. Ahn and Lee (2015) modeled social interactions among construction personnel using an ABM, and the model was also used to develop organizational policies to better manage human resources.

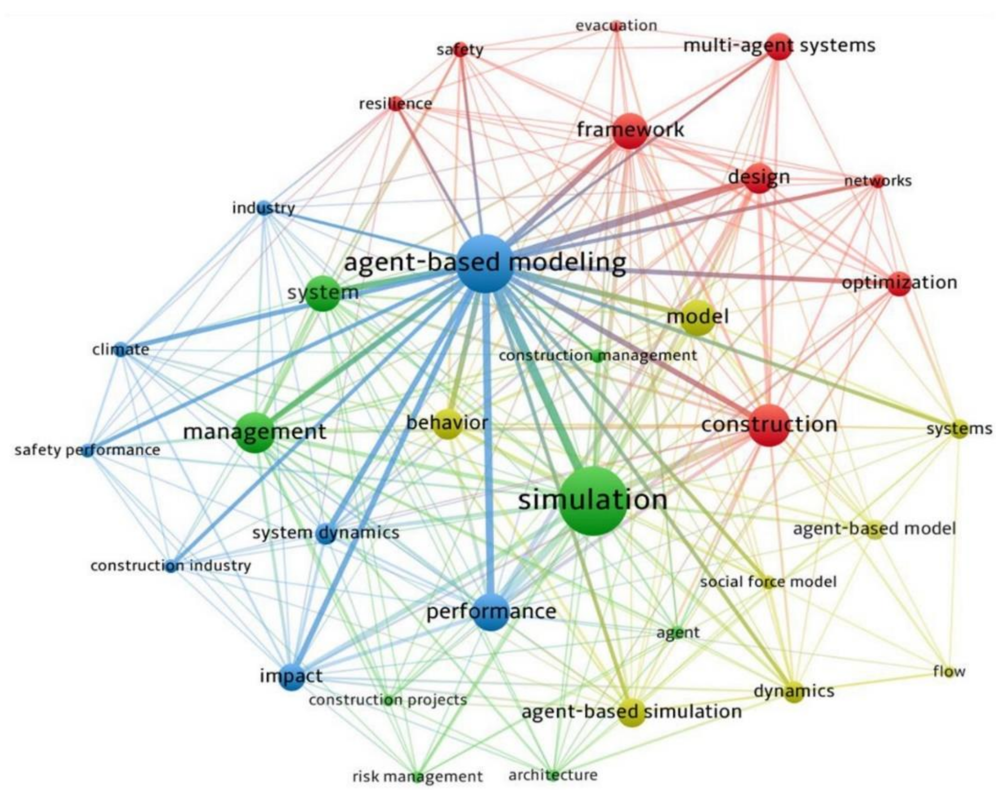


Figure 6. Keywords co-occurrence network

The possibility of modeling such agent-to-agent interactions is the main way ABM differs from other computational models, and it is well suited to this study. The interactions or communications among the agents are governed by predefined rules that influence outcomes/predictions. This is particularly important in this study, where procurement outcomes are not solely driven by static variables but by dynamic interactions among stakeholders with differing risk attitudes, incentives, and access to information. Traditional analytical or optimization models are limited in their ability to capture these adaptive behaviors, whereas ABMs enable the explicit representation of behavioral mechanisms (Du et al. 2016). As a result, ABM provides a suitable framework for examining how micro-level behavioral changes, such as variations in GMP timing or compensation structures, propagate to influence system-level outcomes, including collaboration, rework, and innovation adoption.

3.8.2. Integration of Qualitative Insights into ABM

The development of the ABM is grounded in empirical insights derived from the qualitative interview analysis. To ensure that the model reflects real-world construction practices, a structured translation process was implemented to convert qualitative themes into formal model components. Following the thematic coding, key themes representing coordination mechanisms, risk perceptions, contractual dynamics, and behavioral patterns were identified across stakeholder groups. These themes were mapped to corresponding constructs, including agent attributes, decision variables, and interaction mechanisms.

A coding-to-model mapping framework was developed to maintain traceability between interview data and simulation design. Figure 7 illustrates how interview transcripts are systematically coded, grouped into thematic categories, and translated into model variables for simulation development. Each interview quote was linked to a specific code (theme), categorized into higher-level constructs, and subsequently associated with a corresponding model variable. For example, the theme of early supplier involvement was operationalized as collaboration level, which influences the intensity and frequency of interactions between agents. Similarly, lead-time risk was translated into a risk-perception parameter, along with external volatility, to affect decision-making. Behavioral themes were further translated into decision rules and probabilistic mechanisms**.** For instance, conditional participation was modeled as a probability function that determines whether suppliers engage in a project under uncertainty. At the same time, buffer strategies were represented as safety margins that account for design clarity and cost commitments. Contract-related themes, such as GMP timing, were incorporated as variables influencing commitment timing and risk allocation. Additionally, the relative frequency and strength of themes identified during qualitative analysis were used to prioritize key drivers. Dominant themes, such as schedule risk and buffer strategies, were assigned greater influence in shaping agent behavior and system outcomes.

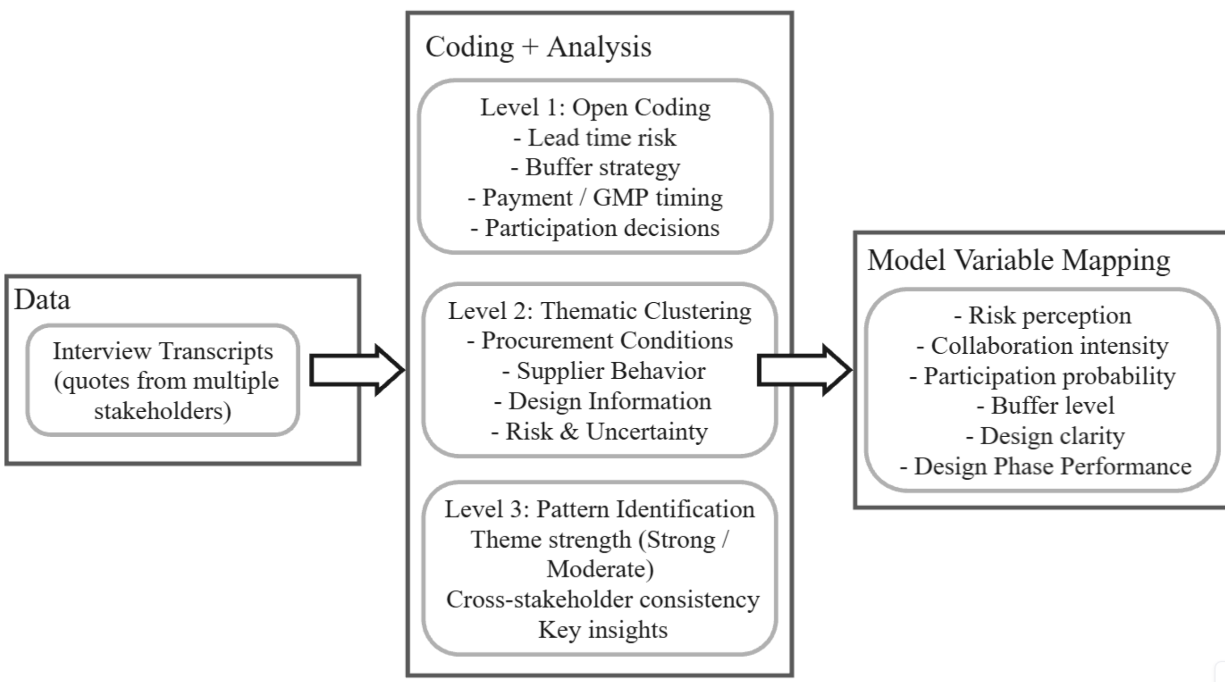


Figure 7. Coding and thematic analysis process linking interview data to model variables.

This approach ensures that the ABM is not based on abstract assumptions but is instead empirically grounded in observed industry practices. By maintaining explicit traceability between qualitative data and model structure, the study enhances both the transparency and credibility of the simulation framework. Building on the qualitative-to-model mapping described, this section formalizes the ABM by defining agent types, state variables, behavioral rules, and interaction mechanisms. The detailed formulation of the ABM, including agent definitions, interaction structures, and mathematical representations, is presented in Chapter 5.

3.9 Research Validation Strategy

The validation approach adopted in this study follows a structured multi-stage framework. Triangulation is applied by integrating qualitative interview insights, thematic coding results, and simulation outputs to ensure consistency across multiple sources of evidence.

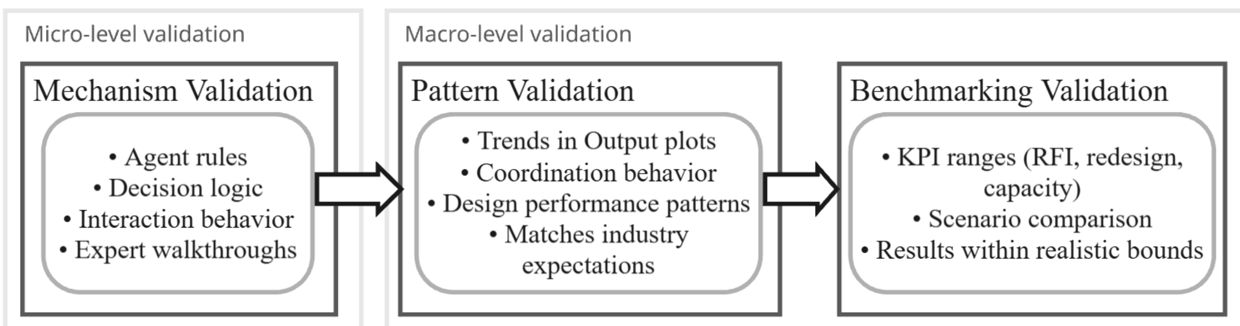


Figure 8. Validation Approach for Agent-Based Model

After triangulation of findings, the validation process, as illustrated in Figure 8, begins with a structured model walkthrough in which domain experts are introduced to the model structure, including agent types (owners, contractors, suppliers, and designers), decision mechanisms, and key simulation outputs. This step ensures that experts understand the model's internal logic before providing feedback. The second stage focuses on mechanism validation, in which experts assess whether the behavioral rules embedded in the model accurately reflect real project dynamics. The third stage involves pattern validation, in which simulation output plots are presented to experts to assess whether emergent system behaviors resemble real-world behavior. Finally, quantitative benchmarking is conducted by comparing simulation outputs with expert-provided ranges for key performance indicators.

This validation process is supported by input from experienced industry professionals representing owners, contractors, and suppliers, ensuring that both behavioral assumptions and performance outcomes reflect real-world practices. Expert feedback is not limited to assessment alone; it directly informs an iterative refinement process in which discrepancies identified during walkthroughs and pattern evaluations are systematically fed back into the model. Specifically, when gaps are identified between simulated and real-world outcomes, model variables, behavioral relationships, and mathematical equations are revisited and adjusted accordingly. This feedback-driven refinement cycle continues until the model achieves acceptable alignment with industry-informed expectations, thereby strengthening its empirical credibility.

3.9.1 Building blocks for Triangulation-based research

A key methodological strategy in case study research is triangulation, as illustrated in Figure 9, originally conceptualized by Denzin (1978) as the use of multiple data sources, methods, investigators, or theories to enhance validity. Over time, scholars have extended this concept to address not only convergent findings but also complementary and divergent insights (Decrop, 2004; Dubois & Gadde, 2002). In the convergence mode, researchers seek corroboration among diverse data sources to reinforce the validity and reliability of their findings (Jick, 1979; Yin, 2018). By integrating multiple data sources, key findings can be confirmed through convergence (Yin, 2018; Miles & Huberman, 1994) while also capturing diverse perspectives that illuminate dynamic relationships.

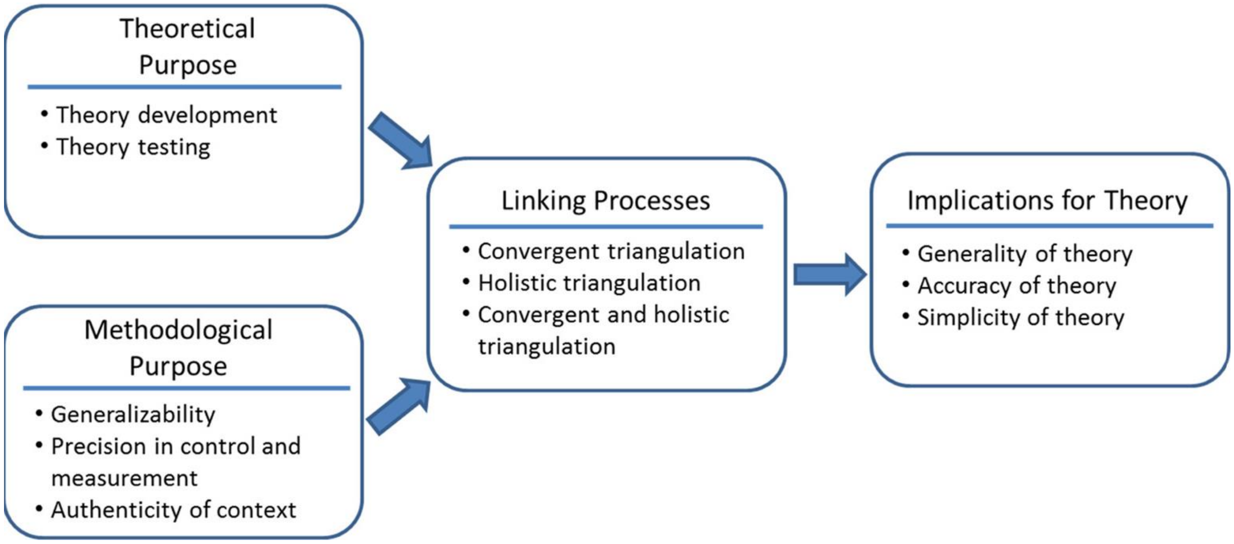


Figure 9. Building blocks for Triangulation-based research

Such a multifaceted triangulation strategy is often adopted in qualitative case study research (Guba & Lincoln, 1994) and enables a deeper exploration of how early supplier involvement impacts design productivity, risk allocation, and collaborative behavior. In addition, qualitative validation is incorporated through expert review of interview interpretations and thematic coding to ensure credibility and alignment with industry practice, consistent with established criteria for trustworthiness in qualitative research, including credibility and confirmability.

3.9.2 Mechanism Validation

Mechanism validation examines whether the underlying rules, agent behaviors, and interaction logic correctly represent real-world processes in construction systems. This is critical because ABMs are bottom-up models in which incorrect micro-level assumptions can still produce superficially correct patterns. Mazzetto (2024) stresses that mechanism validation requires verifying that agent rules are theoretically and empirically grounded, not just calibrated to fit outputs. Osman (2012) highlights that ABM must accurately represent interactions among stakeholders, resources, and infrastructure systems. Additionally, mechanism validation in construction simulation often involves deriving agent rules from process mining or real operational data to ensure that decision logic reflects actual workflows. From a broader methodological perspective, Ahn and Lee (2015) propose hierarchical validation frameworks where mechanism validation is a distinct layer, ensuring that internal processes are correct before evaluating outputs. In this study, mechanism validation is particularly critical because agent behaviors are derived from interview-based qualitative insights. Therefore, validation is conducted through expert walkthroughs, where domain professionals assess whether modeled decision rules such as risk-based participation, buffer strategies, and responses to GMP timing accurately reflect real procurement practices. This ensures that the behavioral assumptions embedded in the model maintain alignment with industry realities before proceeding to output evaluation.

3.9.3 Pattern Validation

Pattern validation assesses whether the emergent behaviors produced by the ABM align with real-world patterns. In construction ABM studies, this often involves comparing simulated outputs with empirical datasets or observed site behaviors. For instance, Sorbi et al. (2024) highlight that agent-based construction simulations must reproduce observable behavioral patterns, ranging from simple movement trajectories to complex decision-making dynamics. That validation is achieved by aligning simulation outputs with real-world site data. The authors also demonstrate that simulation outputs should reflect empirical delay and workflow patterns to ensure credibility. More broadly, Mazzetto (2024) explains that pattern-oriented validation assesses whether macro-level regularities (patterns) emerge correctly, even when micro-rules are uncertain. Lucko & Rojas (2010) emphasize that validation requires demonstrating that model outputs exhibit meaningful trends and patterns consistent with real project data**,** rather than exact point matching.

In this study, pattern validation is applied by comparing simulation outputs with industry-informed expectations of procurement dynamics. Specifically, patterns related to collaboration levels, rework occurrence, and technology adoption under different procurement structures are evaluated against expert insights and observed industry tendencies. The objective is not to achieve exact replication, but to ensure that the model reproduces realistic directional trends and behavioral responses consistent with construction practice.

3.9.4 Benchmarking and Output Validation

Output validation in ABM requires structured approaches that assess whether simulation results are both internally consistent and externally credible, particularly in contexts where empirical ground truth is rarely available, and project variability is inherently high. Benchmarking focuses on comparing ABM outputs against reference models, empirical datasets, or industry benchmarks to assess quantitative accuracy and reliability. In construction research, this often involves comparing simulation results with historical project data, conventional simulation models, or standardized scenarios. For example, Duo et al. (2026) benchmark agent-based simulation outputs against real-world operational data and alternative modeling approaches, demonstrating improved realism in worker-flow simulations. Similarly, authors compare ABM outputs with traditional simulation models to validate improvements in predictive capability. In construction-specific validation discourse, Lucko & Rojas (2010) argue that benchmarking is crucial because perfect ground truth is rarely available; therefore, models must be validated against acceptable ranges or reference standards rather than exact matches. For instance, Mirahadi et al. (2019) benchmark ABM evacuation outputs against performance-based safety indices and simulation standards, demonstrating quantitative agreement. Choi & Lee (2018) extend validation by comparing simulation outputs with empirical datasets, while Dou et al. (2026) benchmark model predictions against observed industry data. In this study, benchmarking is conducted using expert-defined ranges for key performance indicators. Simulation results are compared across procurement scenarios to assess whether the model produces outcomes within realistic, credible bounds. This approach enables quantitative validation while acknowledging the inherent uncertainty and variability of construction systems. Given the small sample size of expert-elicited values and the inability to confirm normality in the data distribution, parametric tests such as the t-test were not appropriate. The Wilcoxon signed-rank test was therefore selected as a non-parametric alternative to compare simulation outputs against expert-defined benchmark ranges without assuming a normal distribution, making it well-suited for validation contexts where expert panels are small, and data assumptions cannot be justified. Statistical consistency between model outputs and expert-elicited values is assessed using the Wilcoxon signed-rank test, a non-parametric test selected for its suitability with small expert samples where parametric assumptions cannot be justified.

Together, this validation framework combines expert-driven evaluation with model-based analysis to assess both behavioral assumptions and system-level outcomes. Because the model is developed from interview-derived rules, expert walkthroughs, and mechanism validation, it ensures alignment with real-world decision-making. Pattern validation and benchmarking are then used to evaluate whether the model produces realistic trends and outcomes consistent with industry expectations. This structured approach ensures that the model provides a credible representation of construction dynamics without requiring exact replication of real-world data.

Building on the derived constructs and validated behavioral relationships, the study now formalizes these insights within an ABM framework. The ABM translates the identified coordination mechanisms, stakeholder interactions, and decision-making processes into a dynamic simulation structure, enabling the analysis of how individual behaviors collectively influence system-level performance outcomes.

Chapter Summary

This chapter presented the research strategy and methodological framework adopted to examine how procurement coordination, governance conditions, and stakeholder behavior influence construction project outcomes. A mixed-methods approach combining qualitative industry interviews with ABM was developed to capture both the behavioral complexity of stakeholder decision-making and the system-level dynamics of procurement coordination.

The chapter established how interview-derived insights were systematically translated into behavioral constructs and simulation logic through thematic coding and structured model development. It also demonstrated the suitability of ABM for representing adaptive stakeholder interactions, feedback mechanisms, and emergent project outcomes that are difficult to capture through traditional analytical approaches. In addition, the chapter outlined the multi-stage validation strategy used to support model credibility, including triangulation, mechanism validation, pattern validation, and quantitative benchmarking.

Together, these methodological components provide the foundation for the development of the ICF and the agent-based simulation model presented in the following chapter.

Chapter 4 Agent-Based Model Development

Construction procurement systems involve multiple stakeholders whose decisions evolve through interaction under varying procurement conditions, risk perceptions, and coordination structures, resulting in emergent project outcomes that are difficult to capture with static analytical approaches. This chapter presents the development of the ABM used in this study, beginning with interview-to-parameter mapping and calibration (Section 4.1), followed by the model architecture and process flow (Section 4.2), agent definitions and behavioral structures (Section 4.3), mathematical representation of decision relationships (Section 4.4), and performance metric formulation (Section 4.5). The chapter then defines model assumptions and system boundaries (Section 4.6), describes implementation and scenario configuration in AnyLogic (Section 4.7), and concludes with face validity assessment (Section 4.8).

4.1 Interview-to-parameter mapping

4.1.1 Parameter Calibration Logic

Parameter values are derived through a structured mapping of interview evidence, including response frequencies, ranked importance, and supporting qualitative insights (Appendix 10.3). Differences between ICF and typical scenarios reflect consistent observations that centralized coordination improves early supplier involvement, communication, trust, and design clarity, while reducing schedule risk and change-related disruptions. All parameters are normalized on a [0,1] scale, where 0 represents the absence of a condition, and 1 represents its maximum intensity. Values are assigned to represent relative levels of influence observed across interview responses rather than exact empirical measurements. Interview evidence is interpreted in terms of strength, where weak presence is represented by values around 0.3, moderate presence by 0.5–0.6, and strong presence by 0.7–0.8. Parameters with stronger and more consistent support are assigned higher values in the ICF scenario and lower values in the typical scenario, ensuring that the model captures observed behavioral differences while remaining interpretable.

The model parameters are defined using standardized notation to maintain consistency across equations and tables that include Supplier participation (P_{gate}), collaboration intensity (C_i), innovation adoption rate (IAR), design rework (R_w), and the number of RFIs (N_{rfi}). Procurement-related variables include GMP timing (T_{gmp}), change order friction (C_o), and project complexity (K). Supplier and coordination conditions are captured through ESI, coordination efficiency (P_d), stakeholder trust (Trust), and communication frequency (Cf_{req}). Design and risk conditions include design clarity (DC), lead time risk (LTR), lifecycle value (V_{lc}), external market volatility (Vol_{ext}), and allowance flexibility (Aw). Additional model variables include risk buffer (RB), schedule stress (SS), and risk perception (R_{perc}), which are computed through the model relationships. Table 5 presents the calibrated parameter values and their roles within the model. Parameters derived from interviews represent behavioral drivers, while structural and external parameters are included to ensure model completeness and isolate the effects of procurement coordination. Project complexity and external market volatility are held constant across scenarios to isolate the effects of procurement coordination.

Table 5. Model Parameters

Description	Used in	ICF	Typical	Source: Interview insight+ Interpretation
Group 1: Procurement/ Contract Structure				
Supplier participation gate (P_{gate})	C_i, IAR, $R_{w,}$ N_{rfi}	0.8	0.2	Interview-based: supplier participation is more likely under coordinated, lower-risk procurement conditions and decreases under fragmented, high-risk conditions; modeled as a continuous participation parameter.

GMP finalization timing (T_{gmp}) 0 = early, 1 = late stage	C_i, RB, IAR, R_w	0.3	0.7	Interview-based: GMP finalized after SD completion, at early DD stage, enabling supplier input during design development. Typical: GMP finalized at DD completion, at CD entry, limiting design flexibility and supplier engagement.
Change order friction (C_o) 0 = smooth, 1 = high	R_w	0.2	0.6	Interview-based: early coordination reduces the occurrence of change orders; modeled as lower friction.
Project complexity/max expected RFIs (K)	N_{rfi}	0.6	0.6	Structural parameter: held constant to isolate procurement effects
Group 2: Supplier and Collaboration Parameters				
ESI 0 = late entry, 1 = design phase	IAR	0.8	0.2	Interview-based: early involvement enables value-added input; modeled as increased contribution to innovation.
Coordination efficiency (P_d) 0 = low, 1 = high	N_{rfi}	0.7	0.3	Interview-based: proactive coordination reduces delays; modeled as improved efficiency.
Strength of the collaboration effect on rework (λ)	R_w, N_{rfi}	0.4	0.4	Behavioral parameter: fixed to represent the intrinsic effect of collaboration on rework and RFIs
Stakeholder trust level (Trust) 0 = low, 1 = high	C_i	0.7	0.3	Interview-based: higher trust supports collaboration despite uncertainty; modeled as a positive driver of C_i.
Communication frequency (C_{freq}) 0 = ad hoc, 1 = continuous	C_i	0.8	0.3	Interview-based: frequent communication improves coordination outcomes; modeled as a driver of C_i.
Group 3: Design and Risk Environment				
Design clarity (DC) 0 = incomplete, 1 = fully defined	B, R_w, N_{rfi}	0.4	0.7	Interview-based: At SD phase, ICF has lower initial design clarity due to innovative materials and uncertain technologies; clarity builds through early collaboration. Typical has higher initial clarity as tried-and-tested technology.

Lead time risk (LTR) Schedule exposure 0=low, 1=high	SS, R_{perc}	0.3	0.6	Interview-based: Schedule risk is a primary project concern and is modeled as a driver of R_{perc} and SS.
Lifecycle Value (V_{lc}) 0=low, 1=high	IAR	0.7	0.4	Interview-based: coordinated procurement supports consideration of longer-term project value; modeled as a positive driver of IAR.
External market volatility (Vol_{ext}) 0 = stable, 1 = high	RB, SS, R_{perc}	0.4	0.4	External condition: market volatility affects pricing validity; held constant across scenarios.
Allowance (A_w) 0 = rigid, 1 = flexible	IAR	0.7	0.3	Interview-based: budget flexibility supports schedule protection and decisions; modeled as a driver of IAR.

Behavioral coefficients governing collaboration (w1, w2, w3) and risk buffer formation (b0, b1, b2, b3) are specified based on directional relationships observed in the interviews and are held constant across both scenarios. These coefficients are not empirically estimated but reflect the relative influence of communication, trust, and procurement timing on coordination behavior.

Stability parameters, including R_{max}, ε, and ε_p, serve as numerical floor values to prevent equations from approaching zero under limiting conditions and ensure stable simulation behavior without influencing directional outcomes. The calibrated parameter values defined in this section serve as the initial inputs for all simulation experiments.

4.2 Model Architecture and Process Flow Diagram

The process flow diagram in AnyLogic (Figure 10) is designed to reflect realistic design-phase workflows by structuring the model around sequential design stages, iterative review loops, and resource-constrained activities. The flow incorporates multiple decision points, such as approvals, redesign triggers, and stage transitions, which are governed by agent interactions and model parameters rather than fixed sequences. Feedback loops (e.g., review–redesign cycles) are explicitly modeled to capture the iterative nature of design coordination. At the same time, resource blocks represent the limited availability of key stakeholders, including designers, contractors, and the CCA. This allows the model to simulate delays, rework, and coordination dependencies that arise in practice.

The process begins with project initiation, during which the owner and the design team generate initial design inputs. Following this stage, the model transitions to a review phase, in which the GCs and relevant stakeholders evaluate design outputs. Based on the review outcomes, the process either proceeds or enters a redesign loop if inconsistencies or constraints are identified. Coordinated design-assist interactions are initiated early in the design phase, allowing suppliers and subcontractors to contribute technical input during conceptual and schematic development. These interactions are supported through shared resource pools and iterative feedback mechanisms. Approval conditions trigger stage transitions, while failed reviews initiate feedback loops that return the process to earlier design stages.

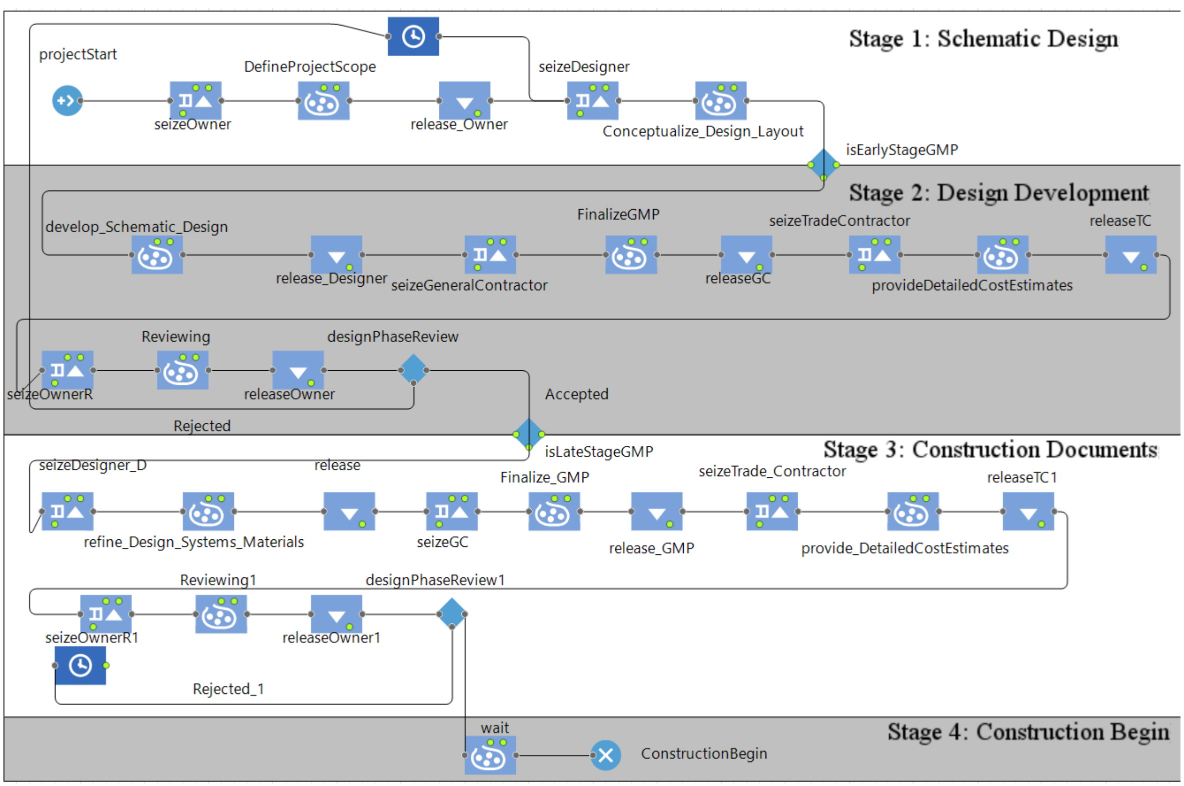


Figure 10. Process Flow Diagram

The design phase progresses through three sequential stages: Schematic Design (SD), Design Development (DD), and Construction Documents (CD). The SD phase establishes the conceptual direction, scope, and budget alignment. Following the completion of SD, a GMP decision point is introduced, where, under ICF conditions, GMP is established early at the entry of DD to enable supplier input during design development. DD refines and deepens design decisions across disciplines, after which a second GMP decision point marks the transition to the CD phase under typical procurement conditions, where GMP is finalized with less design information available. The CD phase produces the finalized drawings, specifications, and documentation required for construction execution. Construction begins only after the successful completion of the CD phase, ensuring that all design documentation is resolved before construction activities are initiated.

4.3 Agent Definitions, Attributes, and Behaviors

This section defines the main agents represented in the model, their roles within the procurement system, and the behavioral structures used to capture their interactions. The interaction logic among agents is summarized in Table 6, which defines the key event-triggered interactions governing coordination, participation, and feedback within the model. Agent interactions are governed by decision thresholds and process triggers embedded within the model. Supplier participation is represented through the calibrated parameter P_{gate}, which reflects the degree of supplier willingness to engage under each procurement condition. Higher P_{gate} values indicate a stronger propensity to participate, increasing the likelihood of supplier involvement in coordination activities. The CCA functions as a coordinating intermediary, facilitating structured communication and alignment among stakeholders during key design phases.

Table 6. Agent Interaction Logic

Sender	Receiver	Trigger Condition	Action
Supplier	CCA	Higher P_{gate} (favorable participation condition)	Joins the coordination process and provides technical input
Supplier	None	Lower P_{gate} (unfavorable participation condition	Does not participate; no coordination or input provided
CCA	GC / Owner	Start of the coordination phase	Initiates structured coordination, increasing communication frequency, trust, and alignment among stakeholders
GC	Supplier	Design requirement / technical clarification needed	Requests supplier input for design development
CCA	All agents	Review outcome (identify design issues)	Triggers redesign loop and coordination feedback
CCA	All agents	Review approval (no major issues)	Approves progression to the next stage
Supplier	None	High R_{perc} / SS	Reduces participation likelihood

The interaction structure defined above is operationalized through agent-specific behavioral models, which are detailed in the following subsections.

4.3.1 Central Coordination Agent: Integration Mechanism

The behavior of the CCA is formalized through the statechart shown in Figure 11, with corresponding state definitions and transition logic summarized in Table 7. The model captures how coordination is structured, evaluated, and iteratively refined throughout the design and decision process. The sequence begins with the establishment of compensation mechanisms, which shape stakeholder incentives and influence engagement decisions. Once these terms are defined, the system enters an integration phase in which design inputs are aligned and prepared for advancement. This enables the transition to technology adoption, in which new methods or solutions are incorporated into the workflow.

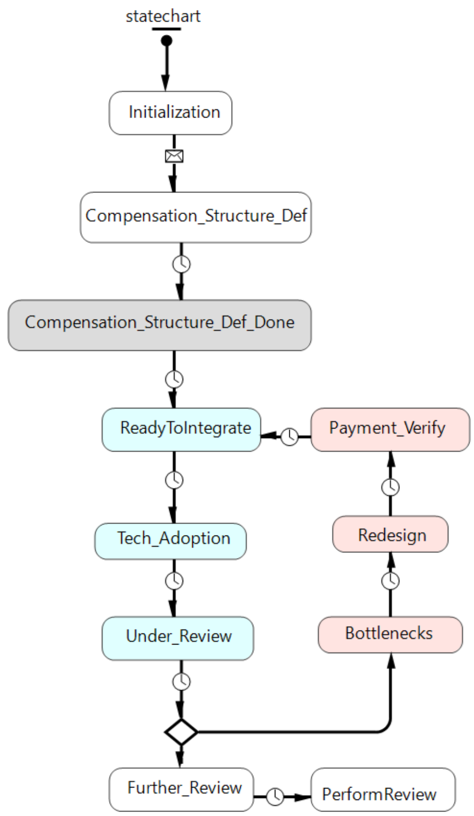


Figure 11. Statechart of the CCA with coordination flow, decision points, and iterative loops.

Following implementation, outputs undergo structured evaluation during the review stage, where both technical feasibility and coordination quality are assessed. When inconsistencies or constraints arise, the process enters an iterative loop of bottlenecks, redesign, and compensation verification. This loop represents the system's ability to adapt to emerging issues by revisiting design decisions and realigning incentives where necessary. Upon successful resolution, the process re-enters the integration phase, ensuring continuity in coordinated progression.

Table 7. CCA Agent State Definitions and Transition Logic

State	Description	Transition logic
Initialization	Establishes the starting conditions for the CCA and activates the coordination sequence.	Transitions to Compensation_Structure_ Def, once the coordination process is initiated.
Compensation_Structure_Def	Defines the competitive institutional structure, incentive	Transitions to the Compensation_Structure_definition_

	conditions, and guidelines that govern stakeholder engagement.	done are completed after compensation is established.
Compensation_Structure_Def_Done	Confirms that the compensation structure has been finalized and is ready to support coordinated action.	Transitions to Ready to Integrate to begin active coordination.
ReadyToIntegrate	Prepares stakeholders for coordinated engagement by aligning inputs and readiness.	Transitions to Tech_Adoption when the system is ready to proceed with innovation activities.
Tech_Adoption	New technologies, methods, or solutions are considered and integrated into the design process.	Transitions to Under_Review after the proposed design or innovation input is submitted for evaluation.
Under_Review	Evaluates the design, coordination quality, and implementation feasibility of the submitted solution.	Transitions to PerformReview if the outcome is acceptable; transitions to Bottlenecks if issues are identified.
Bottlenecks	Captures coordination barriers, process conflicts, or unresolved constraints that interrupt progress.	Transitions to Redesign once identified issues require corrective action.
Redesign	Represents a revision of the design or approach to resolve issues identified during review.	Transitions to Payment_Verify when design changes affect compensation, incentives, or process alignment.
Payment_Verify	Verifies whether compensation terms and incentive conditions remain valid after redesign.	Transitions back to ReadyToIntegrate once compensation alignment is confirmed.
Further_Review	Represents a secondary review for refined evaluation before approval.	Transitions to PerformReview for final assessment.
PerformReview	Conducts the final evaluation of overall readiness, coordination outcome, and process completion.	Completion of the CCA coordination cycle, unless conditions trigger additional iterations.

The final stages involve successive layers of evaluation, culminating in a performance review that reflects the overall effectiveness of coordination and decision-making. Through this structure, the CCA operates not only as a coordinating entity but also as a control mechanism that regulates transitions between progress and rework, enabling dynamic adjustment of both technical and contractual conditions within the system.

4.3.2. GC/Owner Agent: Decision and GMP Strategy

The GC/Owner agent behavior is represented by the statecharts shown in Figures 12 and 13, with the corresponding state definitions and transition logic summarized in Table 8. The model captures two interrelated processes: early-stage GMP input and design-stage decision progression under varying coordination conditions. In this study, early GMP refers to setting GMP after incorporating supplier input during early design, rather than finalizing it before sufficient design information is available. The process begins with initialization, followed by the formulation of GMP and associated inputs on cost, schedule, and constructability. This stage establishes the decision context that influences subsequent design and coordination behavior, and allows for iterative refinement through feedback loops.

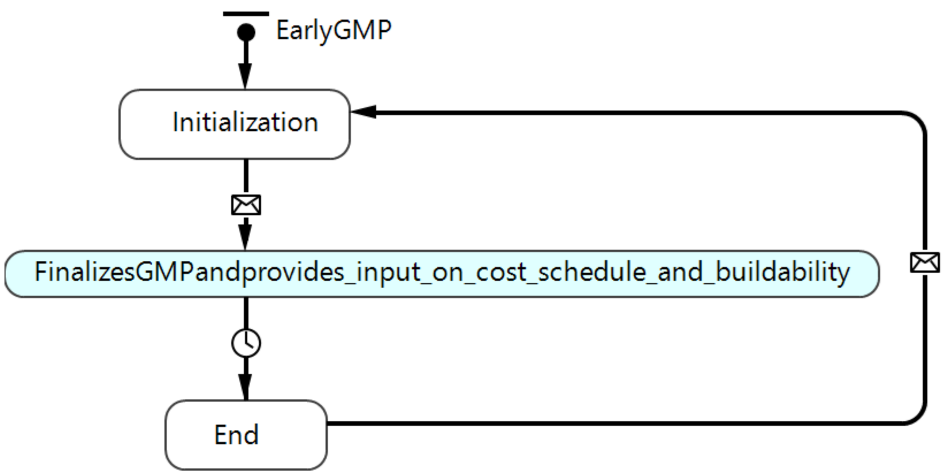


Figure 12. Early GMP definition and feedback loop for GC/Owner agent.

In parallel, the conceptual and design workflow progresses from defining the project vision and budget goals to finalizing the scope and conducting staged design reviews. A key branching point is defined by the presence or absence of the CCA, which distinguishes structured coordination from uncoordinated progression. When the CCA is present, the workflow advances with aligned inputs and integrated decision-making, whereas the absence of centralized coordination results in less structured transitions.

Following the scope definition, the process advances through schematic, design development, and final design review stages, representing increasing levels of detail and evaluation. This staged progression reflects how design decisions are incrementally refined and validated. Across both processes, the GC/Owner agent functions as a decision anchor, shaping both the initial economic conditions through GMP definition and the subsequent design trajectory through structured review and approval stages.

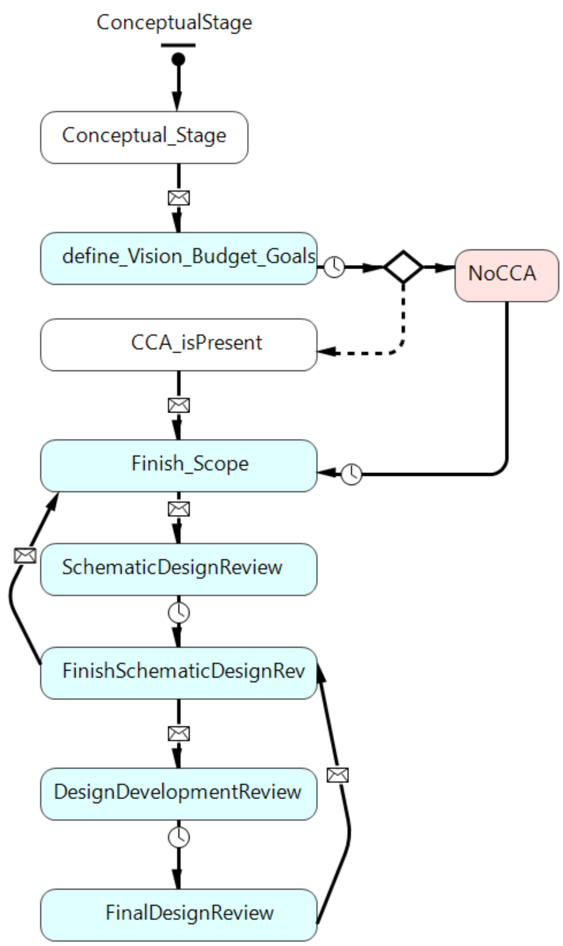


Figure 13. GC/Owner design-stage workflow under ICF and typical conditions

Rather than modeling designers as independent decision-making agents, the design process is embedded within the GC/Owner decision environment, where key decisions related to scope, budget, and coordination influence the evolution of design outcomes.

Table 8. Description of the GC and Owner Agent States and their Transitions

State	Description	Transition Logic
Initialization	Establishes the starting conditions, including early GMP and project setup.	Transitions to Finalize_GMP_and_Provide_Input
Finalize_GMP_and_Provide_Input	The GC/Owner provides input on cost, schedule, and constructability.	Transitions to End; may loop back to Initialization if revisions are required.
Conceptual_Stage	Represents early-stage planning where project scope direction is established.	Moves to define Vision Budget Goals as project objectives are formalized.
define_Vision_Budget_Goals	Establishes project vision, budget constraints, and high-level goals guiding downstream decisions.	Transitions based on coordination structure: to CCA_isPresent if central coordination exists, or to NoCCA.
CCA_isPresent	Indicates structured coordination with the CCA.	Transitions to Finish_Scope with aligned inputs and decision-making.
NoCCA	It reflects the absence of central coordination, resulting in less structure.	Transitions to Finish_Scope with potential misalignment.
Finish_Scope	Finalizes project scope, incorporating inputs from stakeholders and conditions.	Moves to Schematic Design Review for evaluation of early design outputs.
SchematicDesignReview	Reviews schematic-level design for alignment with scope and goals.	Transitions to FinishSchematicDesignRev.
FinishSchematicDesignRev	This represents the closure of the schematic design review and is ready for the next stage.	Moves to DesignDevelopmentReview for detailed evaluation.
DesignDevelopmentReview	Evaluates detailed design development and coordination across disciplines.	Transitions to FinalDesignReview for final validation.
FinalDesignReview	Final assessment of design readiness, completeness, and objectives aligned.	Mark the completion of the design decision process, or trigger iteration if required.

End	This represents the closure of the early GMP evaluation and input process.	May loop back to Initialization if input revisions are needed.

The GC/Owner agent, therefore, operates across both economic and design decision domains, linking early-stage cost definition with downstream design progression. Through GMP formulation and staged design reviews, the GC/Owner establishes the conditions under which coordination occurs, influencing supplier engagement, collaboration intensity, and the evolution of design outcomes. This dual role enables the model to capture how procurement decisions directly shape both coordination structure and design performance. This workflow captures the sequential development of design from conceptualization through schematic and design development stages. Rather than modeling designers as independent agents, the design process is embedded within the GC/Owner decision environment, where key decisions on scope, budget, and coordination shape the evolution of design outcomes.

This representation allows the model to capture how upstream decisions, such as GMP timing and coordination structure, shape design progression without introducing additional agent-level complexity. Designers are not modeled as independent agents, because the study focuses on decision structures and coordination mechanisms rather than individual design behavior. The workflow, therefore, serves as the operational context within which coordination effects and innovation outcomes are realized.

4.3.3. Key Supplier Agents: Participation and Innovation Behavior

The behavior of key suppliers in this study is not represented through a discrete statechart but is instead modeled through decision-based behavioral functions. Suppliers respond to project conditions by evaluating participation, risk exposure, and expected benefits, rather than progressing through predefined process states. Their engagement is governed by factors such as perceived risk, schedule pressure, compensation structure, and coordination quality. Supplier participation is modeled as a conditional decision in which suppliers choose whether to engage in early coordination based on these factors. Once engaged, their level of contribution influences downstream outcomes such as innovation adoption, design quality, and the likelihood of rework. Unlike the CCA and GC/Owner agents, which follow structured process flows, supplier behavior is dynamic and context-dependent, making it more appropriate to represent it through mathematical relationships rather than state-based transitions.

This formulation allows the model to capture how variations in procurement conditions, including GMP timing and coordination structure, directly affect supplier decisions and their willingness to contribute expertise during early design stages. The mathematical representation of supplier behavior is presented in the next section.

4.4 Mathematical Representation of Behavioral Relationships

The behavioral relationships governing agent decisions and project outcomes are represented through a set of mathematical functions embedded within the simulation. These functions capture how procurement conditions, perceived risks, and coordination mechanisms influence supplier participation and downstream project performance. Within the model, supplier decision-making follows a structured sequence consisting of risk assessment, participation evaluation, and collaboration response. This sequence reflects pre-collaboration decision behavior observed in practice, where suppliers first evaluate uncertainty before committing to early design engagement.

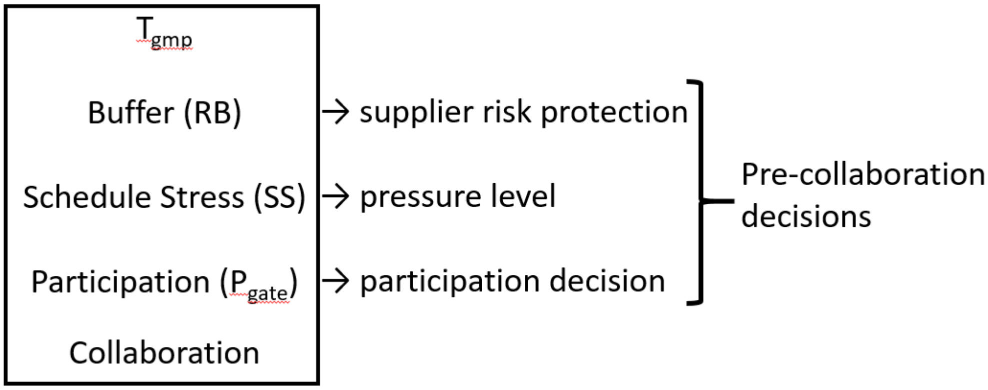


Figure 14. Supplier behavioral decision sequence

Figure 14 illustrates the sequential decision structure that governs supplier behavior prior to collaboration. Procurement conditions, such as GMP timing, shape perceived risk and schedule pressure, which directly influence P_{gate}. Participation acts as a gating mechanism; only when suppliers choose to engage does collaboration intensity emerge. This structure makes participation the primary control point for how procurement conditions shape coordination outcomes, connecting upstream decision environments to downstream project performance.

Supplier decision behavior is first modeled using a risk buffer (RB) mechanism that represents the contingency added to pricing in the face of uncertainty. The supplier risk buffer is defined as:

$$RB = b_0 + b_1 (1 - T_{gmp}) + b_2 Vol_{ext} - b_3 DC$$

The coefficients b_0, b_1, b_2, and b_3 represent weighting factors that capture the relative influence of procurement timing, market conditions, and design clarity on supplier risk perception. These weights are informed by directional relationships observed in interviews and are held constant across scenarios. T_{gmp} represents the timing of GMP finalization, Vol_{ext} represents external market volatility, and DC represents the completeness of design information. Earlier GMP timing without sufficient design information increases uncertainty and leads to higher contingency, while early GMP, supported by supplier input, reduces uncertainty.

Suppliers evaluate schedule-related stress (SS) based on lead-time constraints and market volatility. Schedule stress is defined as:

$$SS = LTR\,(1 + Vol_{ext})$$

A threshold-based decision rule governs participation in early design:

$$P_{gate} = 1 \text{ if Schedule Stress} \leq \tau$$
$$P_{gate} = 0 \text{ if Schedule Stress} > \tau$$

This defines a bounded decision mechanism in which participation occurs only when perceived schedule stress remains within acceptable limits, making P_{gate} the critical filter for early supplier engagement.

Conditional on supplier participation, collaboration intensity (Ci) is determined by communication frequency, trust, and procurement conditions. It is defined as:

$$C_i = P_{gate} \cdot \max\,(0, w_1\, C_{freq} + w_2\, \text{Trust} - w_3\, T_{gmp})$$

The parameters w_1, w_2, and w_3 represent the relative contribution of communication, trust, and procurement conditions to collaboration intensity. These coefficients are not empirically estimated; they are assigned to reflect observed behavioral tendencies and validated through sensitivity analysis. Communication and trust strengthen coordination, while delayed GMP reduces willingness to engage during design development.

```
Function body

Ci = Pgate * max(0, (w1*Cfreq + w2 * Trust – w3 * T_gmp));

RiskPerc = LTR + Volext;

RB = b0 + b1*(1 – T_gmp) + (b2 * Volext) – (b3 * DC);

SS = LTR * (1 + Volext);
```

Figure 15. Implementation of behavioral functions within the supplier agent logic in AnyLogic

These relationships are implemented as functional components (Figure 15) within the supplier agent logic linking procurement conditions to participation decisions and coordination outcomes in the simulation environment.

Building on this behavioral foundation, the following section defines how these interactions are translated into measurable performance metrics.

4.5 Quantification of Performance Metrics

These performance metrics are computed dynamically within the simulation based on agent interactions and procurement conditions defined in the preceding sections. The simulation evaluates procurement coordination performance using four outcome metrics: innovation adoption, design rework, RFI generation, and capacity utilization. All metrics are normalized or expressed in relative terms to enable comparison across scenarios, with higher values indicating improved performance. These metrics are directly derived from the behavioral relationships defined in Section 4.4, ensuring consistency between agent decision mechanisms and system-level performance outcomes.

IAR captures the extent to which new technologies, materials, or methods are integrated during the design phase. It is defined as:

$$\mathrm{IAR} = \frac{(\varepsilon + \mathrm{Pgate}) \cdot \mathrm{ESI} \cdot \mathrm{Aw} \cdot \mathrm{Vlc}}{[\omega 2\ \mathrm{Rperc}(\varepsilon + \mathrm{Tgmp})]}$$

Here, P_{gate} denotes supplier participation, ESI reflects early supplier involvement, Aw captures allowance flexibility, and V_{lc} represents lifecycle value. This formulation links participation and early engagement to innovation outcomes, while accounting for the constraining effects of risk and delayed cost commitment. R_{perc} represents the level of uncertainty influencing decision-making. It is defined as:

$$R_{perc} = LTR + Vol_{ext}$$

R_{perc} represents the combined effect of lead-time risk and external market volatility on perceived uncertainty. As R_{perc} increases, suppliers become more risk-averse, reducing their willingness to contribute to early design decisions and limiting the integration of new technologies or methods. Conversely, lower R_{perc} values indicate more stable conditions, enabling greater engagement and higher adoption of innovation.

Design Rework (R_w) represents the extent of revisions required due to coordination issues, incomplete design information, or procurement constraints. It is modeled as:

$$Rw = \frac{(1 - Pgate + \varepsilon)Rmax + Pgate\,[(1 - DC)(1 - Tgmp) + Co]}{(1 + \lambda\, Ci)}$$

Here, R_{max} denotes the upper bound of rework, DC reflects design clarity, T_{gmp} represents GMP timing, C_o captures change order friction, and Ci denotes collaboration intensity. Rework increases under limited participation and low design clarity, and decreases as collaboration improves coordination effectiveness.

RFI Generation (N_{rfi}) represents coordination queries arising from unresolved design issues and stakeholder misalignment, serving as a proxy for coordination breakdowns and design uncertainty. It is defined as:

$$Nrfi = \frac{(1 - Pgate + \varepsilon p) \cdot K\,(1 - DC)}{(1 + \lambda Ci) \cdot (1 + p\,(1 - Pd)) + \varepsilon}$$

Here, K represents project complexity, DC reflects design clarity, Ci denotes collaboration intensity, and Pd captures coordination efficiency. RFIs increase with poor design clarity and limited participation, and decrease as collaboration and coordination efficiency improve.

Capacity Utilization (CU) reflects the efficiency of resource use under coordination conditions and serves as a proxy for coordination effectiveness during the design phase. In this model, disruptions from RFIs, rework, and iterative feedback loops undermine workflow continuity, leading to underutilization of available resources. CU is therefore defined as a function of coordination disruptions, where higher RFI levels reduce effective utilization due to interruptions, rework cycles, and delays in decision-making. It is defined as:

$$\mathrm{CU} = \frac{1 - \alpha \mathrm{Nrfi}}{\mathrm{Nrfi, max}}$$

Here, $N_{rfi,\ max}$ denotes the upper bound on RFIs under severe coordination breakdown conditions. Higher RFI levels reduce effective capacity due to workflow interruptions and rework. This formulation links coordination breakdowns directly to resource efficiency, allowing the model to capture not only design outcomes but also the operational impact of coordination quality. Figure 16 illustrates the implementation of behavioral and performance metrics within the simulation, linking procurement conditions to participation decisions, coordination mechanisms, and project outcomes.

```
IAR = Pgate * ( (ESI * AW * V_lc) / max(0.1, (w2 * RiskPerc * (ε + T_gmp))) );
Rework_ = ( 1 - Pgate + ε) * R_Max + (Pgate * ((1 - DC) * (1 - T_gmp) + Co)) / ( 1 + (λ * Ci));
RFI = (1 - Pgate + ε_p) * ((K*(1-DC)) / (1+(λ*Ci)) * (1+P*(1 - Pd) + ε)));
```

Figure 16. Implementation of Behavioral and Performance Metrics

Together, these formulations establish a unified behavioral structure through which procurement conditions influence supplier participation, collaboration, and downstream performance metrics. This integrated representation provides the basis for evaluating how variations in procurement timing, risk perception, and coordination affect innovation adoption, rework, RFIs, and capacity utilization in the simulation.

4.6 Model Assumptions and System Boundaries

The model adopts the following simplifying assumptions to represent procurement coordination during the design phase.

1. The model is limited to the design coordination stage, where key procurement and technical decisions are made. Downstream construction execution, logistics, and financial flows are not explicitly modeled, allowing isolation of procurement-driven coordination effects.

2. The model does not explicitly simulate cost calculations or bidding behavior. Cost-related effects are represented indirectly through perceived risk, contingency buffers, and participation decisions.

3. Supplier participation decisions are based on schedule stress, market volatility, and design clarity. Decisions follow a threshold-based mechanism (P_{gate}), in which participation occurs only when perceived risk remains below an acceptable tolerance level, reflecting bounded-rational decision-making.

4. Behavioral relationships are represented using simplified linear and threshold-based functions to capture directional effects observed in interviews, prioritizing interpretability over precise quantitative prediction.

5. The model abstracts time into discrete design and construction-phase iterations, enabling representation of iterative review–redesign cycles without modeling detailed scheduling dynamics.

6. Procurement parameters (e.g., GMP timing, ESI, and communication frequency) are treated as exogenous inputs set by the user, while outcomes such as collaboration intensity, rework, RFIs, and innovation adoption are generated within the model through agent interactions.

These boundary conditions allow the model to isolate the effects of procurement coordination on design-phase performance. These assumptions define the behavioral and structural scope of the model, which is implemented by initializing procurement conditions as input parameters and executing agent-level decision rules to simulate coordination dynamics and generate performance outcomes.

4.7 Model Implementation in AnyLogic

The simulation integrates the agent behaviors, calibrated parameters, and mathematical relationships defined in the preceding sections within a dynamic, time-based environment. Model execution is driven by parameter inputs that represent procurement structure, coordination conditions, and behavioral responses, allowing the system to evolve through interaction-driven updates at each simulation step. To operationalize the model, parameter values are assigned via the input interface, where all variables are defined on a normalized scale and grouped by their functional role within the system. These include procurement and contract parameters, supplier and collaboration factors, design and risk conditions, behavioral coefficients, and system stability constants. This structure ensures that parameter inputs directly correspond to the mathematical relationships governing collaboration intensity, risk perception, innovation adoption, rework, and RFIs. The simulation is configured to evaluate the effect of procurement structure by comparing two conditions: structured procurement (ICF with CCA enabled) and a baseline typical procurement. Differences between these scenarios arise from parameter settings for P_{gate}, ESI, P_d, trust, C_i, and T_{gmp}. All other structural and stability parameters, including K, λ, and Vol_{ext}, as well as behavioral coefficients (w_1–w_3, b_0–b_3), are held constant to isolate the impact of coordination and decision conditions. During each simulation run, agent interactions iteratively update system states. Supplier participation influences the intensity of collaboration, which in turn affects design clarity and downstream outcomes. Changes in R_{perc} and SS propagate through the system, influencing risk buffering behavior and participation decisions. The model is designed to evaluate how variations in coordination structure and GMP timing influence system performance. Output measures, including innovation adoption, rework, RFIs, and capacity utilization, are tracked over time to assess differences between scenarios. The resulting simulation outputs provide the basis for analyzing how procurement decisions and coordination mechanisms shape project outcomes. The parameter configurations used to represent these conditions are implemented through the simulation input interface, and the corresponding scenario setups are presented in the following subsection.

4.7.1 Model Inputs and Scenario Configuration

The simulation model incorporates a set of adjustable input parameters that represent procurement structure, supplier engagement, design conditions, and behavioral decision factors. These parameters are controlled through interactive sliders within the AnyLogic 8.9.8 experiment interface (Figures 17–18), enabling systematic evaluation of different procurement environments. Parameters are organized into five functional categories reflecting their roles within the model structure. The slider-based interface allows parameters to be adjusted prior to each simulation run, enabling controlled experimentation by systematically varying coordination conditions while maintaining consistent baseline settings.

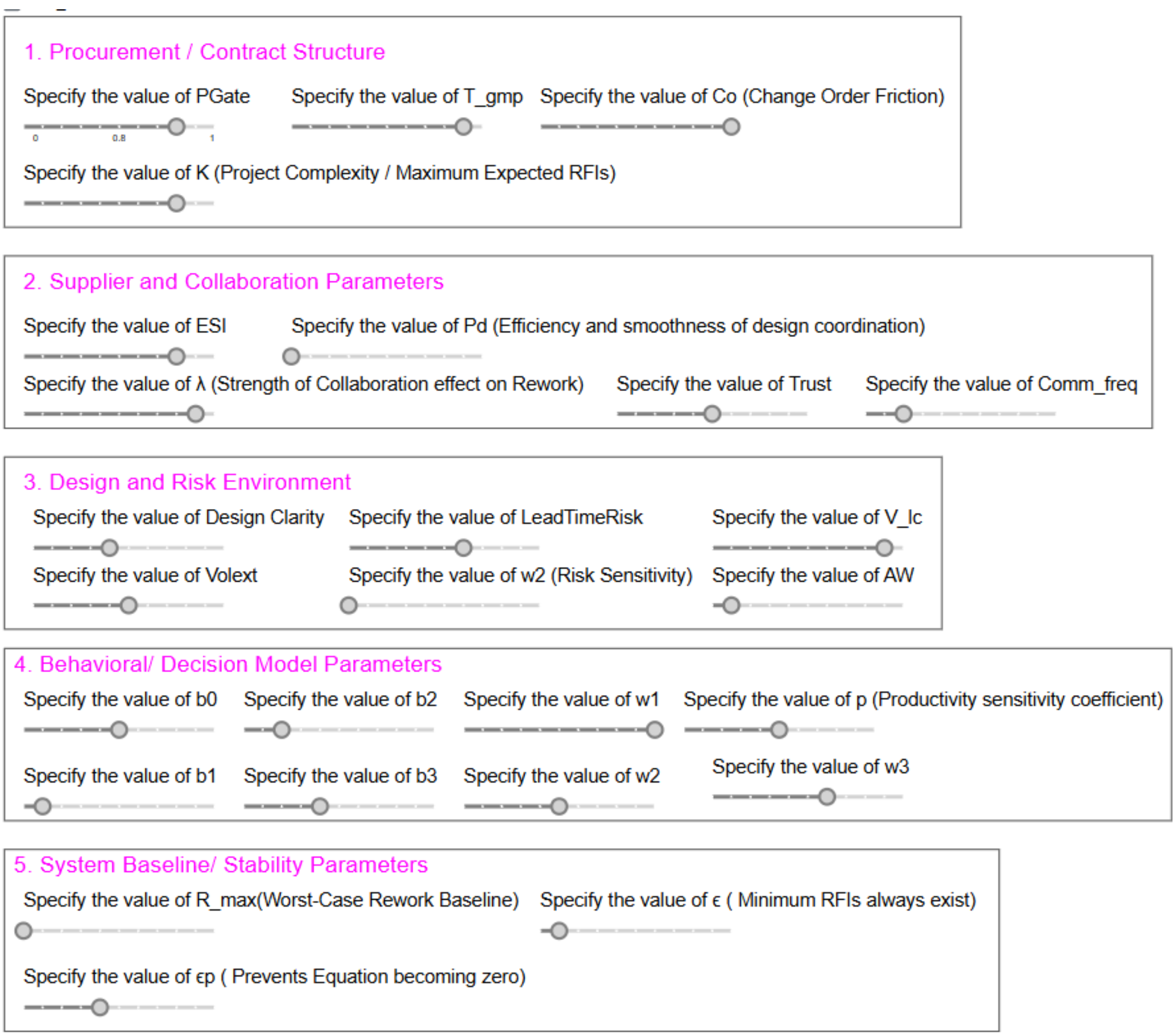


Figure 17. Simulation input configuration for a typical procurement scenario

The model evaluates two primary procurement scenarios. In the typical scenario, procurement operates under a fragmented structure, with supplier involvement occurring later in the design process. Coordination among stakeholders is limited and primarily reactive, resulting in lower communication frequency, reduced trust, and greater exposure to schedule and design risks. Procurement conditions such as delayed GMP finalization, greater change-order friction, and increased lead-time risk reflect typical traditional project settings. Under these conditions, supplier participation is constrained, collaboration intensity is lower, and design uncertainty remains elevated. Supplier and collaboration parameters, such as early supplier involvement, communication frequency, and trust, are enhanced, while design and risk conditions reflect improved design clarity and reduced schedule exposure. These conditions support higher supplier participation, stronger collaboration intensity, and more stable design progression.

Figure 18. Simulation input configuration for ICF scenario

Across both scenarios, parameter values are assigned through the input interface and propagated through the model's mathematical relationships. During each simulation run, procurement conditions are initialized, supplier participation decisions are evaluated, collaboration intensity is computed, and downstream performance outcomes are generated. These interactions evolve dynamically, allowing the model to capture how changes in coordination structure and procurement conditions influence system behavior over time. The two scenarios differ only in coordination structure and associated parameter settings, while all structural and stability parameters remain constant. By systematically varying parameter values across the two scenarios, the simulation enables direct comparison of traditional and coordinated procurement environments. These comparisons are used to evaluate differences in supplier participation, collaboration dynamics, innovation adoption, rework, and coordination-related performance outcomes.

The simulation, therefore, functions as a controlled experiment in which coordination structure and associated behavioral parameters are varied. At the same time, structural conditions are held constant to isolate their impact on system outcomes.

4.8 Face Validity Assessment

To establish face validity before simulation experiments, the practitioners who participated in the original interviews reviewed the calibrated parameter table and scenario configurations. Practitioners were asked to evaluate whether the parameter values, relative differences between scenarios, and overall coordination assumptions reflected conditions consistent with their project experience. Reviewers from the ICF group confirmed that the modeled coordination conditions, engagement structures, and risk exposures aligned with structured procurement environments they had experienced. Practitioners from the typical procurement group similarly confirmed that the baseline configurations reflected the coordination constraints and limited early engagement characteristic of traditional delivery.

While some variation was observed in how individual stakeholders described the magnitude of specific parameters, particularly in areas such as trust, communication frequency, and allowance flexibility, there was consistent agreement on the direction and relative differences between coordinated and typical procurement conditions. These variations reflect project-specific conditions and stakeholder perspectives and do not undermine the model's validity, as it is designed to capture aggregated behavioral patterns rather than exact project-level values.

Chapter Summary

This chapter presented the full development of the ABM used to simulate procurement coordination dynamics in construction systems. The chapter began by establishing a structured parameter-calibration logic, in which interview evidence was systematically translated into normalized model inputs that reflect behavioral differences between the ICF and typical procurement environments. These parameters, spanning procurement structure, supplier engagement, design conditions, and risk exposure, were assigned based on the frequency, consistency, and directional strength of qualitative insights, ensuring empirical grounding rather than abstract assumptions.

Building on this foundation, the model architecture was defined through a process flow diagram that captured sequential design stages, iterative review-redesign loops, and resource-constrained activities, reflecting realistic design-phase workflows. The process flow reflects the three sequential design stages of Schematic Design, Design Development, and Construction Documents, with GMP decision points positioned to distinguish between ICF and typical procurement conditions. Three agent types were formalized: the CCA, which regulates transitions between progress and rework while managing compensation and alignment; the GC/Owner agent, which anchors both economic conditions through GMP formulation and design progression through staged review and approval; and key supplier agents, whose participation and innovation behavior are governed by dynamic, context-sensitive decision functions rather than fixed process states.

The mathematical representation of behavioral relationships formalized how procurement conditions propagate through the system, from risk buffer formation and schedule stress evaluation to the participation gate mechanism and downstream performance outcomes. Four performance metrics were derived directly from these behavioral relationships: innovation adoption rate, design rework, RFI generation, and capacity utilization, each capturing a distinct dimension of coordination effectiveness across the design and construction lifecycle.

The chapter then defined the model's assumptions and system boundaries, establishing that the simulation is scoped to design-phase coordination, with cost flows, bidding behavior, and detailed scheduling dynamics intentionally excluded to isolate procurement-driven effects. Implementation in AnyLogic was described, including the slider-based input interface that enables controlled scenario experimentation, followed by a face validity assessment confirming that practitioners across both ICF and typical procurement environments recognized the calibrated parameters and scenario configurations as consistent with real-world project experience.

The next chapter applies this model under different scenarios to examine how variations in key inputs influence participation behavior, interaction dynamics, and performance outcomes. Together, these components establish a coherent, empirically grounded simulation framework that captures how micro-level procurement decisions propagate into system-level performance outcomes, providing the analytical foundation for the simulation experiments and results presented in Chapter 5.

Chapter 5 Results

The results presented in this chapter are derived from the ABM model developed in Chapter 4, in which agent-based interactions among stakeholders generate dynamic performance outputs throughout the project lifecycle. Rather than presenting static outcomes, the simulation captures how coordination decisions made early in the project propagate through the system, producing compounding effects that manifest differently across design and construction phases. The analysis compares a coordinated procurement environment, represented by the ICF, with a typical fragmented procurement environment, shifting from the model structure to a dynamic evaluation of system behavior under different coordination conditions. The objective is to examine how differences in coordination structure and timing affect key performance outcomes, including innovation adoption, redesign, RFI generation, and capacity utilization, interpreted at the system level to demonstrate how structural differences in coordination lead to distinct performance trajectories over the project lifecycle. The chapter begins with the simulation setup and experimental design (Section 5.1), followed by the definition of comparative procurement scenarios (Section 5.2). It then analyzes simulation outputs across key performance metrics (Section 5.3) and examines overall system behavior and performance differences between ICF and typical environments (Section 5.4).

5.1 Simulation Setup

The simulation experiments are designed to evaluate how coordination structures influence stakeholder behavior and project performance in a dynamic, project-timeline-based environment. The model is implemented in AnyLogic and operates over a normalized project timeline, where the x-axis represents progression from 0% to 100% of the design and construction lifecycle. This normalized timeline allows comparison of system behavior across conceptual design, schematic design, design development, and construction phases.

The experimental design follows a controlled comparative approach in which differences between scenarios are introduced through key behavioral and coordination parameters, including supplier participation (P_{gate}), early supplier involvement (ESI), collaboration intensity (C_i), coordination efficiency (P_d), trust, communication frequency (C_{freq}), and GMP timing (T_{gmp}). All structural and stability parameters are held constant across scenarios to isolate the effect of coordination conditions on system behavior.

Simulation execution proceeds in discrete time steps, with agent interactions updating system states at each step. At each time increment, supplier participation influences the intensity of collaboration, which in turn affects design clarity, risk perception, and downstream performance variables. These interactions create feedback effects that drive system behavior over time. During each simulation run, these interactions generate dynamic outputs for innovation adoption rate (IAR), design rework (R_w), RFI volume (N_{rfi}), and capacity utilization (CU). Simulation outputs are recorded continuously, enabling phase-wise comparison. This setup allows direct evaluation of how variations in integration conditions influence patterns and the evolution of project performance over time. The simulation setup enables controlled comparison of alternative procurement scenarios, described in the following section.

5.2 Simulation Scenarios

Using this simulation setup, the model compares two procurement scenarios that differ in their coordination structures and information-flow dynamics. The Typical Baseline represents a traditional, siloed procurement environment characterized by a sequential flow of information. In this setting, key suppliers are engaged only after major design milestones are reached, resulting in delayed technical feedback and limited early interaction. Within the model, this behavior is reflected in lower initial parameter values. The parameter values and behavioral assumptions used in both scenarios are defined in Chapter 4. As a result, coordination remains reactive, with issues identified and addressed later in the project lifecycle. In contrast, the ICF introduces a CCA that functions as a structural bridge across stakeholders. This shifts the system from sequential to parallel information flow, in which supplier input is incorporated during the early design stages. In the model, this is represented through higher P_d and earlier activation of P_{gate}, enabling continuous interaction and alignment.

To ensure a controlled comparison, all structural and system-level conditions are held constant across both scenarios, including project complexity, agents' baseline productivity, and overall task structure. This isolation ensures that observed differences in the outputs can be attributed directly to differences in coordination timing and interaction patterns, rather than external project factors. The following section presents the simulation outputs generated under these two scenarios across four key performance indicators.

5.3 Simulation Output Analysis

The simulation results illustrate how coordination structures influence stakeholder behavior and project outcomes across the design and construction timeline. The outputs focus on four key performance indicators, which provide a dynamic view of how coordination mechanisms affect project performance across both procurement environments. Innovation adoption and redesign are evaluated over the design timeline, while RFI volume and capacity utilization are assessed during the construction phase.

5.3.1. Innovation Adoption Rate

The simulation results, shown in Figure 19 and summarized in Table 9, reveal a fundamentally different innovation adoption process in the ICF and Typical environments, rather than merely a difference in final adoption levels. Unlike RFI generation and redesign activity, innovation adoption is represented as a smooth progression rather than an episodic one. This reflects its nature as a gradual decision-making process in which design teams evaluate alternatives, build confidence, and incrementally commit to new solutions. Adoption accelerates as coordination conditions improve and stabilizes once major design decisions are finalized. It is worth noting that the ICF design timeline extends to 150 time units compared to 100 in the typical environment, reflecting the additional time required for early coordination, supplier alignment, and iterative design evaluation inherent to the ICF process. Across both scenarios, the design phases progress from broad system selection during conceptual design, through spatial coordination and system integration during schematic design, to detailed refinement during design development, with innovation adoption responding differently to these transitions depending on the level of early coordination.

In the ICF scenario, innovation adoption begins at a slower rate during the conceptual phase, reaching approximately 5-8%, not due to limited innovation activity, but because early-stage effort is directed toward stakeholder alignment, system evaluation, and integration of supplier input. During this phase, early supplier involvement increases stakeholder interaction. Suppliers are actively involved in constructability and feasibility assessments during this phase, thereby extending the decision-making process and improving the quality and feasibility of subsequent innovation decisions.

As the project transitions into the SD phase, the adoption of innovation accelerates. This shift occurs as improved collaboration and early technical input reduce perceived risk, enabling faster integration of new technologies. Innovation shifts from exploratory evaluation to implementable solutions, resulting in a sharp increase in adoption. By the DD stage, the rate of increase slows and stabilizes at a high level, approaching approximately 75%. At this point, most system-level decisions have already been made, and the design process shifts toward detailing, coordination, and integration. This stabilization indicates that most major design decisions are complete, with fewer new changes introduced.

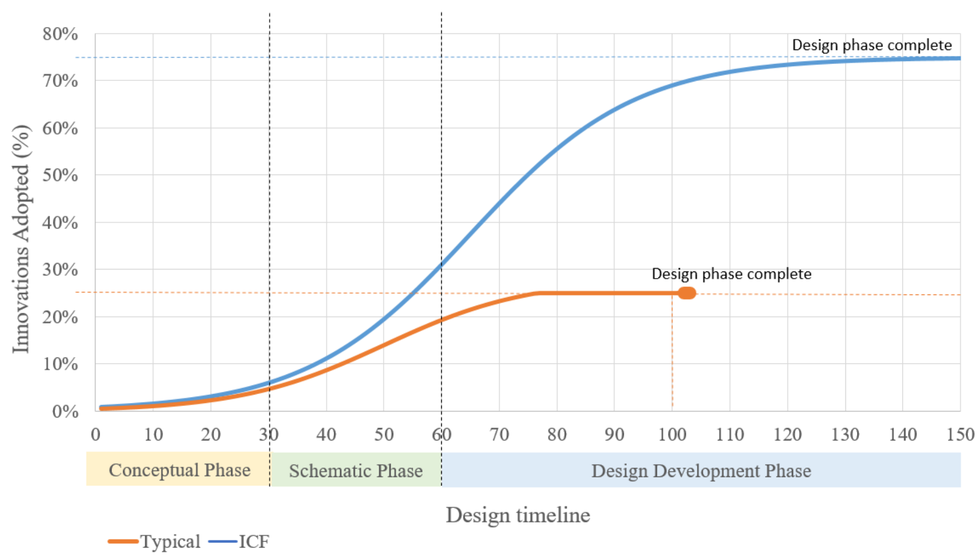


Figure 19. Innovation adoption rate over the design timeline under ICF and Typical scenarios

In the typical scenario, innovation adoption remains limited because delayed supplier involvement limits early input and slows the integration of new solutions. During the conceptual phase, innovation appears to progress slightly, reaching only about 5–8%, due to reliance on familiar or previously used systems that require minimal validation. However, this early activity is limited in scope and does not represent meaningful integration of new technologies. As the project progresses into the schematic and design development stages, the adoption of innovation gradually increases but remains constrained, plateauing at approximately 25%. The absence of early technical input leads to higher risk perception (R_{perc}) and unresolved feasibility concerns, discouraging the adoption of unfamiliar systems. By the time sufficient information becomes available to evaluate new solutions, design decisions have already been formalized, and the cost and effort required to introduce changes become prohibitive.

Table 9. Phase-wise comparison of innovation adoption behavior.

Phase (%)	ICF Scenario Results	Typical Scenario Results	Underlying Design Dynamics
Conceptual (0–30%)	Limited coordination impact; stakeholders explore options.	Similar behavior with no structured coordination.	Both systems behave similarly under early uncertainty.
~20–30%	Coordination begins influencing decisions.	Limited coordination restricts early decision influence.	Divergence begins due to the structure.
Schematic Design (30–60%)	Strong collaboration and ESI improve integration and reduce emerging issues.	Coordination remains fragmented, leading to increasing conflicts.	Early coordination accelerates stabilization and improves outcomes.
Design Development (60% to Design Completion)	Earlier issue resolution stabilizes design and limits downstream disruption.	Ongoing conflict discovery leads to continued redesign.	Early coordination reduces late-stage inefficiencies.

The Construction Documents phase is not included in this comparison because major design decisions are largely resolved by the end of the Design Development stage, making CD primarily a documentation and detailing phase rather than a decision-making one. Overall, the ICF environment shifts innovation earlier in the design process, while the typical environment delays integration. This is driven by earlier supplier involvement and improved coordination, which enable earlier and more effective integration of innovation. These differences in innovation timing influence downstream design performance, which is examined through redesign behavior in the following section.

5.3.2. Design Rework

Unlike innovation adoption, design rework is represented as a cumulative stepped progression rather than a smooth curve. This reflects its nature as a reactive process in which design rework iterations are triggered by discrete coordination events, such as the identification of constructability conflicts or integration gaps, rather than accumulating continuously over time. As a result of this extended coordination process, the ICF design phase spans 150 time units, compared to 100 in the typical environment, because additional time is required to facilitate early supplier involvement, conduct constructability assessments, and align the design iteratively before construction begins. The simulation results, shown in Figure 20 and summarized in Table 10, reveal fundamentally different design-rework patterns between the two scenarios. During the conceptual phase, design decisions remain high-level, focusing on structural system selection, mechanical strategies, and facade approaches, limiting the emergence of detailed conflicts. In the ICF, redesign activity increases during the early conceptual phase (0–30%), then reaches moderate levels as stakeholders coordinate, evaluate alternatives, and align on design decisions. This initial increase reflects active problem identification rather than inefficiency. While redesign follows an overall cumulative trend, minor variations in the curve reflect localized coordination adjustments rather than fully episodic behavior. Early coordination exposes constructability and integration constraints at earlier stages, when design decisions are still flexible. As a result, conflicts are addressed during the initial stages rather than deferred.

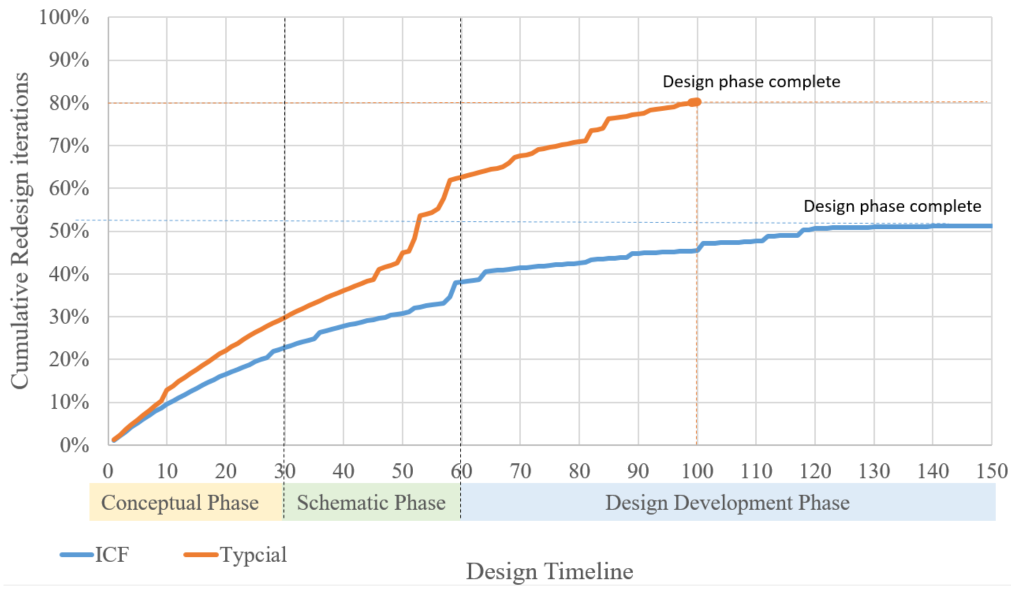


Figure 20. Cumulative redesign iterations over the design timeline under ICF and Typical scenarios.

As the project enters schematic design, systems begin competing for space, MEP routing, structural sizing, and facade attachments create the first real interdisciplinary conflicts. As the project transitions into the schematic phase (30–60%), the rate of redesign begins to stabilize. Improvements in design clarity, supported by continued collaboration, reduce the need for repeated revisions. Since many coordination issues have already been identified through early interaction, redesign shifts from iterative correction to controlled refinement rather than repeated cycles. During design development, the focus shifts to detailing and clash resolution: early coordination in ICF means most conflicts are already resolved, whereas in Typical they continue to accumulate. By the design development stage (60–Design Completion), redesign activity flattens at a relatively low level (approximately 50%), indicating stable design progression with minimal late-stage disruption. At this stage, most coordination issues have already been resolved, and the redesign no longer spans multiple systems.

Table 10. Phase-wise comparison of redesign behavior under ICF and Typical scenarios.

Design Phase (%)	ICF Scenario Results	Typical Scenario Results	Underlying Design Dynamics
Conceptual (0–30%)	Gradual increase in redesign iterations beginning from the early stages.	Redesign remains low.	Higher P_{gate} and C_i in ICF expose issues early. In the Typical scenario, limited interaction delays the identification of constructability and integration constraints.
Schematic (30–60%)	Redesign growth slows and begins stabilizing.	Redesign increases sharply.	Higher C_i and improved DC in ICF resolve issues early. In the baseline, unresolved conflicts begin to surface, increasing the number of redesign cycles.
Design Development (60% to Design Phase Completion)	Curve flattens (~5–6 redesign iterations, ~50%).	Curve continues rising (~18–20 iterations, ~80%).	Early resolution in ICF stabilizes design. In a typical model, late discovery of conflicts drives continued redesigns.

In contrast, the typical scenario exhibits a delayed but significantly higher redesign trajectory. Redesign remains low during the conceptual phase, as limited early P_{gate} and lower C_i reduce interaction and delay the identification of issues. However, this low initial activity reflects unresolved constraints rather than effective coordination. As the project progresses into the schematic phase, redesign activity increases sharply due to the emergence of previously unaddressed constructability and integration conflicts. The absence of early C_i and limited improvement in DC result in repeated redesign iterations as issues are identified later in the process. This trend continues into the design development stage, where redesign accumulates further, reaching substantially higher cumulative levels (approximately 80%) as late-stage corrections require design rework across multiple systems and propagate across disciplines.

Overall, redesign occurs earlier and stabilizes with coordination, whereas it is delayed and accumulates without coordination. In the ICF environment, early coordination improves design clarity and shifts redesign to earlier stages, where changes are less costly and more manageable.

In contrast, the typical procurement environment delays issue identification, resulting in lower early redesign but significantly higher cumulative design rework due to repeated late-stage corrections. Redesign patterns indicate when issues are identified, while RFI volume reflects how unresolved coordination gaps translate into formal clarification during project execution.

5.3.3. Request for Information Volume

The simulation results, shown in Figure 21 and summarized in Table 11, reveal distinct differences in RFI generation patterns between both environments. Unlike innovation adoption and capacity utilization, RFI generation exhibits episodic behavior, with step-like increases corresponding to concentrated coordination breakdowns during key construction phases.

In the ICF scenario, RFI levels remain consistently low throughout the project lifecycle, with only a gradual increase over time. This behavior is associated with stronger coordination and earlier alignment, which enhances design clarity in the early stages. As a result, many design ambiguities and integration requirements are resolved before formal RFIs are issued. Consequently, RFIs that do occur represent minor clarifications rather than unresolved coordination issues, preventing escalation during construction. As the project progresses from the early (0–30%) to the later (60–100%) stages, RFI growth remains controlled and stable. Improvements in design clarity, supported by continuous coordination, reduce the occurrence of unresolved issues.

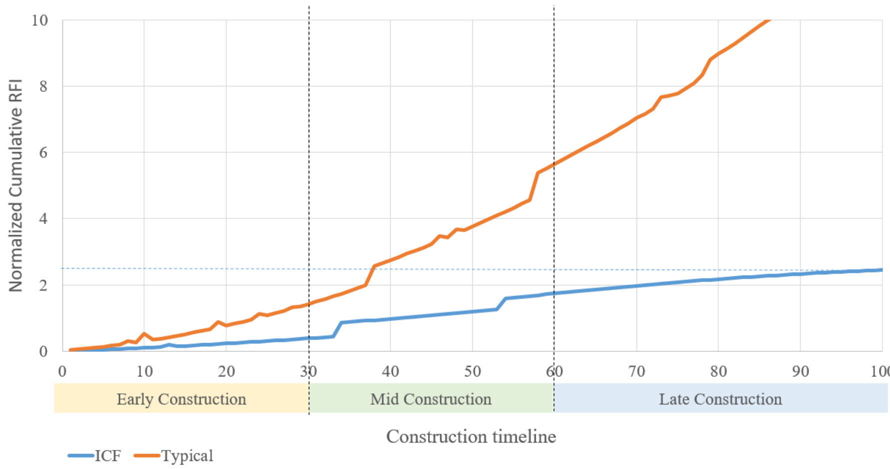


Figure 21. Normalized cumulative RFI volume over the construction timeline.

In contrast, the typical environment exhibits a delayed but rapidly increasing RFI trajectory. RFI levels remain low during the early phase, not due to effective coordination, but because lower P_{gate} and weaker C_i limit early issue identification. As the project transitions into the mid-phase (20–60%), unresolved design conflicts and integration gaps begin to surface, leading to step-like increases in RFIs during key coordination phases. This period corresponds to the critical construction phase in which MEP, structural, and facade systems are installed concurrently, creating significant trade overlap and intensifying coordination demand. The absence of early improvements in DC and lower coordination P_d results in repeated clarification cycles as issues are identified later in the process. This pattern continues into later stages, where RFIs accumulate through additional localized spikes driven by field-level coordination challenges and late-stage system interactions.

Table 11. Phase-wise comparison of RFI generation patterns

Construction Phase (%)	ICF Scenario Results	Typical Scenario Results	Underlying Construction Dynamics
Early Construction (0–30%)	RFIs remain low and increase gradually.	RFIs remain low.	Early coordination in ICF resolves issues before they require formal RFIs. In traditional projects, issues are

			not yet identified due to limited early interaction.
Mid Construction (30–60%)	RFIs increase gradually with minor localized variations.	RFIs increase sharply through episodic spikes.	Trade overlap increases coordination demand. ICF limits escalation through prior alignment, while unresolved conflicts typically lead to increased RFIs.
Late Construction (60–100%)	RFIs stabilize with minimal growth.	RFIs continue increasing.	Early resolution in ICF prevents the accumulation of issues. In a typical scenario, unresolved problems persist, leading to higher cumulative RFIs and ongoing clarification needs.

Overall, the ICF scenario demonstrates controlled RFI generation with substantially lower cumulative levels. In contrast, the typical environment exhibits delayed but accelerated RFI growth, resulting in significantly higher total RFI counts. The timing of coordination drives this difference. In the ICF with a CCA-enabled environment, early coordination enhances design clarity in the project lifecycle, preventing issues from escalating into N_{rfi}. In contrast, the baseline procurement environment delays coordination, allowing unresolved issues to accumulate. This dynamic reflects the reinforcing feedback mechanism embedded in the model structure, whereby delayed coordination increases risk perception, which further suppresses early participation, reducing design clarity and generating additional RFIs as the project progresses. The accumulation of RFIs directly affects workflow continuity, making capacity utilization a downstream reflection of how effectively coordination issues are managed.

5.3.4. Capacity Utilization

Unlike RFI generation, capacity utilization shows a smooth, continuous decline rather than an episodic one. This reflects its nature as an aggregate workflow measure that responds gradually to the cumulative effect of coordination conditions, rather than reacting sharply to discrete events. As coordination issues accumulate over time, their combined pressure on workflow continuity produces a steady rather than abrupt change in available capacity. The simulation results, shown in Figure 22 and summarized in Table 12, reveal clear differences in capacity utilization (CU) patterns between the two environments. In both scenarios, CU begins at approximately 95% and declines gradually during the early phase (0–30%), with ICF reaching around 93–94% and the typical environment reaching approximately 90–91%, indicating minimal disruption during initial construction stages. The divergence between the two scenarios becomes more evident during the mid-construction phase (30–60%).

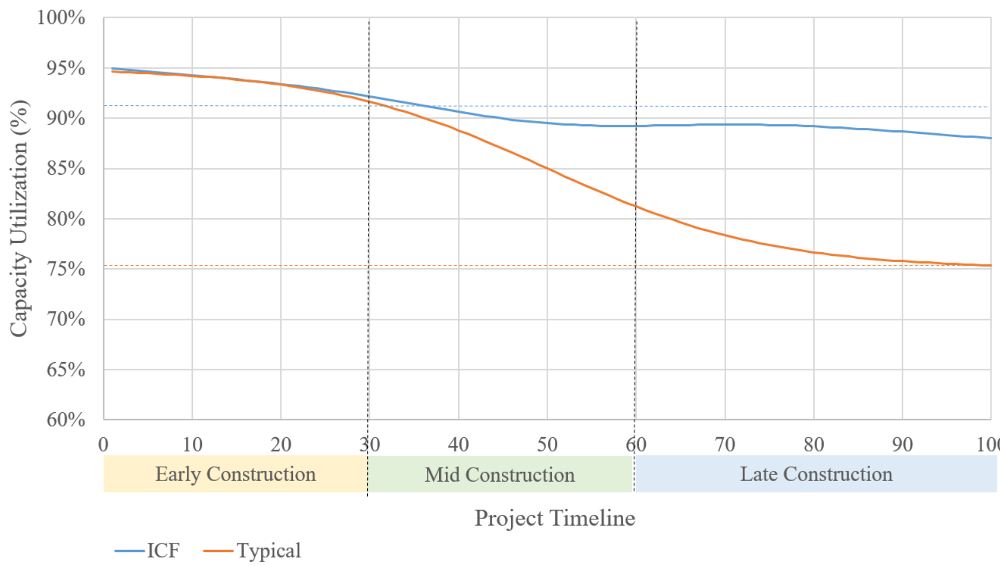


Figure 22. Capacity utilization dynamics over the project timeline

In the ICF environment, CU declines gradually, reaching approximately 90–91% by mid-construction, then stabilizes at approximately 87–88%. In contrast, the typical environment experiences a more pronounced decline, dropping to approximately 83–84% during the mid-phase. This decline coincides with the period of highest trade interaction, when concurrent MEP, structural, and facade activities increase the demand for coordination and amplify the impact of unresolved design issues on workflow continuity. This reduction reflects growing disruptions in coordination as unresolved issues surface.

During the late construction phase (60–100%), CU in the ICF environment remains stable at approximately 87–88%, with only minor fluctuations, indicating that most coordination issues have been resolved earlier in the project lifecycle. In contrast, CU in the typical environment continues to decline gradually, reaching approximately 75–76% by project completion. This continued decline reflects persistent coordination inefficiencies, leading to ongoing workflow interruptions.

Table 12. Phase-wise comparison of capacity utilization behavior

Construction Timeline %	ICF	Typical	Underlying Construction Dynamics
Early Construction (0–30%)	~95% → ~93% (slight decline).	~95% → ~91% (moderate decline)	Low coordination demand; early alignment in ICF helps maintain workflow continuity, while coordination gaps in the Typical environment have not yet fully emerged.
Mid Construction (30–60%)	~93–94% → ~91% (moderate decline, stabilizing).	90-91% → 83-84% (continued decline)	Increased coordination demand; improved coordination and design clarity in the ICF limits the accumulation of RFIs and redesign, while the Typical environment experiences growing coordination disruptions and delayed issue resolution.
Late Construction (60–100%)	87-88% (stable, minor fluctuations)	83% → ~75% (continued gradual decline)	Early issue resolution in ICF prevents further disruption; in the Typical environment, accumulated RFIs and redesign cause ongoing workflow interruptions and reduced continuity.

Overall, the difference between the two environments is driven by how coordination affects workflow continuity over time. The ICF environment maintains higher, more stable capacity utilization due to earlier coordination, whereas the typical environment shows a steady decline as coordination issues accumulate and disrupt execution. This pattern reflects the structural feedback between RFI accumulation and capacity utilization, in which unresolved coordination issues generate RFIs that interrupt workflow, reduce available capacity, and further delay issue resolution, creating a self-reinforcing cycle of declining performance in the typical environment.

These results demonstrate that differences in procurement structure drive the observed variation in project performance across scenarios. This pattern becomes more evident when outcomes are examined at the system level in the following section.

5.4 System Behavior and Performance

The overall comparison between the two procurement environments highlights consistent and substantial differences across all performance metrics, as shown in Figure 23. Projects operating under the ICF achieve significantly higher innovation adoption, reaching approximately 75%, compared to 25% in the typical environment. Capacity utilization remains higher and more stable in the ICF scenario, ending at approximately 88% compared to 75% in the typical environment. RFI levels reach 100% of the normalized maximum in the typical environment, compared to only 20% under ICF conditions. Similarly, cumulative redesign reaches approximately 80% in the typical environment, compared to 50% under ICF conditions.

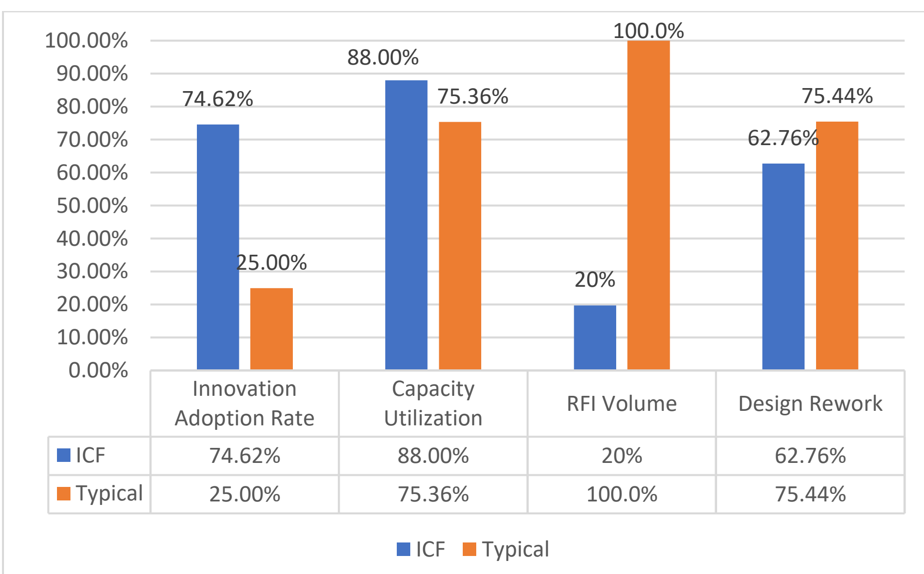


Figure 23. Comparative performance outcomes between ICF and typical scenarios

Beyond these differences in outcome magnitudes, the results reveal a fundamental shift in system behavior resulting from the timing of coordination. In the ICF scenario, coordination effort is front-loaded, allowing the system to stabilize as the project progresses. In contrast, the typical scenario defers coordination to later stages. As unresolved coordination issues surface in later phases, they lead to rapid increases in RFIs and redesigns, resulting in workflow interruptions and declining capacity utilization.

Figures 24 and 25 further illustrate these dynamics over time. Under ICF procurement, performance metrics stabilize, whereas in the typical environment, redesign and RFIs continue to increase. The observed differences indicate that coordination timing alters not only when issues are resolved but also how they propagate through the system. Early coordination limits the transmission of uncertainty across phases, while delayed coordination amplifies its impact. This explains why similar initial conditions can lead to significantly different performance outcomes over time.

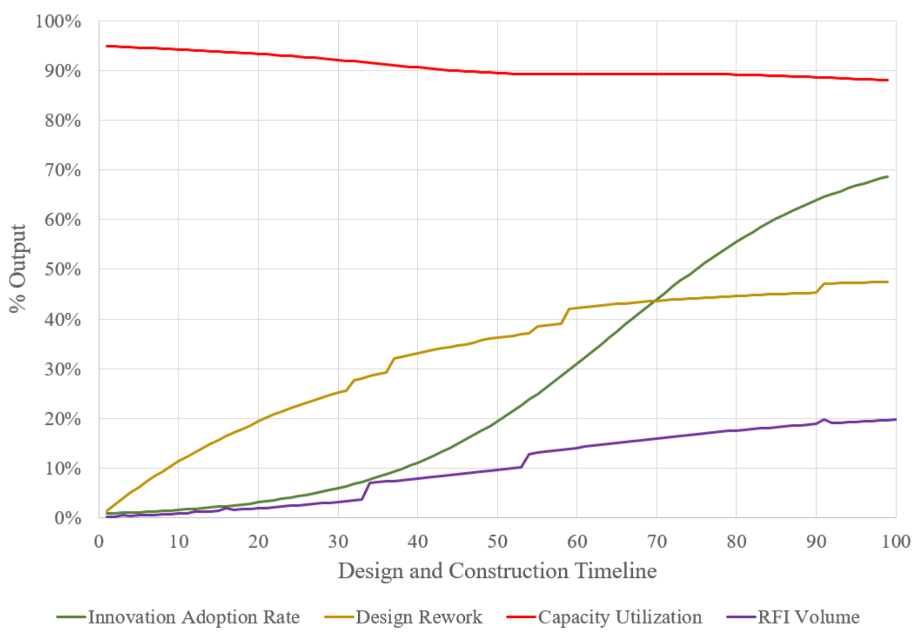


Figure 24. System performance dynamics under ICF

The cross-metric patterns further reveal how performance indicators interact as a system rather than operating independently. In the ICF environment, early stabilization of redesign activity during the design phase directly reduces the volume of unresolved issues entering construction, thereby limiting RFI accumulation and preserving capacity utilization. This chain is visible across Figures 21 and 22, where ICF maintains low, controlled RFI growth throughout construction, while capacity utilization remains stable at approximately 88%. In contrast, the typical environment exhibits a clear compounding effect across metrics. The sharp increase in RFIs during mid-construction, shown in Figure 21, corresponds directly with the accelerating decline in capacity utilization visible in Figure 22, confirming that unresolved coordination issues translate directly into workflow disruption. This cross-metric relationship provides structural evidence that procurement coordination does not influence performance outcomes in isolation, rather, early coordination failures propagate across metrics, amplifying their combined impact on project execution.

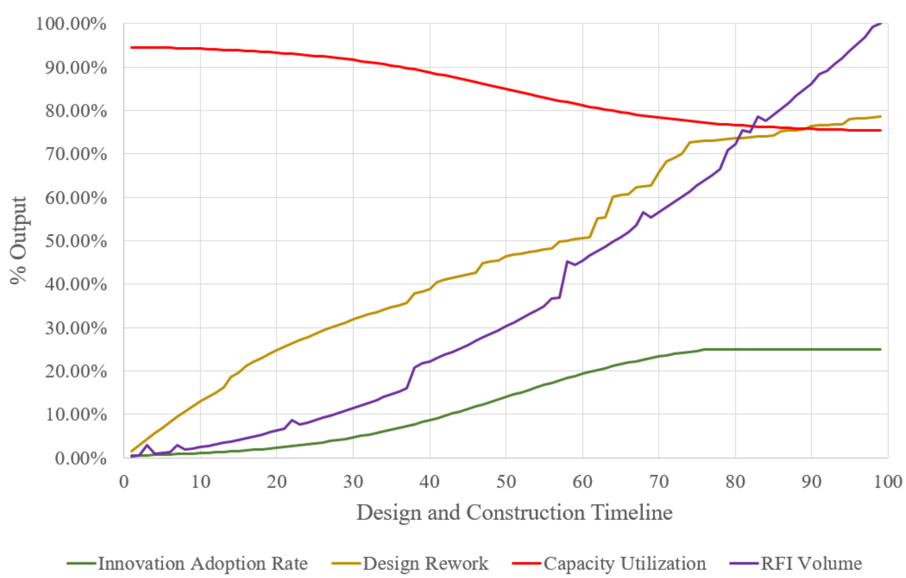


Figure 25. System performance dynamics under typical procurement

Overall, the difference between the two environments is reflected in both performance outcomes and the distribution of coordination across the project lifecycle. The coordinated environment enables earlier resolution of uncertainty, resulting in a more stable and predictable system trajectory. In contrast, the typical procurement delays critical interactions, leading to the accumulation of coordination burden and increased volatility in later stages. The nature of this volatility and its relationship to project stability is examined in the following subsection.

5.4.1. Analysis of Project Stability

In this study, project stability refers to the system's ability to maintain continuous workflow under coordination pressure. A stable project is characterized by high design clarity, which enables uninterrupted task execution and minimizes disruptions caused by unresolved conflicts and excessive clarification cycles.

The simulation results indicate that the two procurement environments achieve stability through fundamentally different mechanisms. In the ICF environment, stability is structural; it is built into the procurement process through early coordination rather than recovered after disruption. Higher levels of early supplier involvement and collaboration intensity lead to moderate increases in redesign and RFI activity during the design phase, reaching approximately 47% and 20%, respectively, as technical issues are identified and resolved while decisions remain flexible. This front-loaded resolution significantly reduces downstream uncertainty, allowing capacity utilization to remain stable at approximately 88% throughout construction, compared with the compounding disruptions observed in the Typical environment.

In contrast, the typical environment exhibits fragile early stability. Limited early interaction suppresses initial redesign and RFI activity, creating an appearance of smooth progress during the conceptual and schematic phases. However, this apparent stability masks the accumulation of unresolved coordination gaps. As the project transitions into phases with higher trade interaction and construction pressure, these gaps surface rapidly, driving cumulative redesign to approximately 80% and RFI volume to 100% of the normalized maximum. The resulting disruptions force repeated workflow adjustments, such as task resequencing and waiting periods, that the system can no longer absorb efficiently, as reflected in a progressive decline in capacity utilization to approximately 75% by project completion.

The contrast between these two stability patterns highlights a fundamental difference in how coordination risk is distributed across the project lifecycle. In the ICF environment, coordination risk is absorbed early when the system has the flexibility to accommodate it. In the typical environment, risk is deferred and accumulates silently until it surfaces under construction constraints, where resolution is significantly more disruptive and costly. This distinction suggests that project stability should be evaluated not only by early-stage performance indicators but by the trajectory of coordination effort across the full project lifecycle.

Chapter Summary

This chapter presented the simulation results evaluating how procurement coordination structures influence project performance across the design and construction lifecycle. Using a controlled comparative design in AnyLogic, the ICF was compared with a fragmented procurement baseline while maintaining consistent structural conditions across both scenarios.

The results demonstrated clear performance differentiation across all four key metrics. The ICF achieved substantially higher innovation adoption, lower redesign accumulation, controlled RFI growth, and more stable capacity utilization compared to the fragmented procurement environment. The findings showed that early supplier involvement and structured coordination shift issue identification and resolution upstream into the design phase, where decisions remain flexible and coordination risks can be managed proactively. In contrast, fragmented procurement delayed coordination resolution, resulting in escalating redesign, concentrated RFI generation, workflow disruption, and declining capacity continuity during construction.

At the system level, the findings established that procurement outcomes emerge through interconnected behavioral and coordination dynamics rather than through isolated performance indicators. Early coordination conditions influenced downstream project stability by shaping how unresolved issues propagated across later project phases. The results further demonstrated that apparent early-stage stability under fragmented procurement can mask the accumulation of unresolved coordination risk that later surfaces during construction execution.

Together, the simulation outputs establish a consistent pattern showing that procurement coordination structure significantly influences innovation adoption, workflow continuity, and overall project performance. The following chapter evaluates the credibility of these findings through a structured validation framework examining the behavioral logic, temporal patterns, and quantitative outputs produced by the model.

Chapter 6 Validation

Construction procurement systems involve complex coordination dynamics that must be validated against real-world behavior to ensure that simulation outputs are credible and meaningful. This chapter presents a multi-stage validation of the ABM, beginning with model verification and internal consistency checks (Section 6.1), followed by mechanism validation of behavioral relationships through expert assessment (Section 6.2), and pattern validation using simulation outputs (Section 6.3). The chapter then evaluates the magnitude of model outputs through quantitative benchmarking against industry-informed ranges (Section 6.4). It concludes with an overall assessment of the model's credibility, limitations, and expert insights into model simplifications (Section 6.5). The simulation outputs presented in Chapter 5 reflect minor refinements made during the iterative validation process to better align model behavior with observed industry patterns.

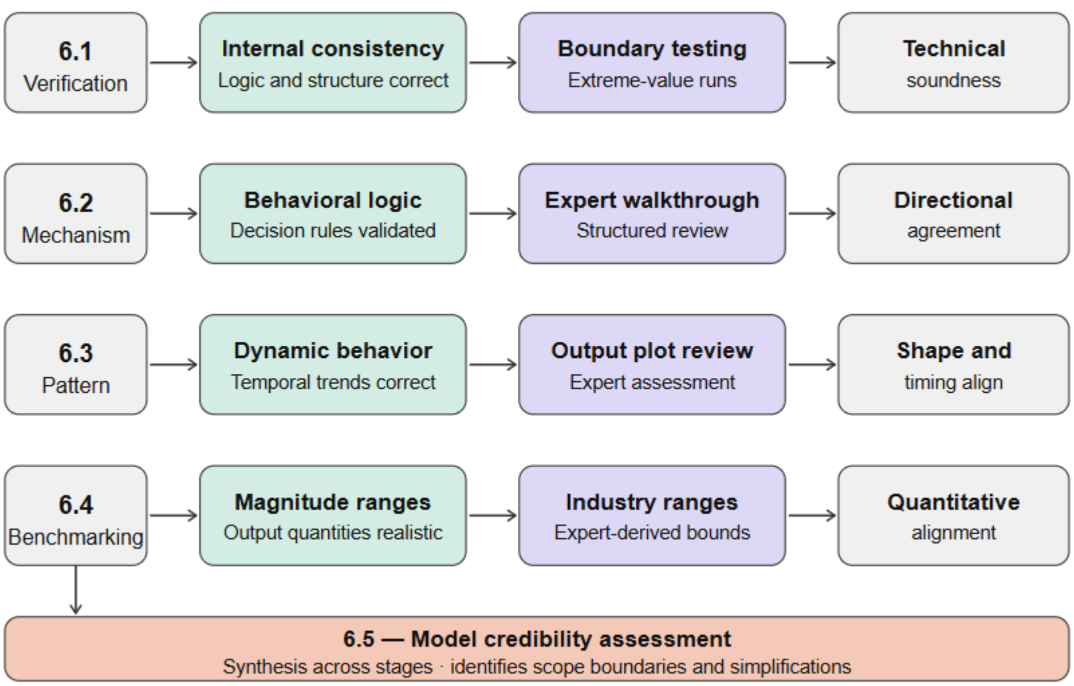


Figure 26. Overview of the model validation framework applied

Expert insights are used across multiple validation stages, as illustrated in Figure 26, which summarizes the four-stage validation framework applied, mapping each stage to its purpose, method, and expected output. This ensures that the model is evaluated against real-world practices and reflects how coordination and decision-making occur in real construction projects.

6.1 Model Verification and Internal Consistency

Verification procedures were conducted during model development to confirm that the simulation logic operates as intended before validation begins. This includes systematic checks of agent decision rules, interaction sequences, and process flows to ensure logical consistency across all stages. The translation of interview-derived parameters into model inputs is reviewed to confirm that values are correctly assigned and operate within expected ranges. Multiple simulation runs are performed under identical conditions to confirm model stability and reproducibility of results. Internal consistency is further evaluated by examining whether changes in key input parameters lead to expected directional changes in outputs, ensuring that the model behaves logically under varying conditions. These verification procedures confirm that the model is technically sound, internally consistent, and suitable for subsequent validation and simulation analysis.

6.2 Mechanism Validation (Behavioral Logic)

6.2.1 Mechanism Validation in the ICF Model

Mechanism validation is conducted through structured expert walkthroughs, in which domain experts from GCs, suppliers, subcontractors, and CCA organizations review key behavioral relationships. These discussions focus on how decisions are actually made in practice, including how risk perception influences supplier participation, how early engagement affects collaboration, and how structured coordination impacts design outcomes. Experts assess whether these cause–and–effect relationships reflect real-world procurement and project delivery behavior based on their experience. The evaluation focuses on confirming that the direction and practical relevance of these relationships are consistent with how coordination and decision-making are carried out. Table 13 summarizes how industry professionals evaluated the behavioral relationships embedded in the model, along with detailed stakeholder-level responses provided in Appendix 10.4.

Table 13. Mechanism Validation of Behavioral Relationships under the ICF model

Relationship	Expert Observations	Agreement
Risk → Participation	A consistent inverse relationship was observed across all stakeholder groups.	High
Participation → Collaboration	Higher participation consistently increases the intensity of coordination among stakeholders.	High
Collaboration → Design Clarity	Strong consensus across all stakeholder groups; minimal variability with no notable exceptions	High
Design Clarity → RFI Volume	Relationship observed, with moderate variation, depending on project type and delivery context.	Moderate
ESI → Innovation	Relationship observed, but effectiveness varies with stakeholder risk tolerance and decision conditions.	Moderate
GMP Timing → Collaboration	Relationship observed, but highly dependent on compensation structure and stakeholder alignment	Variable

The level of expert agreement reported reflects the consistency of these assessments across different stakeholder groups. High agreement indicates relationships that were widely and consistently recognized in practice, suggesting stable coordination mechanisms across project settings. Moderate agreement reflects relationships that are generally observed but vary in strength depending on project characteristics, stakeholder roles, or decision context. Variable agreement indicates relationships whose effects are more contingent on contractual arrangements, organizational structure, or delivery conditions. Within the model, this variability is operationalized through parameter calibration rather than through structurally distinct equations. Specifically, the GMP timing parameter (Tgmp), the primary source of variability in agreement, is assigned different values across scenarios (ICF: Tgmp = 0.3; Typical: Tgmp = 0.7), reflecting the differing contractual contexts in which GMP finalization occurs early or late. Its influence on collaboration intensity is governed by a weighting coefficient (w3) within the collaboration equation, which captures the directional effect of GMP timing while acknowledging that the magnitude of this effect varies with contractual and organizational conditions. This approach reflects a deliberate modeling decision: rather than introducing separate equations for each contractual context, the model captures the central directional tendency of each relationship while using scenario-level parameter differences to represent the range of conditions observed in practice.

6.2.2 Mechanism Validation in the Typical Model

In addition to evaluating coordination under structured environments, mechanism validation also examined how these behavioral relationships operate under typical fragmented procurement conditions. Experts reflected on project settings characterized by delayed supplier involvement, limited coordination, and reactive decision-making.

Across all stakeholder groups, experts confirmed that the inverse relationship between risk and participation is equally observable in typical environments. When integration structures are absent, risk perception remains elevated throughout the design phase because there is no mechanism to resolve uncertainty early. As a result, supplier participation remains low and is typically triggered only after major design decisions have already been made, limiting the ability to influence outcomes, as detailed in Table 14.

Table 14. Mechanism Validation of Behavioral Relationships under Typical Procurement

Relationship	Typical Scenario Behavior
Risk → Participation	Confirmed: High sustained risk perception suppresses participation throughout design
Participation → Collaboration	Confirmed: Low participation produces reactive, conflict-driven coordination

Collaboration → Design Clarity	Confirmed: Limited collaboration leaves design ambiguities unresolved until late stages.
Design Clarity → RFI Volume	Confirmed: Lower design clarity drives higher mid-construction RFI concentration
ESI → Innovation	Confirmed: Absence of early involvement constrains innovation to post-design value engineering.
GMP Timing → Collaboration	Conditional: Late GMP in typical procurement limits early coordination by shifting stakeholder focus toward cost protection rather than collaborative exploration. The effect is stronger in typical than in ICF due to the absence of structured coordination mechanisms.

The relationship between participation and collaboration is present but weaker and less consistent. Experts noted that in fragmented environments, coordination is often reactive, driven by emerging issues rather than by proactive engagement. As a result, increased participation does not always translate into effective collaboration. The relationship between collaboration and design clarity is also observed, but the timing of engagement constrains its effectiveness. In typical environments, design decisions are often made with incomplete input, leading to unresolved conflicts that emerge later during construction. Experts across all groups observed that limited collaboration results in design information remaining incomplete or ambiguous for longer, which, in turn, delays issue identification and forces resolution into later project phases, where changes are more costly. Subcontractors and suppliers noted that they frequently receive incomplete design packages, consistent with the model's lower design-clarity trajectory under such conditions.

Regarding the relationship between design clarity and RFI volume, experts emphasized that RFIs are often driven by incomplete or evolving design information rather than by coordination breakdowns alone. This leads to higher, more variable RFI generation than in ICF environments, particularly during periods of intensive trade interaction. Trade partners and subcontractors described this as the most visible indicator of delayed coordination, a concentration of formal clarification requests precisely when workflow disruption is most costly.

ESI is limited in typical procurement, and when it does occur, it is often not sustained or integrated into decision-making. As a result, its impact on innovation is inconsistent and highly dependent on project-specific conditions. Experts noted that in typical procurement, suppliers are selected after major design decisions are finalized, which effectively eliminates the window during which technical input could influence the selection of new technology. GCs observed that innovation in typical environments is largely limited to value-engineering substitutions after design completion, which tend to reduce rather than add value.

The relationship between GMP timing and collaboration is also weaker and more variable. In this scenario, GMP is often finalized after key design decisions, limiting its influence on early coordination and reducing its role as a driver of collaborative behavior. Several participants observed that once GMP is locked, stakeholders shift immediately into cost-protection mode, further reducing the collaboration that might otherwise support coordinated problem-solving.

6.2.3 Key Insights

The validation results show consistent agreement for some relationships and conditional variation for others, reflecting differences in how coordination operates across project contexts. Rather than treating expert agreement as uniformly supportive, this interpretation distinguishes between relationships that are widely observed across roles and those shaped by organizational and contractual conditions.

Three relationships, risk influencing participation, participation influencing collaboration, and collaboration-improving design clarity, were confirmed consistently across all stakeholder groups. This convergence is notable given the structurally different roles and incentives across these groups. The fact that all groups independently identified the same directional effects suggests these relationships reflect stable mechanisms rather than role-specific perceptions. GCs and trade partners in particular emphasized that early participation resolves constructability concerns and aligns system interfaces before they escalate into field issues, a pattern observed consistently regardless of project type or delivery method.

Two relationships showed moderate variability, driven by a specific, identifiable condition: decision-making authority. For the design-to-RFI volume relationship, trade partners noted that RFI reduction depends not only on coordination quality but also on the maturity and completeness of design information at the time of release. This factor varies across project types. For ESI and innovation, the critical condition identified by trade partners and suppliers is whether involvement is accompanied by genuine influence over design decisions. GCs also noted that the adoption of innovation is often limited by project cost pressures and value-engineering decisions, even when coordination conditions are favorable. This means that innovation outcomes depend not only on the coordination structure but also on budget-driven decisions that can restrict the implementation of new technology.

The GMP timing-to-collaboration relationship showed a high variability across stakeholder groups. All groups agreed that GMP timing influences collaboration, but the nature of that influence varied across the procurement context. In ICF environments, both GCs and CCA participants emphasized that earlier GMP, when established after early supplier input during design, improves collaboration by creating earlier alignment, clearer expectations, and stronger stakeholder commitment. In typical procurement environments, however, GMP is often finalized too late, after major design decisions are already set, limiting opportunities for supplier input and reducing the potential for collaborative innovation. This variation reflects differences in procurement structure rather than disagreement on the value of early GMP itself. The model captures the directional influence of GMP timing on collaboration, but does not separately model these context-specific pathways, which remain outside the scope of the current framework.

Taken together, the pattern of agreements and divergences points to a consistent finding: the model reliably captures coordination mechanisms at the level of participation, information flow, and design clarity, where stakeholder roles converge in their experience of how coordination operates. In practice, stakeholder behavior may also be influenced by strategic considerations, such as selective participation or limited commitment, which are not explicitly represented in the model. Similarly, ESI does not always translate into influence over decisions, as the incorporation of inputs depends on governance structures and decision-making authority. These factors indicate that while the model captures the direction of behavioral relationships, it simplifies how these relationships operate under varying organizational conditions.

6.3 Pattern Validation Using Simulation Output

6.3.1 Pattern Validation in the ICF Model

Pattern validation is conducted by comparing simulation output trends with expected real-world project behavior based on expert insights. Simulation output plots from Chapter 5 are presented to domain experts, who assess whether the temporal patterns of key performance metrics reflect the project dynamics. During these sessions, experts were shown the simulation plots with phase context and output definitions and asked to comment on whether the timing, shape, and progression of each curve were consistent with the project behavior they had observed in practice.

a) Innovation Adoption Pattern: During the early conceptual phase (0–30%), innovation adoption remains low in ICF projects, reflecting conditions of exploration, uncertainty, and limited commitment to design decisions. Expert feedback confirms that centralized coordination has minimal influence during this phase, as key trade engagement has not yet been activated. This extended early phase also reflects the longer time required to establish coordination among multiple stakeholders, as early collaboration with suppliers and trade partner's demands additional alignment before innovation decisions can be accelerated. As projects transition into the early schematic phase (~20–30%), coordination begins to influence decision-making through structured engagement with key trades. Experts noted that this stage represents a critical transition point at which coordination mechanisms begin to shape design decisions. This indicates that coordination effects emerge once key stakeholders are engaged, whereas the model represents this transition as gradual.

This influence becomes more pronounced during the schematic design phase (30–60%), with a clear increase in the innovation adoption. Experts confirmed that ESI reduces uncertainty related to constructability and system integration, enabling more confident and timely adoption of innovative solutions. In the design development phase (60–Design phase complete), innovation adoption stabilizes as major system decisions are resolved through early collaboration. Experts agreed that this stabilization reflects the closure of key design decisions rather than continued growth in innovation activity.

Experts emphasized that innovation adoption in practice occurs through discrete, system-driven decisions triggered by trade engagement and resolution of key uncertainties, rather than as a continuous process. In the model, however, innovation adoption is represented as a smooth curve to capture cumulative system-level innovation performance over time rather than individual decision events. Unlike RFIs and design reworks, which occur as distinct, episodic events and are therefore modeled as step patterns, innovation adoption reflects the aggregate effect of many incremental coordination outcomes, making a continuous representation more appropriate for showing the overall progression of innovation.

b) Design Rework: Experts agreed with both the shift in timing and the episodic nature of redesign between ICF environments, confirming that real-world redesign occurs in concentrated bursts tied to specific coordination events rather than as a smooth continuous progression. Early engagement with key trades enables earlier identification of constructability and integration issues. However, this early redesign is not uniformly distributed; instead, it occurs in concentrated bursts tied to specific system decisions, such as façade systems or major MEP routing. At the same time, some level of late-stage redesign remains unavoidable due to evolving owner requirements, scope changes, or unforeseen site conditions.

This reinforces the model's representation of higher cumulative redesign in typical scenarios, although experts noted that the magnitude varies with project complexity and team experience. Overall, the model captures the temporal shift from early, controlled adjustments to late, disruptive rework. The episodic stepped representation of redesign adopted in the simulation aligns with expert observations.

c) RFI Volume: Experts agreed with both the direction and timing of RFI accumulation, while noting that real-world behavior is more uneven and project-dependent than the smooth progression. In the early construction phase, RFI activity is typically limited across both environments, consistent with the model's low initial RFI levels. At this stage, fewer coordination conflicts have yet surfaced because major trade interactions and system overlaps have not fully begun. As projects progress into mid-construction, this phase is consistently identified as the most critical for RFI generation. Specialty contractors highlighted that RFI spikes commonly occur during intensive trade interactions, particularly in MEP installation, where spatial conflicts and sequencing issues become apparent. The model captures this mid-phase escalation as a consequence of delayed issue resolution and increased trade interaction. However, RFIs are not eliminated in ICF environments and continue to arise due to field conditions, minor design gaps, or evolving requirements.

Overall, the model captures the key drivers and temporal distribution of RFI volume through an episodic stepped representation that reflects the concentrated, trigger-based nature observed in practice. Experts confirmed that this episodic behavior, particularly the mid-phase spikes driven by trade overlap and concurrent system installation, is well represented in the simulation.

d) Capacity Utilization: Experts interpreted capacity utilization in terms of workflow continuity, crew productivity, and work readiness, rather than as a direct percentage measure. In ICF environments, early alignment and structured coordination support more stable workflow conditions during construction. When design decisions are resolved early, crews experience fewer interruptions, leading to more consistent capacity Utilization. However, sustained high utilization is rarely achieved in practice due to trade interdependencies, site constraints, sequencing limitations, and variability in workface readiness. This suggests that while the model captures stable performance, it may slightly overstate consistency.

The mid-construction period is identified as the most disruptive to workflow. Coordination breakdowns manifest as waiting time, out-of-sequence work, and frequent adjustments to planned activities, often linked to unresolved RFIs and late-stage design changes. These disruptions are mitigated through improved sequencing and pre-coordination, enabling more predictable work patterns. At the same time, even well-coordinated projects experience some level of disruption due to field variability and evolving conditions. This indicates that while the model captures the directional impact of coordination on workflow performance, it simplifies the inherent variability of construction execution.

Overall, expert feedback supports representing capacity utilization as an outcome of coordination effectiveness, while highlighting that real-world performance is better understood as variable workflow behavior rather than as smooth percentage trends. This reinforces that capacity utilization is better interpreted as an indicator of workflow stability rather than a direct measure of resource efficiency. Unlike redesign and RFI generation, which are represented episodically to reflect their discrete, event-driven nature, capacity utilization is intentionally modeled as a smooth, continuous trend. This reflects its character as an aggregate workflow measure that responds gradually to the cumulative effect of coordination conditions rather than reacting sharply to individual events, a distinction confirmed by expert feedback.

6.3.2 Pattern Validation in the Typical Model

Simulation output plots for the typical scenario were presented to the domain experts, who assessed whether the temporal patterns of innovation adoption, redesign, RFIs, and capacity utilization are consistent with observed behavior in typical procurement environments without structured early coordination.

a) Innovation Adoption Pattern: Experts confirmed that the innovation adoption pattern in the typical scenario reflects observed behavior. The gradual increase in the early and mid-design stages, followed by stabilization at a lower level, was interpreted as consistent with limited integration of supplier input under fragmented coordination. In particular, experts noted that the absence of structured early coordination reduces opportunities for innovation during the design process. As a result, innovation adoption progresses incrementally and stabilizes in the later stages of design, when most system-level decisions have already been made. This limits the potential for further incorporation of new technologies. Overall, the pattern characterized by gradual progression and early stabilization was validated as representative of typical procurement environments, where innovation is constrained by delayed engagement and lack of coordinated decision-making.

b) Design Rework: Experts confirmed that the redesign pattern observed in the typical scenario reflects the cumulative nature of issue resolution. The consistently higher redesign levels throughout the design timeline were interpreted as evidence of decisions made without integrated coordination, resulting in ongoing adjustments as additional information became available. Rather than being concentrated at a specific phase, redesign activity was understood as continuously accumulating from early design onward. Experts noted that in fragmented environments, initial design progress often proceeds without full visibility across disciplines, leading to decisions that require revision as challenges emerge. This creates a sustained need for redesign rather than a distinct correction phase. Experts confirmed that this continuous accumulation of redesigns is representative of typical procurement conditions, in which coordination is reactive, and design evolution continues throughout the process.

c) RFI Volume Pattern: Experts confirmed that the RFI pattern in the typical scenario reflects ongoing issue discovery during construction rather than early resolution. The continuous and accelerating increase in RFI volume was interpreted as consistent with fragmented environments, where unresolved design gaps are progressively identified as construction advances. Unlike ICF scenarios, where RFI activity stabilizes after early resolution of major conflicts, experts noted that in typical procurement, clarification processes remain active throughout execution. As work progresses and trade interactions intensify, unresolved design inconsistencies surface incrementally, leading to sustained and escalating RFI generation with no evidence of stabilization. Experts further emphasized that this pattern reflects the timing of issue exposure rather than coordination effectiveness alone. The absence of early alignment shifts problem identification into later project stages, resulting in a continuous escalation of RFIs.

d) Capacity Utilization: Experts confirmed that the capacity utilization pattern in the typical scenario reflects a gradual decline in workflow stability over the project timeline. The steady reduction in utilization was interpreted as consistent with the accumulation of coordination-related disruptions, including rework, resequencing, and waiting time associated with unresolved issues. In contrast to ICF, where disruptions are stabilized, experts noted that fragmented procurement conditions lead to persistent inefficiencies that are not fully recovered. As coordination gaps translate into execution challenges, workflow continuity deteriorates progressively rather than experiencing a distinct disruption phase. Typical environments experience stop-and-go conditions and resequencing, leading to lower effective productivity. Experts also highlighted that this pattern reflects real-project conditions, where interdependencies among trades and evolving workface readiness contribute to ongoing variability. The absence of early coordination amplifies these effects, resulting in sustained decline rather than stabilization. Overall, the observed pattern was validated as representative of workflow behavior in traditional procurement environments.

6.3.3 Synthesis

Across all performance metrics, a consistent pattern emerges in how coordination structures influence system behavior. A summary of these patterns and their alignment with expert observations is presented in Table 15. In ICF, key issues related to design clarity, system integration, and constructability are addressed earlier in the project lifecycle, resulting in more stable downstream performance. Detailed cross-phase Pattern Validation is provided in Appendix 10.5 and 10.6.

Table 15. Synthesis of Pattern Validation across ICF and Typical Procurement Scenarios

Output	ICF Key Pattern	Typical Key Pattern	Real-world Alignment	Model Simplification
Innovation Adoption	Slow start, accelerates in mid-phase, stabilizes at ~75%	Gradual increase, constrained early, plateaus at ~25%	Matches expert input for both scenarios	Smooth curve retained, reflects a gradual confidence-building process rather than discrete events.
Design Rework	Early increase, stabilizes at ~50% through front-loaded resolution	Continuous accumulation reaches ~80% through late-stage corrections	Strong alignment for both scenarios	The episodic stepped representation adopted aligns with expert confirmation of burst-based redesign activity.
RFIs	Low and controlled throughout, reaching ~20% of the normalized maximum	Accelerating trajectory with episodic spikes, reaches 100%	Strong alignment for both scenarios	Episodic stepped representation adopted, aligns with expert confirmation of trigger-based mid-phase spikes.
Capacity Utilization	Stable workflow maintained at ~88% throughout construction	Progressive decline from ~90% to ~75% by project completion	Matches field behavior for both scenarios	Smooth trend retained; reflects aggregate workflow response rather than discrete-event reaction.

In contrast, typical environments do not exhibit delayed issue identification at a single stage, but rather a continuous accumulation of unresolved issues across the project lifecycle. Experts confirmed that in fragmented procurement environments, coordination gaps are not resolved early but persist and propagate as the project progresses. This results in consistently higher redesign, continuously increasing RFI generation, and a progressive decline in workflow stability.

The model captures this difference not only in the magnitude of outcomes, but also in the underlying behavior of the system. While ICF demonstrates early resolution and stabilization, typical environments reflect ongoing issue discovery and reactive adjustment throughout both design and construction phases. This distinction highlights that the coordination structure influences not only when issues are addressed but also whether they are resolved proactively or carried forward into execution. Expert feedback informed a key modeling decision in this study: redesign and RFI generation are represented episodically through stepped progressions to reflect their discrete, trigger-based nature, while innovation adoption and capacity utilization are retained as smooth continuous trends reflecting their gradual, aggregate character. A key modeling decision emerging from pattern validation was the differentiated representation of output behaviors: redesign and RFI generation are represented episodically to reflect their discrete, trigger-based nature, while innovation adoption and capacity utilization are retained as smooth, continuous trends reflecting their gradual, aggregate character. This differentiated representation directly responds to expert observations and enhances the simulation's behavioral realism.

6.4 Quantitative Benchmarking with Industry Observations

6.4.1 Benchmarking in the ICF Model

Quantitative benchmarking is conducted using expert-provided ranges for key performance metrics, including innovation adoption, redesign, RFIs, and capacity utilization. During the interview process, industry experts provided approximate ranges based on their project experience. These responses are consolidated into representative minimum, maximum, and average values for comparison. Simulation outputs are then compared with these ranges to assess whether the magnitude of the model results falls within realistic, acceptable industry bounds. The comparison between model outputs and expert-informed benchmark ranges is illustrated in Figure 27. Validation focuses on alignment within expert-informed ranges rather than exact numerical matching.

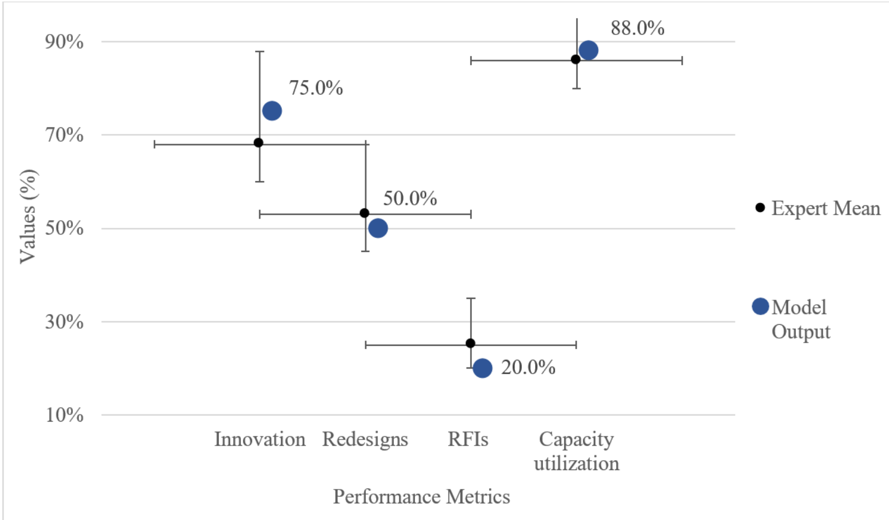


Figure 27. ICF model outputs plotted against expert-informed benchmark ranges across four performance metrics

For innovation, the model value (75%) is slightly higher than the expert mean (68%) but remains within the observed response range. Practitioners from CCA and trade partners indicated that early coordination can enable greater innovation, although GCs noted that adoption is often constrained by cost and risk considerations. This indicates that the model captures the enabling effect of coordination on innovation while reflecting constraints imposed by cost and risk considerations.

For design reworks, the model value (50%) closely aligns with the expert mean (53%), indicating strong agreement across stakeholders. GCs and trade partners emphasized that early coordination shifts redesign to earlier stages, allowing issues to be addressed before they circulate. The close alignment suggests that the model realistically represents the balance between the need for early design iteration and the reduction of late-stage rework.

For RFIs, the model value (20.00%) falls within the expert range (20–25%) and shows a moderate deviation of -5% from the expert mean (25%). Experts confirmed that coordinated projects experience fewer RFIs due to early resolution of design ambiguities, although RFIs still arise from field conditions and minor coordination gaps.

For capacity utilization, the model value (88%) is slightly higher than the expert mean (86%) but remains within the observed range (80–90%). GCs described coordinated projects as having more stable workflows and fewer disruptions, while trade partners noted that some variability is unavoidable due to site conditions and sequencing constraints. This indicates that the model captures improved workflow stability while slightly underrepresenting real-world variability. A summary of model values relative to expert-informed benchmarks is presented in Table 16.

Table 16. Deviation of Model Outputs Relative to Expert-Informed Benchmark Ranges

Metric	Model	Mean	Min	Max	Deviation (%)
Innovation	75%	68%	60%	80%	+7%
Redesigns	50%	53%	45%	60%	-3%
RFIs	20%	25%	20%	30%	-5%
Capacity utilization	88%	86%	80%	95%	+2%

Rather than exact numerical matching, validation focuses on alignment within expert-informed ranges. Model deviations from the expert mean remain within a narrow band (approximately ±5%), indicating strong consistency with practitioner expectations while avoiding exact calibration to a single reference value.

To complement the descriptive benchmarking analysis, a Wilcoxon signed-rank test was conducted for each performance metric to assess whether differences between model outputs and expert-elicited values are statistically meaningful, with results summarized in Table 17. This non-parametric test was selected given the small sample size and the ranked nature of expert responses, making it more appropriate than parametric alternatives.

Table 17. Wilcoxon Signed-Rank Test Results for ICF Model Output Validation

Metric	Model Output	Expert Mean	n	T	z	Effect r	p-value

Innovation	75%	68%	3	0	1.36	0.79	0.25
Redesign	50%	53%	3	1.5	0.54	0.31	0.50
RFIs	20%	25%	4	0	1.70	0.85	0.125
Capacity Utilization	88%	86%	4	1	1.29	0.64	0.25

Results indicate no statistically significant difference between model outputs and expert expectations across all four metrics: innovation adoption (T = 0, z = 1.36, effect r = 0.79, p = 0.25), design rework (T = 1.5, z = 0.54, effect r = 0.31, p = 0.50), RFI volume (T = 0, z = 1.70, effect r = 0.85, p = 0.125), and capacity utilization (T = 1, z = 1.29, effect r = 0.64, p = 0.25). All p-values exceed the 0.05 significance threshold, indicating that the model outputs are statistically consistent with practitioners' expectations. Effect size values ranging from 0.31 to 0.85 further indicate moderate-to-large practical agreement between model outputs and expert-informed ranges, thereby strengthening the simulation's quantitative credibility.

The Wilcoxon test results confirm that the simulation outputs align with expert-elicited values across all metrics, supporting the quantitative validity of the model under ICF conditions.

6.4.2 Benchmarking in the Typical Model

Quantitative benchmarking for the typical scenario compares simulation outputs against documented industry evidence from projects delivered under similar procurement conditions, in which ESI is absent, and coordination occurs reactively rather than through structured early engagement. Statistical testing was not applied to the typical scenario benchmarking, as outputs are compared against documented industry ranges from large-scale empirical studies rather than expert-elicited point estimates, making the Wilcoxon test inappropriate in this context. Benchmarking draws on contractor-focused analyses and Department of Transportation (DOT)-aligned datasets from US construction projects delivered, ensuring alignment with observed field performance under fragmented, low-integration delivery conditions.

For innovation, the typical scenario yields a model output of 25%. The Design-Build Institute of America and FMI (2018) found that traditional low-bid procurement actively constrains innovation because contractors and suppliers are engaged only after design completion, leaving no meaningful opportunity for technical input to influence system-level decisions. Owners reported that innovation in such environments is largely absent and, where present, limited to minor material substitutions or field-driven adjustments during construction. This finding is reinforced by evidence from Hanna et al. (2005), which shows that high RFI volumes and late-stage coordination further suppress innovation potential. Across these projects, effective innovation contribution typically falls within the 10% to 25% range, reflecting the reactive nature of decision-making. The model value of 25% aligns with the upper bound of empirically observed outcomes, representing a realistic estimate under constrained procurement conditions.

For redesign, the typical scenario produces a model output of 80%. Love et al. (2002), in their study of 161 construction projects, found that rework contributed to 52% of total cost growth**,** with design-related errors stemming from the separation of design and construction identified as the primary cause. Hwang et al. (2018), analyzing 359 projects from the Construction Industry Institute (CII, 2005, 2009) database, further confirmed that projects lacking early contractor and supplier integration experience have significantly higher levels of rework, with direct rework costs ranging from 5% to 20% of the total contract value. Complementary contractor- and DOT-based analyses by Hanna et al. (2005) demonstrate that rework escalates in proportion to RFI intensity and late-stage design clarification, generating substantial indirect impacts through workflow disruption and resequencing. When interpreted as a cumulative system effect, these conditions correspond to an overall rework influence ranging from 60% to 85% across the project lifecycle. The model's episodic, stepped redesign trajectory, reaching 80%, directly reflects the empirically observed accumulation of unresolved issues and iterative corrections, and is therefore strongly supported by both academic and case-study evidence.

For RFIs, the model produces a continuously increasing trajectory throughout construction, reaching the upper bound of the normalized scale with no evidence of stabilization. The Navigant Construction Forum by Hughes (2013), based on 1,362 projects, reported an average of approximately 796 RFIs per project, with large and complex projects exceeding 1,000 RFIs and showing no late-stage reduction. Similarly, CII (2012), DOT benchmarks, and Hanna et al. (2005) provide empirical evidence indicating RFI frequencies ranging from 0.8 to 8 RFIs per $1 million in construction value, corresponding to approximately 80–800 RFIs for mid-sized projects and higher counts for large-scale works**.** These studies consistently demonstrate that RFI generation is cumulative and self-reinforcing, increasing as unresolved design issues surface and trade interactions intensify during mid-construction.

Because RFIs are not inherently measured as a percentage in industry practice, normalization is required to enable comparison within the model. The 100% value, therefore, does not represent a literal proportion of RFIs, but rather the upper-bound condition observed in practice corresponding to high-fragmentation projects with RFI volumes in the range of approximately 800 to 1000+ and no evidence of stabilization. These studies collectively demonstrate that RFI volume escalates substantially from early to late construction phases in typical environments, reflecting a compounding increase in coordination demand over time (Hughes, 2013; CII, 2012; Hanna et al., 2005)**.** The model's normalized maximum, therefore, represents this peak accumulation state, capturing the magnitude and persistence of RFI growth rather than an absolute quantity**.** On this basis, the model's use of 100% as the upper bound is analytically justified and aligns with observed field behavior in traditional procurement systems.

For capacity utilization, the typical scenario produces a model output of 75%. The Construction Industry Institute (CII, 2005, 2009) rework research program, based on over 150 industrial and commercial projects, found that rework-intensive environments produce sustained workflow disruption, including stop-and-go execution, trade stacking, and extended waiting periods, all of which reduce effective utilization. Construction productivity has stagnated or declined, with several studies attributing this trend to industry fragmentation, poor coordination, and sequential procurement structures that limit integration across project phases (Bühler et al., 2025). Hanna et al. (2005) further quantify the direct impact of RFIs and rework, reporting productivity losses of 10% to 30% due to delays, rework cycles, and inefficient sequencing, corresponding to effective capacity utilization levels of 65% to 80% in typical construction environments. The model's 75% value falls within this empirically validated range and reflects the sustained degradation of efficiency observed in typical project environments.

6.4.3 Key Insights

Across both scenarios, the benchmarking results reveal that model accuracy varies depending on whether outcomes are primarily governed by coordination mechanisms or by external execution conditions. Metrics directly driven by integration structure demonstrate strong alignment with both expert expectations and documented industry behavior. This reflects the model's ability to represent the redistribution of issue resolution, where early coordination shifts iterative adjustments into the design phase. This redistribution is captured by an episodic, stepped representation in both ICF and typical scenarios, reflecting expert confirmation that redesign in practice occurs in concentrated bursts tied to specific coordination events rather than as a smooth, continuous process. Table 18 summarizes the benchmark validation outcomes for both ICF and typical scenarios across all four performance metrics.

Table 18. Benchmark Validation Summary: Model Outputs against Industry-Informed Ranges

Metric	ICF Scenario		Typical Scenario		Validation Interpretation
	Model Output	Expert Range	Model Output	Industry Range	
Innovation Adoption	75%	60–80%	25%	10–25%	ICF aligns with upper-bound performance enabled by early coordination; it typically reflects constrained innovation under fragmented procurement conditions.
Redesign	50%	45–60%	80%	60–85% (cumulative)	Coordination redistributes redesign to earlier stages, while typical environments exhibit continuous accumulation of unresolved design iterations.
RFIs	20%	20–30%	Upper-bound 100% (normalized)	~800–1000+ RFIs per project; no stabilization	ICF shows stabilized RFI behavior; under typical conditions, cumulative non-stabilizing escalation occurs.
Capacity Utilization	88%	80–95%	75%	65–80%	ICF maintains a stable workflow and sustained productivity; fragmented procurement leads to a progressive loss of efficiency.

Metrics such as innovation adoption and RFI generation exhibit greater variability in expert-provided ranges, not due to model inaccuracy, but because they are inherently sensitive to contextual factors beyond coordination alone. Cost constraints, risk tolerance, and approval structures influence innovation outcomes. At the same time, the intensity of trade interactions, RFI response and resolution cycles during construction, and field-level conditions shape RFI behavior. Although RFI generation is modeled episodically to reflect its trigger-based nature, the timing and magnitude of individual spikes remain project-dependent. They cannot be fully captured in a generalized simulation framework.

The comparison between these scenarios further highlights that performance differences are not isolated to individual metrics but emerge as a system-level effect of how and when issues are addressed. In ICF, early alignment reduces the propagation of design-related uncertainty into construction, resulting in stabilized RFIs and sustained workflow continuity. In contrast, typical environments exhibit cumulative inefficiencies, in which delayed coordination leads to continuous redesign, escalating RFIs, and a progressive degradation of capacity utilization.

Overall, the validation demonstrates that the model functions effectively as a behavioral representation of procurement-driven dynamics. Rather than serving as an exact predictive tool, it captures the relative performance shifts, timing effects, and accumulation patterns in the delivery systems, providing a robust basis for scenario-based analysis. The differentiated representation of output behaviors, episodic for redesign and RFIs and smooth for innovation adoption and capacity utilization, directly reflects expert feedback and strengthens the behavioral realism of the model.

6.5 Expert Assessment and Model Credibility

The model is assessed as a credible representation of procurement-driven coordination dynamics, suitable for analyzing how early engagement and structured coordination influence project outcomes under different scenarios. While benchmarking establishes quantitative alignment, real-world outcomes remain influenced by organizational, contractual, and commercial conditions not explicitly captured in the model. Coordination should be understood not only as a structural mechanism, but as a process influenced by governance, decision authority, and execution conditions.

During benchmarking discussions, experts identified several practical conditions that influence project outcomes beyond the coordination mechanisms represented in the model. General contractors emphasized that owner-driven approval cycles and delayed decision-making can introduce redesign and disruption independently of coordination quality. These effects are not explicitly modeled but can significantly influence downstream performance.

Experts also noted that drawings are often released in stages to maintain project schedules, which leads to repeated cycles of clarification and coordination. These cycles are driven by evolving information rather than coordination breakdown, indicating that some observed RFIs and redesign activities are a function of information maturity rather than coordination effectiveness. Practitioners also pointed to staged design-release strategies, in which drawings are issued progressively to maintain the schedule. While this enables early mobilization, it can generate additional cycles of clarification and redesign, reflecting the evolution of information rather than a coordination failure.

From a procurement perspective, experts noted that early supplier involvement is effective only when supported by decision authority and integration into the design process. Early engagement without influence over final decisions does not consistently translate into improved coordination outcomes. Experts further emphasized that field-level conditions, including installation tolerances, sequencing conflicts, and unforeseen constraints, introduce variability even in ICF environments. These factors contribute to RFIs and productivity fluctuations that are not fully captured by coordination-based mechanisms. These observations indicate that while the model captures primary coordination-driven dynamics, real-world performance is also shaped by execution-level conditions beyond the current model scope.

The ranges used in this study reflect practitioner judgment rather than measured datasets and therefore represent informed approximations rather than precise benchmarks. In addition, the model does not explicitly account for project-specific conditions such as delivery constraints, contractual variations, or execution environments, which can influence coordination outcomes in practice. As a result, the validation reflects generalizable industry tendencies rather than exact performance thresholds for individual projects.

Chapter Summary

This chapter presented a multi-stage validation of the ABM, evaluating its credibility through verification, mechanism validation, pattern validation, and quantitative benchmarking. Together, these validation stages assessed whether the model is technically consistent, behaviorally grounded, temporally realistic, and quantitatively aligned with industry expectations.

Model verification confirmed that the simulation logic, behavioral rules, and mathematical relationships operated consistently under both normal and extreme conditions. Mechanism validation further demonstrated that the core behavioral relationships embedded in the model reflect real-world procurement dynamics. Expert assessments showed strong agreement regarding the relationships between risk perception and participation, participation and collaboration, and collaboration and design clarity, indicating that these mechanisms remain stable across stakeholder groups. Moderate variability emerged in relationships involving innovation adoption, RFI generation, and GMP timing, reflecting differences in project context, decision authority, design maturity, and contractual environments rather than inconsistencies in the model structure.

Pattern validation established that the temporal progression of innovation adoption, redesign, RFI generation, and capacity utilization aligned directionally with practitioner expectations under both ICF and fragmented procurement conditions. Experts consistently validated the model's representation of front-loaded coordination and early issue resolution under the ICF, compared to the delayed accumulation of coordination failures under fragmented procurement environments. These findings indicate that the model captures not only performance differences across procurement structures but also the underlying timing and progression of coordination dynamics throughout the project lifecycle.

Quantitative benchmarking further demonstrated strong alignment between simulation outputs, expert-informed ranges, and documented industry evidence. Across the key performance metrics, the model outputs remained within acceptable bounds relative to expert expectations, and statistical testing supported the quantitative consistency of the simulation results. The findings also showed that outcomes more directly governed by procurement coordination structures exhibited the strongest agreement. In contrast, metrics influenced by broader project and organizational conditions displayed greater, yet still realistic, variability.

Collectively, the validation results establish the model as a credible behavioral representation of procurement-driven coordination dynamics rather than a precise predictive tool. The model reliably captures the direction, timing, and relative magnitude of performance differences between coordinated and fragmented procurement environments while acknowledging that real-world outcomes remain influenced by organizational governance, contractual structures, execution-level conditions, and project-specific constraints beyond the model scope. Having established the credibility of the simulation framework, the following chapter interprets the findings in relation to the study propositions, theoretical foundations, and broader implications for procurement governance, stakeholder coordination, and construction project performance.

Chapter 7 Discussions

The report discusses four themes that emerge from the results. Section 7.1 summarizes the simulation results and evaluates each research proposition against the evidence. Section 7.2 situates the simulation findings within pull planning theory, examining how procurement structure determines when pull logic is activated across the project lifecycle and why the ICF prevents coordination failures from propagating into the construction phase. Section 7.3 explores how central procurement structures affect different stakeholder groups, and which governance conditions determine whether early supplier involvement translates into real design influence or remains advisory. Section 7.4 situates GMP timing as an upstream governance constraint that shapes how much of the potential benefit can be realized in practice, drawing on case evidence from public- and private-owner contexts. Section 7.5 extends the simulation findings to their schedule and cost implications, arguing that workflow disruption is the mechanism through which coordination failures translate into productivity losses. Section 7.6 synthesizes these findings and demonstrates how the simulation tool extends the research into a practical decision-making tool.

7.1 Summary of Simulation Results and Response to Research Propositions

This section evaluates each research proposition against the simulation evidence presented in Chapter 5 and the validation findings from Chapter 6. Table 19 provides an overview of the outcomes, followed by a detailed discussion of each proposition and the mechanisms behind the observed results.

The level of support assigned to each proposition is determined using two sources of evidence already established in this study. First, the frequency of participant confirmation from the interview-based parameter calibration in Appendix 10.3, where 9 or more of 13 participants confirming a parameter indicates strong support, 7 to 8 indicates moderate support, and 6 or below indicates limited support. Second, the deviation of model outputs from expert-informed benchmark ranges reported in Table 16, where outputs within ±5% of the expert mean indicate strong quantitative alignment. Propositions where outcomes depend on conditions outside the model scope, such as owner governance structures, are classified as partially supported regardless of directional confirmation.

Table 19. Summary of Propositions, Outcomes, and Supporting Evidence from Simulation

Proposition	Outcome	Evidence from Simulation
P1: ICF outperforms typical environments in innovation adoption and design performance	Supported	IAR reaches ~75% under ICF vs ~25% in Typical; redesign stabilizes at ~50% under ICF vs ~80% in Typical
P2: CCA integration reduces coordination inefficiencies, lowering RFIs and cumulative redesign	Strongly Supported	RFI volume reaches only 20% of the normalized maximum under ICF vs 100% in Typical; cumulative redesign reduced by ~30%
P3: GMP timing acts as a governance constraint that shapes the extent to which coordinated procurement can enhance stakeholder engagement and innovation adoption	Partially Supported	Case evidence shows that GMP timing is driven by the owner's governance culture rather than by coordination readiness, constraining how much of the ICF benefit can be realized in practice.
P4: ICF maintains higher and more stable capacity utilization under integrated coordination-intensive conditions	Strongly Supported	ICF capacity utilization remains stable at ~88% throughout construction, vs a progressive decline to ~75% in Typical, directly correlated with RFI accumulation
P5: Performance advantages are mediated through stakeholder behavior, participation, collaboration, and risk perception	Supported	All four metrics show consistent divergence driven by behavioral differences in Pgate, Ci, and Rperc rather than project complexity, confirming behavioral mediation.

P1: Projects operating under the ICF will outperform typical procurement environments in terms of innovation adoption and overall design performance.

P1 is supported. Beyond confirming that structured procurement yields better outcomes, this finding explains why procurement structure strongly affects innovation, a capability often assumed to depend on technology or organizational culture. The simulation results show that innovation adoption in construction is primarily shaped by procurement conditions that determine when technical input can meaningfully influence design decisions. This is consistent with Song et al. (2009) and Dou et al. (2026), who show that supplier involvement typically occurs only after major design decisions are finalized, effectively removing the opportunity for technical expertise to shape system-level decisions. The gap between 75% and 25% innovation adoption, therefore, reflects a constraint in opportunity rather than a difference in capability. This finding directly addresses Gap 7 identified in the literature review, which noted that limited research examines how procurement structures and design-stage conditions jointly influence innovation adoption levels.

The reduction in cumulative redesign from approximately 75.44% to 62.76% supports the findings of Bemelmans et al. (2012) and Koolwijk et al. (2018), who showed that engaging suppliers early is a structural precondition for meaningful contribution, not simply a process preference. When suppliers are engaged early under ICF conditions, constructability and integration constraints are identified while design decisions remain flexible. The study by Love et al. (2014) supports this interpretation, showing that fragmented design information and weak coordination increase perceived risk and reduce stakeholder willingness to adopt unfamiliar solutions, with risk perception suppressing both participation and innovation. This reframes design performance as a system-level property shaped by procurement governance rather than an individual-level outcome, responding directly to Gap 6 in the literature review.

P2: The integration of a CCA will outperform a typical model by reducing coordination-related inefficiencies, resulting in lower levels of RFIs and cumulative redesign

P2 is strongly supported. While P1 establishes outcome differences, P2 explains the mechanism behind them: the CCA does not simply improve the quality of coordination but changes where, in the project lifecycle, issues are identified and resolved. Under ICF, design ambiguities are absorbed early through structured coordination before they reach construction. Under typical conditions, they are carried forward unresolved, surfacing as formal clarification requests precisely when workflow disruption is most costly. This directly reflects the patterns documented by Xue et al. (2005, 2010), who attributed persistent procurement inefficiencies to fragmented interfaces among participants and the absence of integration mechanisms across project stages.

The CCA's role is therefore not simply administrative but systemic. It absorbs uncertainty early, preventing its downstream amplification. Love et al. (2013) show that RFI generation and processing disrupts workflow continuity, often triggering rework, delays, and decision bottlenecks, a pattern clearly visible in the typical scenario's sustained performance decline. Similarly, Luo et al. (2020) show that procurement failures, including unclear specifications and delayed approvals, contribute directly to higher rework rates, supporting the model's representation of elevated cumulative redesign under fragmented conditions. This finding responds directly to Gap 5 in the literature review, which identified the missing link between coordination failures and measurable outcomes, showing that unresolved design issues accumulate and amplify their collective impact on project execution.

P3: Earlier GMP timing within ICF environments will enhance stakeholder engagement and increase innovation adoption, particularly when design information is incomplete, and risk perception is high

P3 is partially supported. The simulation cannot fully isolate GMP timing as an independent variable because, as the case evidence in Section 7.4 demonstrates, it is shaped by governance conditions outside the project team’s control. It is a downstream expression of the owner's governance culture, shaped by statutory requirements, budget approval cycles, and audit accountability structures, rather than a coordination decision in response to design readiness. The partial support, therefore, reflects a real-world constraint rather than a modeling gap. When GMP timing is structurally determined by governance conditions outside the project team's control, it cannot function as a clean variable in either a simulation or a procurement strategy. This finding reframes the proposition itself. The more important question is not whether earlier GMP improves outcomes, but whether owner governance conditions allow earlier GMP to happen at all.

The simulation confirms that under high risk perception and incomplete design information, supplier participation and collaboration intensity are suppressed, thereby limiting the innovation benefits intended by earlier engagement. This is consistent with what would be expected if GMP timing were acting as a governance constraint on stakeholder behavior rather than a coordination trigger. Kim and Rhee (2026) provide the most direct theoretical grounding for this pattern, formally demonstrating that under conventional GMP structures, the cost savings from innovation accrue to the owner while the contractor bears the cost risk of pursuing it. This asymmetry is structural rather than incidental, and it produces contractor risk aversion as a rational response rather than a behavioral failure. Without explicit incentive mechanisms to rebalance this risk, innovation is suppressed, a pattern the simulation reflects in reduced participation and collaboration intensity under high-risk-perception conditions. In practice, GMP timing is rarely a purely technical or coordination-driven decision. It is fundamentally shaped by the governance and budget culture of the owner organization, and this finding adds important real-world context to the simulation outputs.

The relationship between GMP timing and innovation is therefore not linear, as earlier timing does not necessarily improve outcomes. It is mediated by how risk is distributed and compensated among stakeholders, a complexity the current model captures in broad terms but does not fully resolve. Ogundare et al. (2024) offer a practical resolution through phased GMP strategies, in which cost agreements are progressively established at different design milestones, enabling ESI while managing exposure to incomplete design information. The broader governance implications of GMP timing, including why owners and suppliers consistently fail to move first, and the sharp behavioral reset observed once GMP is established, are examined in detail in Section 7.4.

P4: ICF will outperform fragmented procurement environments by maintaining higher and more stable capacity utilization under integrated coordination-intensive conditions

P4 is strongly supported and addresses a dimension of performance that P2 does not capture. While P2 examines how the coordination structure determines where issues are resolved, P4 examines what happens to the construction-phase workflow when those issues are either resolved early or carried forward unresolved. P2 explains the location of resolution, while P4 captures the downstream operational consequence of unresolved issues during construction. Capacity utilization is not a coordination metric but a consequence metric. It measures whether the construction phase receives complete, resolved work packages that allow crews to work continuously, or whether it inherits the unresolved uncertainty that fragmented procurement failed to address during design. The progressive decline in capacity utilization in the typical scenario is therefore the downstream result of the same coordination failures that P2 identifies. Unresolved design issues generate RFIs during construction, which interrupt workflow, delay task sequences, and reduce effective labor availability, producing a progressive decline. This directly extends the findings of Love et al. (2013) and Han et al. (2013), who show that RFI-related disruptions create idle time, disrupt task sequencing, and produce productivity losses that grow over time rather than stabilize as the project advances. Hwang et al. (2018) further establish that poor integration leads to inefficient resource use, a relationship that the simulation makes explicit by linking RFI accumulation directly to a decline in capacity utilization through a structural feedback mechanism.

In contrast, the stability of capacity utilization throughout construction under ICF conditions reflects the system-level benefit. By resolving design ambiguities before construction begins, the ICF prevents this cycle from initiating in the first place. This finding relates to the broader productivity decline documented by Goolsbee and Syverson (2023) and discussed further in section 7.5. This directly addresses Gap 5 from the literature review, which noted that the direct link between RFIs and capacity utilization remains underexplored, and Gap 8, which identified the lack of integrated system-level analysis capturing how procurement conditions influence overall project performance.

P5: The performance advantages of ICF are mediated through changes in stakeholder behavior, participation, collaboration intensity, and risk perception

P5 is supported, and this finding has important theoretical implications. The consistent divergence across all four performance metrics, despite identical project complexity and baseline conditions, confirms that procurement structure does not directly influence outcomes but operates through the behavioral changes it induces among participating stakeholders. This directly addresses Gap 1 and Gap 2 from the literature review: existing literature largely treats procurement as a static, contract-driven process, and while behavioral drivers are rarely formalized as measurable decision variables or explicitly modeled. This study demonstrates that when these behavioral mechanisms are formalized and embedded within a dynamic framework, they yield measurable, consistent performance differences across scenarios.

The behavioral chain identified in the simulation reflects patterns documented across multiple streams of the literature. Procurement conditions shape risk perception and participation, which in turn determine collaboration intensity and ultimately design clarity and performance outcomes. Raoufi and Fayek (2018) and Simonsen et al. (2023) describe how adversarial procurement environments generate win-lose attitudes and siloed behavior that suppress collaborative decision-making, precisely the dynamic reproduced in the typical scenario. Kache and Seuring (2014) establish that trust and commitment are fundamental to relational integration, a finding operationalized in the model through the Trust parameter's contribution to collaboration intensity. Eriksson (2015) further demonstrates that inclusive decision-making is essential to avoiding supply chain sub-optimization, supporting the model's finding that limited participation constrains performance even when coordination structures formally exist.

Critically, the simulation also reveals a boundary condition that the literature has not fully articulated: behavioral mediation is dynamic rather than fixed. Risk perception evolves as engagement progresses, participation responds to changes in perceived benefit and uncertainty, and collaboration intensity fluctuates with the quality of information exchange. This dynamic mediation suggests that the effectiveness of procurement structures cannot be fully evaluated at contract signing. It must be assessed through the behavioral trajectories they generate over time, a finding that extends transaction cost economics and relational contracting theory by showing that their behavioral predictions operate as evolving patterns rather than fixed contractual conditions.

These behavioral dynamics are not fully explained by structural or contractual factors alone. Social embeddedness theory suggests that economic decisions are shaped not only by formal incentives but by social relationships, trust norms, organizational norms, perceived fairness in risk and reward distribution, and the role structures through which participants engage with one another (Granovetter, 1985), which helps explain why structurally similar procurement arrangements produce different behavioral outcomes in practice. Under ICF conditions, the CCA functions not only as a coordination mechanism but also as a social stabilizer that establishes clearer role boundaries, reinforces norms of reciprocal commitment, and creates conditions that stakeholders perceive as fair, encouraging behaviors that extend beyond purely rational cost-benefit calculations, a pattern consistent with Bresnen and Marshall (2000), who argue that collaborative behavior in construction is deeply shaped by organizational culture and relational norms, not merely by contractual design.

7.2 Pull Planning, Supplier Engagement Timing, and System-Level Outcomes

The simulation results reveal a pattern that goes beyond confirming that earlier supplier engagement produces better outcomes. The procurement structure determines when coordination is resolved in the project lifecycle. It also determines whether construction receives complete work packages or inherits previously unresolved design issues that later surface as RFIs. Pull planning theory provides a clear explanatory framework for understanding why this timing difference consistently produces different system-level outcomes. Ballard and Howell (1994) established that workflow reliability, not speed, is the primary driver of construction productivity, because unreliable handoffs between phases generate the idle time, rework, and resequencing that compound into schedule and cost overruns. Tommelein et al. (1999) extended this empirically, showing that variability introduced at any point in a production flow propagates downstream and amplifies: when one trade's output is late or incomplete, every downstream trade absorbs the disruption. Sacks et al. (2010) demonstrated that this propagation dynamic intensifies in complex building projects where system interdependencies are high, precisely the conditions under which ICF coordination produces its greatest benefit.

The simulation results suggest that the timing of supplier engagement matters more than its intensity. Both procurement environments involve supplier engagement, but the point at which it occurs fundamentally changes how issues move through the system. In the typical procurement environment, engagement is not absent; it is deferred. Issues that are not resolved early appear to have disappeared but have only been delayed, surfacing later under construction constraints where they are significantly harder and more costly to address. Shen et al. (2022) and Dou et al. (2026) show that supplier input during early design has a much greater impact on project performance than input introduced after major decisions are already made. The simulation results reflect this directly: deferring engagement does not eliminate coordination requirements; it shifts them to a point where the system can no longer absorb them without disruption.

Under ICF conditions, early supplier involvement means constructability and integration constraints are identified while design decisions remain flexible and changes are relatively low-cost. The moderately higher redesign activity observed during the conceptual and schematic phases is not a sign of inefficiency; it reflects active problem identification when resolution is cheapest. By the time construction begins, most coordination issues have already been resolved, and the construction phase receives clean, resolved work packages rather than ambiguous handoffs that generate RFIs. Under typical conditions, this failure is structural: suppliers and subcontractors are not positioned to define their downstream requirements before upstream design decisions are made, and the resulting progressive decline in capacity is a direct consequence. Hamzeh et al. (2012) empirically confirmed this relationship, finding that projects with higher rates of constraint removal in upstream planning phases achieved significantly higher Percent Plan Complete scores in construction, providing field evidence for the mechanism that the simulation models structurally capture.

The Last Planner System (LPS) illustrates why this upstream resolution matters so much. The LPS requires that tasks be released into committed work plans only when prerequisite conditions, including design clarity, material availability, crew readiness, and access, are confirmed in advance. It is a powerful tool for managing workflow reliability at the construction phase level.

However, it cannot compensate for upstream pull failures. When design ambiguities are carried forward into construction unresolved, they enter the weekly planning process as constraints that cannot be cleared at the trade level because their resolution requires input from designers, engineers, or owners who are no longer in an active coordination loop. Albalkhy and Sweis (2021) found that the most persistent barrier to LPS implementation was not resistance to the tool itself but insufficient design completeness and supplier input at the start of construction, a failure that originates upstream and cannot be resolved through weekly planning alone (Ballard & Tommelein, 2021). The ICF addresses this at the right level, not by improving weekly planning, but by ensuring the upstream design phase produces outputs that the downstream construction phase can reliably pull from. Montazeri et al. (2024) observe that organizations deferring supplier involvement consistently face higher rates of late-stage design changes that earlier engagement would have prevented. The ICF does not eliminate coordination requirements; it front-loads coordination into upstream phases where it stabilizes workflow and prevents downstream disruption, positioning procurement structure as a mechanism for embedding pull-based coordination.

7.3 Supplier Participation beyond Coordination: Governance and Design Influence

7.3.1 Structural and Behavioral Mechanisms Shaping Supplier Participation

The simulation results demonstrate that coordination structures improve procurement performance across all four metrics. However, they do not explain why similar coordination arrangements produce different levels of supplier contribution in practice. The literature on ESI offers a useful explanatory framework, distinguishing between two dimensions that together determine whether supplier participation generates real design influence. Structural mechanisms define when suppliers enter the design process and what roles and decision authority they hold. Behavioral mechanisms shape whether suppliers commit knowledge, engage consistently, and move beyond advisory input once structural access is established.

Structural mechanisms operate at the project level through procurement arrangements, contractual scope definitions, and the timing of supplier engagement relative to key design decisions. When suppliers are brought in early and given formally defined roles, they are better positioned to contribute constructability input and flag integration constraints while design decisions remain flexible. However, structural access alone does not guarantee influence. Franz et al. (2020) and Bemelmans et al. (2012) consistently show that suppliers brought in early frequently remain in advisory roles, contributing input that improves information flow without shaping the core decisions. Dou et al. (2026) extend this finding to complex building projects, showing that even when formal early-involvement protocols existed, supplier input was systematically filtered through the GCs before reaching design decision-makers, further diluting its influence on outcomes. The structural conditions create the opportunity for influence but do not by themselves convert participation into decision-relevant contribution.

Behavioral mechanisms explain why this gap persists. Suppliers will invest in engineering mechanisms and share technical knowledge only when the governance conditions surrounding their participation make it rational to do so. When compensation is unclear, risk falls disproportionately on the supplier, or experience suggests their input will be ignored, suppliers respond by limiting their engagement. Several studies observed this dynamic directly, showing that when downside risk is concentrated among suppliers, they become cautious and limit early design commitments even when participation is formally permitted. Ballard et al. (2015) similarly demonstrate that when suppliers remain outside shared risk-reward structures, they bear coordination and design risk without proportional reward, which weakens early engineering commitment regardless of how early they are brought into the process. Suppliers who experienced unrewarded early contributions in previous engagements reduced their knowledge sharing in subsequent engagements, even under more favorable governance conditions, suggesting that behavioral suppression accumulates over time rather than resetting with each new contract. The result is that structurally similar early-involvement arrangements produce consistently different outcomes depending on whether the behavioral conditions surrounding participation support or undermine sustained commitment.

The performance gap between ICF and typical procurement environments, therefore, reflects not only a difference in when suppliers are engaged but also a difference in the behavioral conditions that the ICF creates. Understanding which governance conditions sustain supplier commitment is central to translating the simulation findings into practice and directly addresses Gap 3 in the literature review.

7.3.2 Governance Conditions for Leveraging Supplier Expertise

The validation data reveal a consistent pattern: suppliers and subcontractors experience coordination benefits differently from general contractors and CCA participants. Even within ICF environments, supplier input does not automatically translate into real design influence. Coordination improves, but design authority remains concentrated at the top of the procurement chain. For early involvement to produce the outcomes the model predicts, three governance conditions need to be in place.

First, compensation for early engineering work needs to be transparent and predictable. When suppliers absorb coordination and design risk without clear rewards, they limit their commitment and withhold technical knowledge that could improve design decisions. Second, decision authority needs to be explicitly defined. Early involvement that is structurally advisory, where supplier input is welcomed but not formally linked to design outcomes, yields weaker coordination benefits than involvement in which suppliers hold a defined role in shaping decisions. Volker and Lauche (2022) found that suppliers without formally defined decision authority in design workshops withheld technically valuable input, expecting it to be ignored in the absence of a contractual basis for action. Third, continuity of collaboration across projects matters. A CCA that maintains relationships with the same suppliers and subcontractors across multiple projects accumulates shared understanding, reduces uncertainty, and produces stronger coordination outcomes than one that treats each project as a relational starting point.

These conditions are difficult to establish within transactional procurement environments, where short-term contracts, competitive tendering, and risk transfer to suppliers actively work against the continuity, clarity of compensation, and legitimacy of role that participation requires (Cheung et al., 2006). Taken together, the findings suggest that procurement governance should be understood as a layered system. At the top, owner governance sets the conditions for budget flexibility, risk allocation, and procurement timing within which coordination structures operate. At the middle layer, the CCA operationalizes governance by structuring compensation for early engineering work, defining supplier decision authority, and maintaining relational continuity across projects. These are not coordination activities but governance conditions that determine whether structural access to early design converts into genuine influence. Project-level coordination, including pull planning, structured meetings, and RFI management, sits below this layer and is bounded by what the CCA has made possible above it. Strengthening this middle layer offers a practical improvement for organizations seeking to get more out of central coordination and represents an actionable target.

7.4 GMP Timing as a Governance Constraint on Coordination Outcomes

The simulation results indicate that earlier GMP agreements support collaborative exploration and the adoption of innovation when accompanied by effective coordination mechanisms. The case evidence examined alongside the simulation, however, reveals that achieving this in practice depends on governance conditions that most owner organizations do not currently have in place.

Across both public- and private-owner cases examined in this study, a consistent pattern emerged: owners delay GMP finalization not because early commitment is technically impossible, but because their internal budget governance structures make cost variance difficult to justify after approval. Public sector owners face statutory requirements, biennial funding cycles, and audit accountability that effectively prescribe when GMP can occur regardless of coordination readiness. In the UW portfolio, RCW 39.10 mandates that approximately 90% of the design be completed before GMP can be established. In contrast, the Port of Seattle requires 100% construction documents before GMP approval, driven by an internal audit culture that demands full cost traceability. As one participant described, if a single component cannot be price-verified, it raises concerns with auditors. The Mason Health MRI project illustrates what this costs in practice. The contract prescribed GMP at 90% design, and RCW contingency thresholds prevented early involvement of MEP partners, resulting in late design changes that substantially exceeded allowances and caused significant owner frustration. Private sector owners, despite having greater procurement flexibility, exhibit the same conservative behavior. In the Microsoft East Campus case, GMP was not finalized until 75-85% design completion, driven by the need for a stable, auditable cost baseline rather than by any coordination-based trigger. The behavioral outcome is the same across both contexts: owners consistently prioritize cost certainty over coordination timing, regardless of the procurement structure.

This has a direct consequence for how the ICF operates in practice. When GMP is delayed until 90 to 100% design completion by statute or internal policy, the window for coordination-driven innovation narrows significantly, as reflected in P3, which was only partially supported precisely because of this governance constraint. ESI and collaborative design exploration can still occur under these conditions, but their impact on final decisions diminishes as design becomes increasingly fixed before GMP is established.

The cost of this delay extends beyond the innovation window. At the Port of Seattle, the six-to-eight-week reconciliation between the owner's and contractor's estimates was not simply a disagreement about the numbers. It was a negotiation over who would absorb the cost of uncertainty that neither party had been compensated to hold, compounded by unresolved questions about escalation rates and the absence of shared-savings provisions. Several studies similarly identified asymmetric risk allocation during the pre-commitment phase as a structural contributor to scope instability, confirming that the pattern observed at the Port of Seattle is not unusual but characteristic of environments where cost uncertainty goes uncompensated. This dynamic is self-reinforcing. Owners delay GMP until they have full cost visibility, but suppliers withhold the technical input needed to provide that visibility when the early engineering mechanism goes uncompensated. Each party waits for the other to move first, and coordination suffers in the gap.

The case evidence further reveals that innovation behavior changes sharply once GMP is set, regardless of how collaborative the pre-GMP process was. Kim and Rhee (2026) focus on innovation aversion as a post-GMP phenomenon. The Microsoft case confirms this, but adds a dimension: even robust pre-GMP collaboration does not insulate a project from this reset. Trade partners who had been genuinely engaged in design exploration before GMP became immediately cost-protective once the GMP was established, pursuing innovation only when it carried no financial risk. This suggests that GMP does not simply change incentives but resets relationships. The collaborative norms built during pre-GMP engagement are not strong enough to survive the shift in financial stakes that GMP creates. Pre-GMP trust does not transfer into post-GMP risk tolerance. Several studies observed the same pattern in complex project alliances, finding that trust built during early project phases broke down once contractual risk shifted, regardless of how collaborative the original agreement had been. This dynamic is not captured in the simulation, which treats coordination benefits as cumulative throughout the project lifecycle.

The one exception observed was the UW Vivarium project, where a phased-GMP approach maintained partial design flexibility while preserving audit visibility. By establishing partial cost commitments at progressive design milestones, the phased approach kept the incentive structure open longer. This narrowing of the gap between cost commitment and design decision-making is precisely what the model predicts would reduce innovation aversion. The case evidence is consistent with this prediction that the phased approach preserved a longer window of genuine design exploration than any other case examined. Alhava et al. (2015) reached a similar conclusion in their analysis of hospital projects, finding that progressive cost-commitment structures produced higher rates of design innovation and lower rates of late-stage redesign than single-point GMP arrangements. However, the Vivarium approach required deliberate governance design by an owner willing to absorb planned variance within an overall funding model, a condition that statutory and institutional constraints preclude for most public-sector projects.

Taken together, the simulation and case evidence suggest that GMP timing cannot be optimized through coordination structure alone. Owner governance culture is an upstream constraint that shapes what coordination can achieve, regardless of how well the ICF operates. The barrier to early GMP is not the contract, but an owner culture. Early or phased GMP mechanisms might only work where institutions have already accepted that cost certainty and coordination timing cannot both be maximized, and that a trade-off between them is necessary. For the ICF to fully realize its potential, the governance conditions surrounding GMP, including funding flexibility, compensation clarity, contingency management, and shared-savings provisions, need to align with the coordination structure. Examining how different contractual and governance arrangements can expand the pre-GMP collaboration window across different contexts, therefore, represents a direct and important direction for future research.

7.5 Workflow Disruption as a Schedule and Cost Mechanism

The four performance metrics captured in the simulation indicate the effectiveness of coordination. However, they do not directly represent schedule duration or cost outcomes. The decline in capacity utilization observed under typical procurement conditions points to a mechanism by which coordination failures produce consequences that the model does not directly measure. The progressive decline in capacity utilization observed under typical conditions is not merely a measure of resource efficiency. It reflects the cumulative effect of workflow interruptions stemming from previously unresolved design conditions, demands for task resequencing, and waiting periods during construction. When a task requires clarification from a designer, engineer, or owner before it can proceed, releasing it into the weekly work plan disrupts the sequence of dependent activities. The result is a cascading interruption across multiple trades and work sequences, in which labor sits idle, resources are redirected to reactive problem resolution, and planned activities are deferred. Over time, these interruptions do not simply reduce efficiency; they accumulate into schedule overruns as the project cannot recover the time lost to repeated workflow adjustments. Hanna et al. (2005) quantify productivity losses of 10-30% attributable to RFIs, rework cycles, and inefficient sequencing in fragmented procurement environments. These losses translate directly into labor cost escalation, extended general conditions, and the growing overhead of managing a project that has fallen behind its own coordination capacity. Goolsbee and Syverson (2023) document a sustained, multi-decade decline in construction labor productivity, attributing part of this to fragmented procurement structures that push coordination into phases where it is most costly. By resolving design ambiguities before construction begins, the ICF prevents this pattern of decline from initiating in the first place.

The lean construction literature provides the theoretical account of why this dynamic is structurally rooted rather than incidental. Koskela (1992, 2000) developed the Transformation-Flow-Value theory, which reframes construction as a production system in which flow, the continuous and reliable movement of work from one phase to the next, is as important as the transformation occurring within each phase. Conventional project management treats construction almost entirely as transformation: tasks are planned, resourced, and executed in sequence, with the assumption that outputs will be available when needed. The consequence is that variability introduced at any point in the system does not stay local. Each downstream activity that depends on a disrupted output inherits the variability, and because construction involves dense interdependencies across trades, propagation amplifies. Tillmann et al. (2014), in a study of IPD cases, found that design-phase variability was the strongest predictor of construction-phase workflow disruption, and that procurement structures that enable ESI were the most effective at reducing it. Critically, TFV theory locates the origin of this variability not in construction execution but in how the design phase is governed. When design produces incomplete or ambiguous outputs, it generates flow failure before a single trade has mobilized on site.

Koskela and Howell (2002) further developed this by identifying the release of work before its prerequisite conditions are met as the fundamental dysfunction of push-based delivery. In this framing, an RFI is not a communication tool. It is evidence that work entered construction before the design was ready to support it. The simulation's finding that ICF reduces RFI volume is not only a coordination result but evidence that the ICF addresses the root cause of RFI generation rather than managing its downstream effects. Bolviken et al. (2014) reinforced this interpretation in a sample of Norwegian construction projects, finding that RFI rates correlated strongly with design completion at the construction handoff, with projects beginning construction at lower completion levels generating disproportionately higher RFI volumes in later phases. Several studies extended this finding, showing that the timing of design resolution relative to construction mobilization was a stronger predictor of RFI volume than project size, complexity, or delivery method, which further supports the simulation's framing of RFI accumulation.

Ballard (2000) demonstrated that even small improvements in weekly work plan reliability produced disproportionate gains in workflow continuity, because reliable completion prevents disruption from propagating through the system. However, as Ballard and Howell (2003) subsequently argued, the LPS can only manage variability that reaches the construction phase. It cannot retroactively resolve design ambiguities that should have been cleared upstream. Similar arguments show that improvements in lean performance depend on stabilizing upstream design and planning processes, as the quality and completeness of early-phase project inputs constrain the reliability of downstream construction. Alves et al. (2016), reviewing two decades of LPS research, reached a similar conclusion, finding that the projects with the lowest constraint removal rates, and therefore the worst weekly planning reliability, were consistently those where design completeness and supplier input had not been secured before construction began. In this integrated view, workflow disruption may not be fully addressable through improved construction planning alone. The evidence suggests that connecting design and construction phases through governance structures that support more complete design resolution before construction begins could be a more effective lever, one that procurement decisions appear to shape more directly than scheduling interventions alone. The design and construction phases need to be connected through governance structures that ensure construction begins with fully resolved design outputs, which is precisely what the ICF provides.

7.6 Synthesis

Taken together, these sections converge on a single finding. The gap between what structured procurement can achieve in theory and what it delivers in practice is not a technical problem. It is a governance problem that operates at multiple levels simultaneously.

This study makes a specific and original contribution at this intersection. Existing research either shows that earlier GMP supports innovation, or examines how owner governance shapes GMP timing, or studies supplier involvement as a timing decision. No existing study connects all three as a single system. This study shows that early GMP is beneficial and that owner governance is currently the primary barrier preventing it. However, it also shows that even when GMP is late, the middle layer of governance, covering how supplier participation is compensated, what decision authority suppliers hold, and whether relationships persist across projects, determines how much of the potential benefit can still be recovered. The CCA operationalizes this middle layer in practice by structuring compensation conditions, defining supplier decision-making authority, and maintaining relational continuity across projects, rather than functioning solely as a project-level coordination tool. Strengthening this middle layer is therefore not a fallback when early GMP is unavailable; it is a necessary condition for realizing the full benefit. Figure 28 illustrates how these three governance layers relate, with the CCA and middle governance conditions sitting between owner-level constraints and project-level coordination.

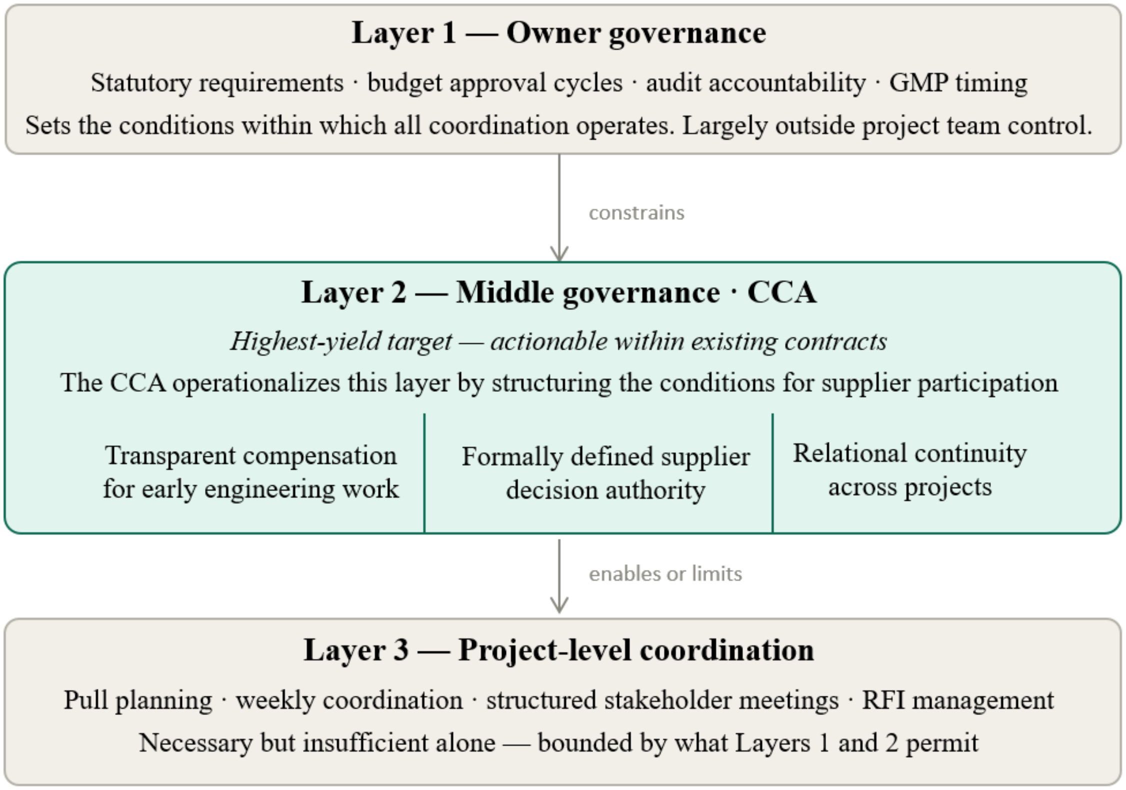


Figure 28. Three-layer procurement governance framework showing how owner governance constrains the CCA and middle governance conditions.

The governance middle layer identified in this study, which covers compensation for early engineering input, formally defined decision authority, and relational continuity, provides organizations with a concrete starting point for improvement that does not require statutory change or a redesign of delivery methods. These three conditions can be addressed within existing contract structures by adding early engineering service agreements with transparent fee structures, incorporating supplier decision rights, and establishing preferred supplier frameworks that span project portfolios. Rahman and Kumaraswamy (2012), in their analysis of relational contracting, highlighted that even within highly regulated procurement environments, organizations that formalized early supplier roles and compensation structures achieved measurably better coordination outcomes than those that treated supplier engagement as informally negotiated. This study's practical contribution is identifying the governance middle layer as the highest-yield target for improvement. It offers a theoretical and empirical basis for prioritizing it over structural procurement changes that are either unavailable in public-sector contexts or insufficient on their own to create the behavioral conditions that translate structural access into real design influence.

A further finding that emerged directly from the case evidence is the post-GMP behavioral reset, discussed in detail in section 7.4. In every project examined, stakeholder behavior changed sharply the moment GMP was established, regardless of how collaborative the pre-GMP process had been. This behavioral reset is not captured in the simulation, which treats coordination benefits as cumulative across the lifecycle. It reframes GMP not simply as a cost-management tool but as a behavioral boundary that determines how much of the collaboration window can actually be converted into innovation outcomes, and it represents an original empirical contribution.

A limitation of the current simulation framework is that it models stakeholder behavior through predefined decision rules calibrated to observable procurement outcomes, effectively treating agents as rational economic actors responding to structural incentives. While this approach produces meaningful performance differentiation, it does not fully capture the extent to which stakeholder behaviors are shaped by organizational norms, relational histories, perceived fairness, and institutional role expectations, dimensions that social embeddedness theory suggests are central to understanding why actors behave differently under different conditions (Granovetter, 1985). Future research might therefore reframe agents not as purely rational decision-makers but as culturally embedded participants whose behaviors emerge from the social and institutional contexts in which they operate, drawing on anthropological and organizational literature to develop behavioral specifications that reflect the relational dynamics observed in practice.

Overall, the procurement structure creates the conditions for better performance, but governance determines whether those conditions are ever activated, and the mechanism connecting the two is behavioral. Risk perception, participation, and collaboration intensity are not fixed at contract signing. They evolve throughout the project lifecycle in response to the governance conditions surrounding them, which means procurement performance can only be meaningfully assessed through the behavioral trajectories those conditions generate over time. This extends transaction cost economics and relational contracting theory by showing that their predictions do not hold as stable contractual outcomes but shift and compound across the project lifecycle as governance conditions change.

7.6.1 Practical Implications for Procurement Design and Tool Use

This section translates simulation results into actionable decision strategies for practitioners. Beyond its research contributions, this study produces outputs that practitioners can engage with directly. The simulation framework serves as a scenario-planning tool that makes three dynamics visible to procurement managers that would otherwise be invisible. First, it reveals the false stability trap. Under typical procurement conditions, early-phase metrics appear smooth and stable, masking the accumulation of unresolved coordination gaps. Without the tool, a procurement manager observing low early redesign activity and minimal RFI generation would reasonably conclude that coordination is working when, in fact, the system is quietly accumulating risk. Second, it exposes the behavioral lag, the behavioral conditions that produce coordination failures, elevated risk perception, and suppressed participation precede their visible consequences by weeks or months. Without the tool, practitioners have no mechanism to detect this lag; they intervene only after the disruption is already embedded in project metrics. Third, it captures how early coordination failures propagate simultaneously across all four performance indicators, amplifying their combined impact on project execution. Conventional project monitoring treats innovation adoption, redesign, RFI volume, and capacity utilization as separate dashboards; the simulation reveals that they operate as a connected system in which a failure in one dimension accelerates decline across all others.

Before a procurement decision is made, a practitioner can input project-specific parameters, including anticipated design complexity, owner governance constraints, GMP timing, and the degree of ESI planned, and observe how these conditions drive divergent performance trajectories, providing a concrete basis for comparing alternatives grounded in projected behavioral dynamics. The model does not predict outcomes with precision, but it identifies the mechanisms by which procurement choices translate into performance differences, which is a more actionable basis for decision-making. Schöttle et al. (2019) argued that the absence of such forward-looking behavioral models was a key reason why procurement decisions in construction remained path-dependent despite consistent evidence that alternative structures produced better outcomes, a gap this study's simulation framework begins to address.

During the design phase, the behavioral parameters formalized in the model, including risk perception (R_{perc}), participation gate (P_{gate}), and collaboration intensity (C_i), function as leading indicators that practitioners can monitor. Procurement managers can track early behavioral signals through structured check-ins, participation tracking in design workshops, or supplier willingness to commit engineering resources without contractual protection, identifying suppressed participation before it compounds into downstream disruption. Pellicer et al. (2020) found that projects with structured early-phase monitoring identified coordination risks an average of four weeks earlier than those relying on conventional progress reporting.

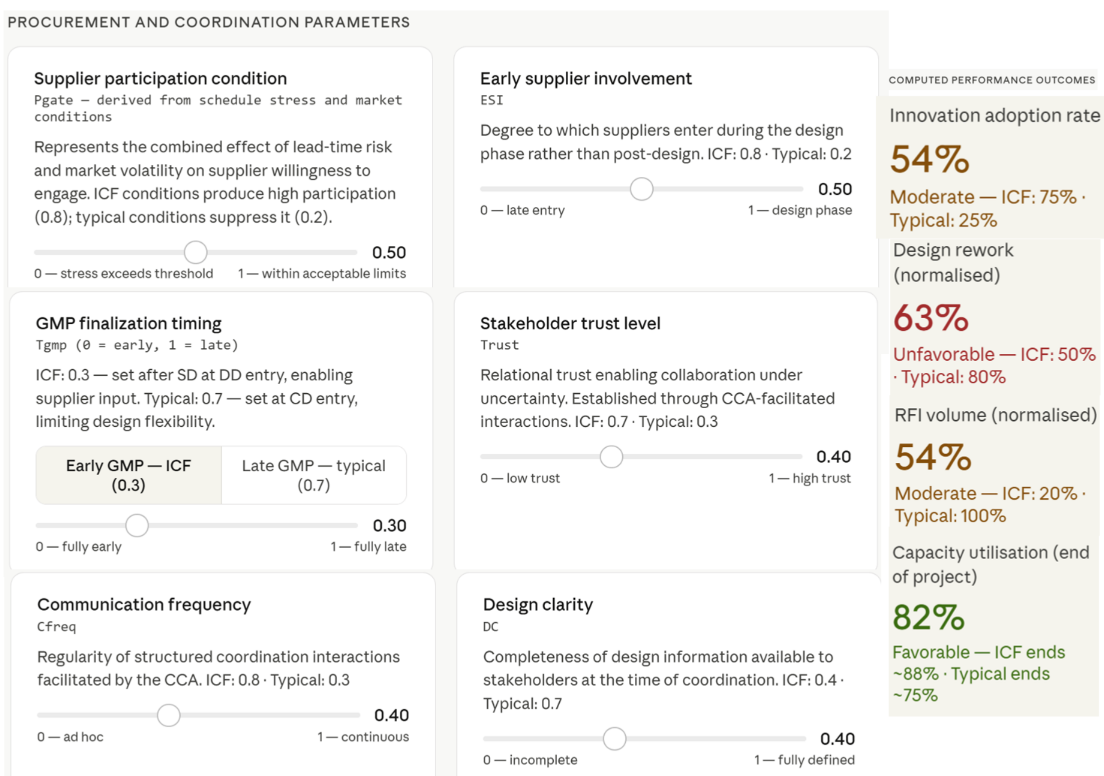
When warning signs emerge, the appropriate response is not to accelerate the construction schedule or increase resource allocation. The model identifies which behavioral parameters are suppressing performance, allowing governance adjustments to be targeted at the root cause. What distinguishes this framework from conventional procurement guidance is not the identification of better structures but the behavioral logic that explains why those structures work, when they fail, and what practitioners can do about it before performance decline becomes irreversible.

7.6.2 Practical value of the tool for decision-making

The simulation tool is designed to be used with project-specific inputs. A procurement manager, owner, or GC can enter the coordination conditions of their own project, including GMP timing, trust levels, communication frequency, and degree of early supplier involvement, and observe how those conditions are likely to drive performance across all four metrics. Rather than mapping a project onto a generic benchmark, the tool generates outputs that reflect the specific behavioral dynamics of that project's procurement environment. The following scenario demonstrates how this works in practice.

To demonstrate the practical utility of the simulation tool, Figure 29 presents a scenario representing a project that has adopted early GMP (Tgmp = 0.30) and Pgate = 0.50, the contractual condition central to the ICF. However, it operates under suppressed behavioral conditions, with stakeholder trust (Trust = 0.40), communication frequency (Cfreq = 0.40), design clarity (DC = 0.40), and partial early supplier involvement (ESI = 0.50). This configuration reflects a transitional procurement condition more commonly encountered in practice.

The tool’s practical value lies in more than simply confirming that coordinated procurement outperforms fragmented procurement. The tool embeds the behavioral relationships calibrated from interview evidence directly into an interactive decision environment, allowing a procurement manager to input the specific conditions of their project rather than mapping it onto an aggregate scenario. The agent-based structure of the underlying model means that outputs are not static predictions but reflect how procurement conditions propagate through stakeholder interactions over time. When a practitioner adjusts trust or communication frequency in the tool, they are not adjusting an abstract input; they are modifying the conditions under which the CCA agent facilitates coordination, thereby reshaping participation decisions, collaboration intensity, and downstream performance across all four metrics simultaneously. This captures something that neither a checklist nor a benchmarking table can: the interdependence of behavioral conditions and the compounding consequences of getting them partially right.



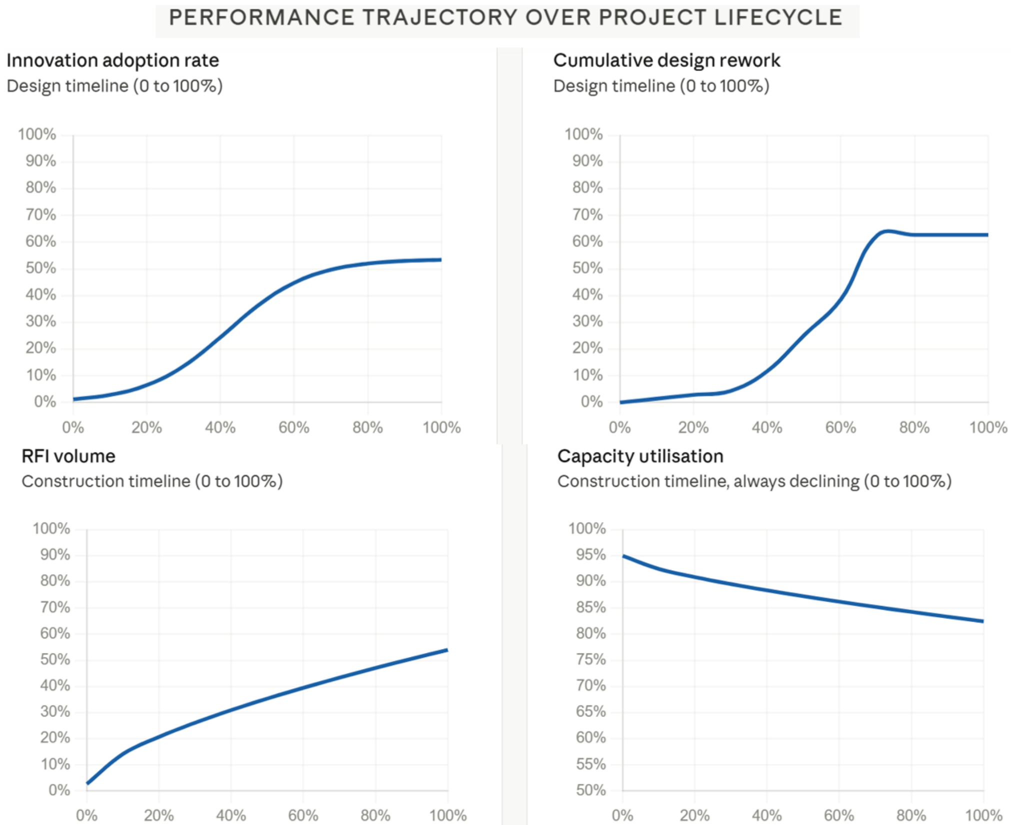


Figure 29. Application of the tool for Practitioners

For practitioners, the tool therefore functions as a decision-making process rather than a prescriptive one. Rather than telling a project team to adopt the ICF, it allows them to identify which specific conditions in their project are suppressing performance and by how much. In this scenario, a practitioner would immediately see that moving Trust from 0.40 to 0.70 and C_{freq} from 0.40 to 0.80, while keeping everything else constant, would substantially shift outcomes toward the ICF benchmark. That intervention is feasible and targeted, and it does not require restructuring the entire procurement approach. This kind of parameter-specific diagnosis, grounded in the model's behavioral logic rather than in generic procurement guidance, is the contribution the tool makes to practice. The tool's contribution to practice lies not in prescribing a procurement approach but in making the behavioral consequences of existing conditions visible early. A practitioner who can see which parameter is limiting performance, and by how much, is in a fundamentally better position to make governance adjustments that are proportionate to the problem and achievable within the constraints of their project.

Chapter Summary

This chapter moved from what the simulation produced to what it means in practice. The central argument is that procurement structure creates the conditions for better performance, but governance determines whether those conditions are ever used.

It is confirmed that ICF conditions produce better outcomes across all four metrics, but the more important finding is what drives that difference. Performance gaps between coordinated and fragmented procurement do not reflect organizational capability or project complexity. They reflect whether governance conditions allow the opportunity created by the procurement structure to be acted upon. Capacity utilization is a consequence metric, not a coordination metric. It captures the cost of unresolved design issues carried into construction, not something that can be managed once construction has started.

Procurement performance cannot be evaluated at contract signing. It must be tracked over time, because the conditions that cause coordination failures appear weeks or months before their effects show up in project metrics. This matters for how procurement managers read early project signals. Low redesign activity and low RFI volume in the early phases do not mean coordination is working. They can just as easily mean that problems are accumulating quietly and will surface once construction pressure builds.

GMP timing, treated in the propositions as a procurement variable, emerged from the case evidence as shaped by owner governance culture, statutory requirements, budget cycles, and audit structures, none of which align with coordination readiness. Owners delayed GMP not because early commitment was impossible but because their internal structures made cost variance hard to justify. More importantly, stakeholder behavior shifted sharply the moment GMP was set in every project examined, regardless of how well the pre-GMP process had gone. Trust built before GMP did not carry over into risk-taking after it. This is a fragility in the ICF that governance design must address directly.

Even within ICF enviRonments, suppliers often remained in advisory roles because the conditions surrounding their participation did not make a genuine commitment worthwhile. Three governance conditions are needed to close this gap: clear compensation for early engineering effort, defined decision authority for suppliers, and continuity of relationships across projects. Together, these form a middle layer of governance between owner policy and project-level coordination, determining how much of the ICF's potential is actually used. This layer can be strengthened within existing contract structures without legislative change.

The simulation tool extends these findings into something practitioners can use directly. It allows a procurement manager to input their own project conditions and see how those conditions are likely to affect performance across all four metrics before construction begins. It identifies the specific parameter that limits performance, allowing the intervention to be targeted.

Chapter 8 Conclusions

This chapter presents the conclusions of a study examining how procurement structure, stakeholder behavior, and governance conditions interact to shape construction project performance throughout the design and construction lifecycle. Section 8.1 summarizes the five key research findings that emerge from the simulation results, case evidence, and validation. Section 8.2 outlines the theoretical, methodological, and practical contributions of the study. Section 8.3 discusses the practical implications for industry practitioners across different stakeholder groups. Section 8.4 acknowledges the study limitations, and Section 8.5 identifies five directions for future research that emerge directly from the findings and limitations of this work.

8.1 Key Research Findings

This research examined how procurement structure and stakeholder behavior interact as a dynamic system to influence construction project performance. Rather than asking whether earlier supplier involvement improves outcomes, the study investigated the mechanisms through which coordination timing, stakeholder decision-making, and governance conditions collectively shape performance trajectories across the design and construction lifecycle. Four findings reframe how procurement performance should be understood, measured, and governed.

The first finding is that procurement structure creates the conditions for better performance, but governance influences whether those conditions are translated into improved outcomes. Projects operating under the Integrated Coordination Framework achieved higher innovation adoption, 80% fewer RFIs, and stable capacity utilization of 88% compared to a progressive decline to 75% under fragmented procurement. These differences seem to depend less on project complexity or technological capability, and more on whether governance conditions allowed teams to act on those opportunities.

The second finding is that the Central Coordination Agent improves performance by shifting coordination and issue resolution upstream into the design phase, where conflicts can be addressed before decisions become fixed. Under the Integrated Coordination Framework, this earlier resolution process resulted in substantially lower RFI generation and more stable workflow conditions during construction. In contrast, under typical procurement, low early redesign activity and limited RFI volume can create the impression that coordination is effective, when in reality unresolved issues are being deferred to later project stages. The simulation shows that these deferred issues tend to surface during construction, where resolution becomes more disruptive, increases RFI generation, and reduces available capacity. This pattern reflects a false sense of early stability, in which risk is not eliminated but shifted downstream to stages where it is more costly to manage.

The third finding is that GMP timing serves as a governance condition that shapes stakeholders' risk-taking behavior and influences the extent to which supplier expertise contributes to innovation during design. The findings suggest that early GMP, when combined with coordinated design collaboration, can encourage more proactive and solution-oriented stakeholder behavior under clearer cost boundaries. In these environments, contractors and trade partners appear more willing to evaluate alternative materials, technologies, and constructability strategies while major design decisions remain flexible. In contrast, under later or conventional GMP arrangements, stakeholders are less likely to pursue risky or less proven alternatives prior to GMP establishment because future cost responsibility remains uncertain. The case evidence further suggests that once GMP is finalized, stakeholder behavior shifts toward protecting established cost commitments, limiting continued exploration of alternative solutions unless associated risks are clearly bounded. This behavioral shift reflects a rational response to the distribution of financial risk within the procurement structure instead of reflecting coordination failure.

The fourth finding is that the highest-impact target for procurement improvement is the middle governance layer between owner policy and project-level coordination. This layer is defined by three conditions that determine whether early supplier involvement produces real design influence or remains advisory. Clear compensation for early engineering work is the first condition, because suppliers are less likely to commit technical knowledge when the reward for doing so is unclear. Formally defined supplier decision authority is the second, because early involvement that is structurally advisory does not consistently translate into improved design outcomes, regardless of how early suppliers enter the process. Relational continuity across project portfolios is the third, because a CCA that maintains deep relationships with the same suppliers across multiple projects accumulates shared understanding, reducing uncertainty and producing stronger coordination outcomes than one that rebuilds those relationships from scratch each time. The CCA functions not only as a coordination mechanism but also as a social stabilizer that establishes role boundaries, reinforces norms of reciprocal commitment, and creates conditions that stakeholders perceive as fair. Strengthening the middle governance layer addresses this directly. It is actionable within existing contract structures through early engineering service agreements with transparent fee structures, formally incorporated supplier decision rights, and preferred supplier frameworks that span project portfolios.

Together, these findings suggest that procurement performance is shaped not just by contract type or delivery method, but also by the governance conditions, behavioral dynamics, and coordination timing that procurement decisions set in motion. These findings also help clarify how this study contributes to existing knowledge.

8.2 Contributions to Knowledge

This study makes contributions across four theoretical dimensions, as well as methodological and practical contributions. Together, these contributions position procurement as a system shaped by evolving governance conditions, stakeholder relationships, and the timing of coordination.

One of the theoretical contributions of this study extends discussions on relational contracting while providing foundational insights relevant to transaction cost economics in construction procurement. The findings suggest that behavioral conditions associated with risk perception, participation, and collaboration intensity may not remain stable throughout the project lifecycle, but instead shift in response to changing governance conditions. The study further indicates that governance structures influence not only contractual efficiency, but also the accumulation of hidden coordination costs associated with repeated RFIs, redesign, delayed decision-making, and downstream disruption. Under fragmented procurement, unresolved coordination issues contributed to greater coordination- and transaction-related inefficiencies. In contrast, early supplier involvement, supported through the Integrated Coordination Framework, reduced these inefficiencies by enabling earlier issue resolution, clearer decision-making authority, and more stable coordination conditions. As a result, the study suggests that procurement performance may be better understood by examining how governance conditions shape coordination dynamics and hidden coordination costs throughout the project lifecycle, rather than relying solely on contractual arrangements established at project initiation.

A second theoretical contribution is the clarification of a boundary condition that existing ESI literature has not fully addressed. This study distinguishes between participatory presence, in which suppliers enter the process early but remain in advisory roles, and genuine decision influence, in which supplier input shapes core design outcomes while decisions remain flexible.

This distinction determines whether early involvement produces measurable performance gains or remains a structural formality.

A third theoretical contribution is the identification of the post-GMP behavioral shift as a governance-related phenomenon rather than only a cost-management issue. While existing literature largely treats GMP in financial terms, this study highlights how GMP timing is also associated with changes in stakeholder behavior. This perspective suggests that procurement research may benefit from giving greater attention to how financial milestones influence behavior, not just cost outcomes.

A fourth theoretical contribution draws on Granovetter's theory of social embeddedness to reframe the CCA as a social stabilizer rather than only a coordination mechanism. This provides a theoretical basis for why the middle governance layer produces stronger performance gains than a coordination structure alone. It also explains why structurally similar procurement arrangements produce different outcomes depending on the relational context in which they operate, a pattern that contractual and coordination-based frameworks alone cannot account for. Beyond its theoretical contributions, this study also advances the methodological and practical dimensions.

The **methodological** contribution of this study is a replicable mixed-methods framework for examining construction procurement as a dynamic behavioral system rather than a static contractual arrangement. The framework integrates qualitative data from 13 industry interviews across owners, general contractors, suppliers, and centralized procurement entities. Interviews were analyzed using thematic coding in NVivo, producing empirically grounded behavioral constructs including collaboration intensity, risk perception, trust, technology adoption behavior, and contract timing. These constructs were translated into agent attributes, decision rules, and interaction mechanisms through a structured coding-to-model mapping process that maintained traceability between qualitative evidence and simulation design.

The ABM implemented in AnyLogic 8.9.8 operationalizes these behavioral constructs as dynamically interacting agents across a normalized project timeline. The model was evaluated through a four-stage validation framework that included internal verification, mechanism validation via expert walkthroughs, pattern validation by comparing simulation output trajectories against expert expectations, and quantitative benchmarking using the Wilcoxon signed-rank test. All four performance metrics showed no statistically significant deviations from expert-elicited values ($p > 0.05$), supporting the model's quantitative credibility. Future researchers can adapt this framework to examine other procurement contexts, delivery methods, or stakeholder configurations where behavioral dynamics and governance conditions shape system-level outcomes.

A practical contribution of this study is highlighting the middle governance layer as a useful point of intervention for improving outcomes. Rather than requiring changes to delivery methods or relying only on project-level coordination, the study points to a set of governance conditions within existing contract structures, such as compensation clarity, decision authority, and relational continuity, that practitioners can adjust to support better performance.

Building on these contributions, the following section translates these insights into practical implications for different stakeholder groups.

8.3 Practical Implications for Industry

The findings of this study carry different implications depending on where in the procurement system a professional operates. For owners**,** the primary implication is to treat GMP timing as a governance decision that shapes when supplier input can meaningfully influence design. Delaying

GMP may reduce financial uncertainty, but it can also limit the role of supplier expertise in early decision-making. Owners should also recognize that stakeholder behavior tends to shift after GMP finalization, which can limit continued collaboration if not anticipated. Owners should be cautious in interpreting low early redesign and RFI activity, as it may not always reflect effective coordination. For general contractors and CCAs, the implication is to apply the conditions of the middle governance layer consistently within existing contract structures, rather than addressing them informally on a project-by-project basis. Maintaining continuity in supplier relationships across projects can support more stable and reliable coordination outcomes over time. For suppliers and specialty trade partners, the findings suggest that early engagement alone may not be sufficient unless it is supported by clear compensation structures, defined decision authority, and continuity of relationships across projects. In environments where these conditions are present, suppliers are more likely to contribute technical expertise that meaningfully influences design outcomes rather than remaining in advisory roles. For the industry more broadly, procurement arrangements should not be evaluated solely on contractual conditions set at project initiation, as stakeholder behaviors and coordination dynamics continue to evolve throughout the project lifecycle.

The conditions that precede visible performance failures often emerge weeks or months before their effects show up in project metrics. Industry practice needs to shift toward monitoring behavioral leading indicators throughout the design phase rather than waiting for RFI volumes and rework rates to confirm that the system has already failed. These behavioral conditions are directly linked to outcomes observed in this study, including higher innovation adoption, reduced RFIs and redesign, and more stable capacity utilization under coordinated procurement conditions. Practitioners across all stakeholder groups can engage directly with the simulation tool developed in this study, which allows project-specific procurement conditions to be entered and their likely performance consequences to be observed. Rather than mapping a project onto a generic benchmark, the tool generates outputs that reflect the behavioral dynamics of that project's specific coordination environment, making it a practical instrument for identifying which governance conditions are limiting performance and where targeted adjustments are most likely to produce improvement. The practical value of these findings is strengthened by the boundaries within which they were developed, which are acknowledged in the following section.

8.4 Study Limitations

This study has limitations related to the simulation design, the qualitative data, the scope of validation, and the boundaries of the findings. The ABM represents stakeholders as bounded rational actors responding to formal incentives. A key methodological challenge in this study is translating qualitative interview insights into quantitative agent decision rules, a process that inherently involves interpretive judgment. While a structured coding-to-model mapping framework was used to maintain traceability, the conversion of nuanced practitioner descriptions into mathematical parameters remains a simplification. Relationships that practitioners described as contextual and nonlinear, such as the effect of design clarity on RFI generation or the conditions under which ESI translates into innovation, are represented in the model as linear or threshold-based functions. Future work using longitudinal project data could provide stronger empirical grounding for these relationships. While this produces validated performance differentiation, it does not fully capture how relational histories, perceived fairness, and organizational culture shape procurement behavior in practice, dimensions that Granovetter's embeddedness theory suggests are central to the differences observed across similar procurement arrangements. More broadly, real-world outcomes remain influenced by organizational, contractual, and commercial conditions that fall outside the model's scope, so the simulation reflects a structured abstraction of procurement behavior rather than a complete representation of the conditions that shape it in practice. In addition, the model does not explicitly account for project-specific conditions such as delivery constraints, contractual variations, or execution environments, which can influence coordination outcomes in practice. As a result, the validation reflects generalizable industry tendencies rather than exact performance thresholds for individual projects. Furthermore, the model does not distinguish between suppliers that participate in early coordination with genuine decision-making authority and those that remain structurally advisory. Since interview evidence consistently showed that these two conditions produce measurably different outcomes, future model iterations should incorporate decision authority as an explicit agent attribute rather than an implied feature of the ICF structure.

A contextual limitation concerns the regulatory environment in which the interview data were collected. Washington State is among the few states that require 90–100% completion of construction documents before GMP finalization (RCW 39.10). This means that participants from public-sector owner organizations operated under procurement constraints that structurally preclude early GMP, regardless of coordination readiness. This limits the generalizability of findings related to GMP timing, particularly P3, to jurisdictions with similar regulatory frameworks. Projects in states or countries with greater GMP flexibility may exhibit different behavioral dynamics than those captured in this study.

Related to this, the post-GMP behavioral reset, which emerges from the case evidence as an important observation, is not formally represented in the simulation. The model treats coordination benefits as cumulative throughout the project lifecycle and does not capture the sharp shift in stakeholder behavior that occurs when GMP is established. This is a boundary condition of the current framework rather than a flaw in its design. However, it means the simulation does not fully represent the governance challenge of sustaining collaborative behavior through the project phase.

The qualitative data underpinning the model were collected through interviews conducted at a single point in time, in which participants were asked to reflect on past project experience. This data captured practitioner perceptions and recollections rather than observed behavioral dynamics as they unfold in real time. Procurement behavior, risk perception, and collaboration intensity evolve throughout a project lifecycle, and a cross-sectional interview cannot fully capture this evolution. Longitudinal observation of real-world projects would provide stronger empirical grounding for the behavioral constructs on which the model is built.

Regarding validation, the expert sample used for quantitative benchmarking is small, and validation relies on practitioner judgment rather than measured empirical datasets. The benchmark ranges used represent informed approximations of industry tendencies rather than precise performance thresholds, and validation reflects generalizable behavioral patterns rather than exact project-level predictions. The Wilcoxon signed-rank test was applied to a small expert sample, and while p-values exceeded the 0.05 threshold, these results should be interpreted with caution. With sample sizes this small, the test has very low statistical power, meaning the absence of a significant difference does not confirm equivalence between model outputs and expert expectations. The results are best interpreted as directional consistency rather than statistical confirmation, and future validation with larger expert panels would strengthen the model's quantitative credibility.

Capacity utilization in the model captures one important coordination-related dimension of workflow continuity by representing it as a direct function of RFI volume. In practice, capacity utilization is also shaped by factors including trade sequencing, crew availability, workface readiness, and site access constraints that are not captured in the current formulation. Future iterations of the model could incorporate these additional dimensions to more fully represent the variability in capacity utilization that arises from execution-level conditions independent of coordination quality.

Finally, the simulation holds project complexity constant across both scenarios to isolate the effect of coordination structure. In practice, the behavioral dynamics may operate differently on smaller projects where stakeholder networks are simpler, or on very large projects where coordination demands exceed what a single CCA can manage. The findings are therefore most directly applicable to mid- to large-scale commercial and institutional projects similar to those represented in the interview sample. These limitations point directly to directions for extending this research.

8.5 Future Research Directions

This study highlights several areas where further research can build on these findings.

The post-GMP behavioral reset should be formally modeled as a discrete state transition within the agent-based simulation. The current framework treats coordination benefits as cumulative. However, the case evidence from this study shows that stakeholder behavior shifts sharply the moment GMP is established, regardless of the quality of prior collaboration. Formally representing this reset as a governed state change, in which agent risk tolerance, willingness to participate, and collaboration intensity recalibrate at the GMP boundary, would improve the simulation's ability to capture real project dynamics and provide practitioners with more nuanced projections of post-GMP performance. Interview and case evidence from this study further suggest that trust and collaborative norms built during pre-GMP phases do not carry over into post-GMP behavior; stakeholders shift immediately into cost-protection mode regardless of the quality of prior engagement. Capturing this as a discrete behavioral reset, rather than a cumulative transition, would more accurately reflect the governance boundary that GMP represents in practice.

The relationship between GMP timing and innovation adoption should be examined empirically across a larger, more diverse set of projects to better understand the conditions under which earlier GMP yields the coordination and innovation benefits this study identifies. A larger empirical study tracking GMP timing, supplier engagement levels, and innovation outcomes across projects with varying owner governance structures would strengthen the generalizability of this study's findings and clarify the specific design-phase conditions under which early GMP produces the greatest benefit.

Future simulation work can extend the model by incorporating more socially embedded representations of agents, including relational histories, fairness perceptions, trust development, and institutional roles. While the current model captures these dynamics at a simplified level through parameters such as trust and communication frequency, future work can explore how these factors develop and evolve across projects. This would help explain why similar procurement structures may lead to different outcomes depending on the relational context.

The simulation trajectories developed in this study should be validated using longitudinal project data that track behavioral parameters across design and construction phases. The current validation relies on expert input and industry benchmarks rather than observed project data. Future validation can examine whether patterns such as early-phase stability and mid-construction RFI accumulation occur in practice with similar timing and magnitude.

The simulation tool presented should also be tested in real procurement decision-making contexts to evaluate whether practitioners engage with it as intended and whether the governance adjustments it identifies translate into observable coordination improvements on real projects. This would allow the tool's diagnostic value to be assessed across different owner contexts, project scales, and delivery environments beyond those represented in the current study.

This study suggests that construction procurement performance is influenced not only at contract signing, but also by the governance conditions, behavioral responses, and coordination timing that develop over the course of a project. In particular, the results indicate that when supplier expertise is engaged early in design through a structured coordination mechanism such as the Integrated Coordination Framework, both structural conditions and stakeholder behaviors align to improve innovation adoption, reduce RFIs and redesigns, stabilize capacity utilization, and strengthen coordination outcomes. From this perspective, opportunities to improve construction performance may lie not only in changes to delivery methods but also in more deliberate structuring of governance conditions that enable the meaningful and timely integration of supplier expertise into design decision-making.

Chapter 9 References

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Chapter 10 Appendix

10.1 Interview Questionnaire

Research Summary: This research examines how procurement structure, governance conditions, and stakeholder behavior interact to influence construction project performance. It develops and evaluates an Integrated Coordination Framework centered on a Central Coordination Agent (CCA) to structure early supplier engagement throughout the design lifecycle. Through agent-based modeling, the study evaluates how coordination timing and governance conditions influence innovation adoption, design rework, RFI generation, and capacity utilization across ICF and typical procurement environments.

Terminologies / Definitions

1. Integrated Coordination Framework: A collaborative organizational structure designed to incorporate early supplier expertise, foster design pull, and streamline inter-organizational coordination in the construction procurement system with a CCA.

2. CCA: An independent entity responsible for orchestrating communication, resource allocation, and decision-making among all stakeholders to optimize project outcomes.

3. Innovation Adoption: The process of integrating new technologies, materials, or methods into construction workflows, shaped by procurement timing, supplier participation, and design-stage information quality.

Obj 1: To develop the Integrated Coordination Framework centered on a CCA, and implement it as an agent-based simulation tool that allows practitioners to analyze how procurement coordination and governance conditions shape system-level performance outcomes.

1. Could you describe a scenario where a centralized coordination structure created measurable improvements in your project outcomes?

2. What are the most significant limitations in engaging suppliers early in the design process? How do these limitations impact innovation adoption?

3. How do you facilitate early supplier involvement and improve innovation outcomes? Are there specific supplier engagement practices that worked particularly well?

Obj 2: To translate interview-derived behavioral constructs into a validated ABM that captures how stakeholder behavior, participation, collaboration intensity, and risk perception propagate through procurement conditions to produce system-level outcomes.

4. How does perceived schedule and financial risk influence your willingness to participate in early design coordination?

5. How does the competitive procurement environment affect your openness to adopting new technologies or materials?

6. At what point does risk become high enough that you limit your early engagement or withhold technical input?

7. How would you describe the relationship between trust, communication frequency, and your willingness to collaborate during early design stages?

8. How do central coordination decisions enhance the ability to allocate risks more equitably among stakeholders?

9. How do you establish clear accountability and transparency for risk management? What steps do you take to encourage a positive attitude toward risk-sharing?

10. What other factors influence stakeholder attitudes toward adopting new or innovative technology?

Obj 3: To evaluate how coordination structure and GMP timing influence innovation adoption, design rework, RFI generation, and capacity utilization across ICF and typical procurement environments.

11. Innovation Adoption: How do you track the adoption of new technologies or methods on your projects? What percentage of proposed innovations are typically adopted under coordinated versus traditional procurement?

12. Design Rework: How do you measure redesign activity? At what stages does rework typically occur, and what drives it?

13. RFI Volume: How do you track RFIs? What factors most influence RFI frequency during construction?

14. Capacity Utilization: How do you assess workflow continuity and resource efficiency during construction? What disrupts it most?

Obj 4: To examine the governance conditions that determine whether early supplier involvement produces meaningful design influence or remains advisory.

15. At what stage is the Guaranteed Maximum Price (GMP) typically finalized in your projects? Early / Mid-design / Late. How does this timing influence stakeholder attitudes toward collaboration, risk-taking, and early supplier engagement?

16. How does the compensation structure influence stakeholders' willingness to collaborate during the design phases? What does the compensation mechanism encourage? Risk-taking / Risk-neutrality / Risk aversion

17. How does the perceived fairness of compensation agreements impact trust and motivation? Was the compensation structure fair? Yes / No / Neutral

18. How do delayed payments or unclear compensation structures affect decision-making and risk-sharing attitudes? Were payment terms clear and timely? Yes / No / Neutral

19. In your experience, when suppliers are engaged early, do they genuinely influence design decisions or remain in an advisory role? What governance conditions make the difference?

20. What compensation, decision authority, or relational continuity conditions would encourage suppliers to commit more fully to early design coordination?

10.2 Validation Questionnaire

Section A: Respondent Profile

Role: Owner / GC / Subcontractor / Supplier / Consultant

Years of experience: ___

Project type experience: ___

Section B: Mechanism Validation (Behavioral Logic)

1. Risk → Participation: How does perceived project risk influence supplier participation in early design? What type of risks influence this the most? (cost uncertainty/scope ambiguity/schedule pressure/contract terms / other)

2. Participation → Collaboration: When suppliers participate early, how does that affect collaboration quality?

3. Collaboration → Design Clarity: How does stronger collaboration influence design clarity and coordination?

4. Design Clarity → RFIs: How does improved design clarity affect the need for RFIs during construction?

5. Early Supplier Involvement → Innovation

6. GMP Timing → Collaboration Behavior: How does the timing of GMP finalization influence stakeholder behavior?

Section C: Pattern Validation (Simulation Output)

7. Innovation Adoption Pattern

8. Redesign / Rework Pattern

9. RFI Pattern During Construction

10. Workflow Disruptions & Capacity

Section D: Quantitative Benchmarking

11. Innovation Adoption: What percentage of proposed innovations are typically adopted in coordinated vs. typical procurement environments? (Expected range for ICF: 60–80%, Typical: 10–25%)

12. Design Rework: What level of cumulative redesign activity is typical before construction? (Expected range for ICF: 45–60%, Typical: 60–85%)

13. RFI Volume: What RFI volumes are typical during construction on medium-sized projects? For coordinated projects, what normalized level relative to the maximum number of project RFIs is typical? (Expected ICF: 20–30% of maximum, Typical: approaching maximum with no stabilization)

14. Capacity Utilization: What effective capacity utilization levels are typical during peak construction phases? (Expected range for ICF: 80–95%, Typical: 65–80%)

Section E: Overall Model Validation

15. How well does the behavioral logic of the model reflect real project dynamics?

16. How well do the simulation output patterns match real-world project behavior?

10.3 Interview-based Parameter Calibration

Parameter	ICF / Typical	Interview Theme / Code	Representative Quote	Frequency & Stakeholder Support	Value Justification
Group 1: Procurement / Contract Structure					
Supplier Participation Gate (Pgate)	0.8 / 0.2	Conditional Participation; Lead-Time Risk	If we feel we cannot meet the supply timeline, we may choose not to pursue the project.	7/13 participants across Suppliers, GCs, and Owners identified schedule exposure as the primary barrier to participation.	A higher ICF value (0.8) indicates a greater likelihood of supplier participation under coordinated, lower-risk procurement conditions. Typical (0.2) indicates a lower likelihood of participation under fragmented, high-risk conditions.
GMP Finalization Timing (Tgmp) 0=early, 1=late	0.3 / 0.7	GMP Timing Effect; Early GMP Need; Commitment Barrier	Early GMP is especially important for long-lead equipment like switchgear. GMP can be set at early or late stages; earlier stages require more buffer.	Ranked as the top procurement variable by 10/13 participants. Suppliers, GCs, and Owners all confirmed that GMP timing directly shapes risk behavior and design flexibility.	Typical value (0.7) reflects delayed GMP constraining design flexibility; lower ICF value (0.3) reflects earlier, better-informed GMP motivating design flexibility.
Change Order Friction (Co) 0=smooth, 1=high friction	0.2/ 0.6	RFI Control; Design Clarity; Late Design Changes	The design team was rushed and did not have enough time to complete thorough quality control... subcontractors priced in additional risk to cover late design changes.	8/13 participants cited friction from change orders as a coordination cost. GCs and Owners confirmed that design incompleteness at GMP drives change order frequency.	High friction (0.6) in a typical scenario reflects late GMP and incomplete design. ICF value (0.2) reflects reduced friction through early alignment.
Project Complexity (K)	0.6 / 0.6	Structural parameter: held constant	Project complexity is driven by system interdependencies, trade density, and technical scope, which remain consistent regardless of how coordination is structured.	Participants consistently described complexity as a function of project scale, system integration, and technical requirements, rather than procurement. As a result, complexity was treated as constant.	Held constant at 0.6 to isolate procurement coordination effects from inherent project complexity.

Group 2: Supplier and Collaboration Parameters					
ESI 0=late entry, 1=early entry	0.8 / 0.2	Early Supplier Involvement; Early Supplier Benefit	Getting involved early in the design process gives us more time to support value-added initiatives and to understand owner and contractor needs.	9/13 participants confirmed ESI as a primary driver of design quality and coordination outcomes. Both suppliers, GCs, and Owners emphasized ESI. MEP involvement was central.	A higher ICF value (0.8) reflects early involvement. Typical (0.2) indicates late entry, with supplier input limited or reactive.
Coordination Efficiency (Pd) 0=low, 1=high	0.7 / 0.3	Proactive Coordination; Full Coordination; Commitment Barrier	Bringing all stakeholders together through centralized coordination improves alignment, reduces communication gaps, and allows for faster issue resolution within the project team.	8 of 13 participants linked centralized coordination to improved design efficiency through reduced RFIs and delays.	ICF value (0.7) reflects structured, CCA-enabled coordination. Typical (0.3) reflects reactive, fragmented coordination without a centralizing agent.
Collaboration Effect Strength (λ)	0.4 / 0.4	Behavioral parameter: held constant	When stakeholders actively collaborate, issues are identified earlier and resolved before they escalate into rework or RFIs.	Across all stakeholder groups, collaboration consistently reduced rework and was treated as a stable behavioral effect.	Held constant at 0.4 to represent the intrinsic moderating effect of collaboration on rework and RFI generation.
Stakeholder Trust (Trust) 0=low, 1=high	0.7 / 0.3	Trust-Based Flexibility; Payment Sensitivity	We tolerate delays if trust exists and all parties follow through, especially when coordination is structured and expectations are clearly aligned.	8 of 13 participants emphasized trust as essential for early engagement under uncertainty.	ICF value (0.7) reflects sustained trust built through structured engagement. A typical (0.3) score reflects limited trust in fragmented procurement environments.
Communication Frequency (Cfreq) 0=ad hoc, 1=continuous	0.8 / 0.3	Proactive Coordination; Weekly Check-ins	Regular coordination meetings and proactive communication help resolve issues early and prevent downstream delays.	9/13 participants across all stakeholders highlighted communication as central to the quality of coordination. Continuous engagement was identified as critical for workflow continuity.	ICF value (0.8) reflects continuous structured communication under CCA-enabled coordination. Typical (0.3) reflects ad hoc, reactive communication patterns.
Group 3: Design and Risk Environment					

Design Clarity (DC) 0=incomplete, 1=fully defined	0.4 / 0.7	Design Clarity; Design Dependency; RFI Control	Clear and complete engineering design improves when early coordination enables input from key trades, reducing assumptions and RFIs.	10 of 13 participants linked early supplier involvement and structured coordination to improved design clarity, while fragmented approaches increased rework.	ICF value (0.4) reflects lower initial design clarity due to innovative materials requiring early collaboration to resolve. Typical (0.7) reflects higher upfront clarity from familiar, tried-and-tested technology.
Lead Time Risk (LTR) Schedule exposure 0=low, 1=high	0.3 / 0.6	Lead-Time Risk; Conditional Participation; Schedule Priority	Lead time risks are better managed when procurement decisions are aligned early through coordinated engagement, reducing uncertainty in delivery commitments.	11 of 13 participants identified schedule risk as the primary behavioral driver and noted that early coordination reduces lead-time uncertainty compared to fragmented procurement.	ICF value (0.3) reflects reduced lead time risk through early coordination and structured engagement. Typical value (0.6) reflects high schedule exposure under fragmented procurement.
Lifecycle Value (Vlc)	0.7 / 0.4	Innovation Openness; Long-Term Value Orientation	Coordinated engagement enables teams to focus on long-term system performance rather than just first cost.	6/13 participants, primarily from coordinated project settings, emphasized lifecycle-driven decision-making enabled by early collaboration.	ICF value (0.7) reflects coordinated procurement enabling lifecycle-oriented decisions. Typical (0.4) reflects a short-term cost focus under typical delivery.
External Market Volatility (Volext) 0=stable, 1=high	0.4 / 0.4	Market Volatility; Price Instability; Buffer Strategy	Pricing is now valid for shorter periods due to material volatility, creating significant uncertainty.	Held constant, referenced consistently across all supplier interviews, but treated as an external condition not influenced by procurement structure.	Held constant at 0.4 across both scenarios as an external environmental condition affecting all projects equally.
Allowance Flexibility (Aw) 0=rigid, 1=flexible	0.7 / 0.3	Allowance Strategy: Budget Flexibility	Flexible allowances support early decision-making under uncertainty when coordination enables better alignment across stakeholders.	7 of 13 participants noted that structured coordination improves allowance flexibility, supporting engagement and reducing downstream risk.	The ICF value (0.7) reflects structured allowance flexibility that supports early engagement. Typical (0.3) reflects rigid allowance structures that limit adaptive decision-making.

10.4 Stakeholder-Level Agreement in Mechanism Validation

Relationship	GC	SC	Suppliers	CCA	Interpretation of Agreement Across Stakeholders
Risk → Participation	Confirms	Confirms	Confirms	Confirms	Convurgent. Higher perceived risk consistently reduces willingness to participate in the absence of contractual protection.
Participation → Collaboration	Confirms	Confirms	Confirms	Confirms	Convergent. Direct effect widely observed; early engagement consistently linked to improved information flow and reduced ambiguity.
Collaboration → Design Clarity	Confirms	Confirms	Confirms	Confirms	Convergent. Strongest consensus; constructability alignment and interface resolution identified.
Design Clarity → RFI Volume	Confirms	Conditional	Conditional	Confirms	Moderate divergence. Trade partners note RFI reduction depends on information maturity at release, not coordination alone; staged releases introduce RFIs independently.
Early Supplier Involvement → Innovation	Conditional	Conditional	Confirms	Confirms	Divergence by role. GCs emphasize cost and value constraints; trade partners highlight the need for decision-making authority to enable meaningful innovation.
GMP Timing → Collaboration	Confirms	Conditional	Conditional	Diverges	Variability reflects procurement context rather than stakeholder disagreement. Early GMP with supplier input improves collaboration; late GMP in typical environments removes incentive for early engagement.

Confirms: Relationship consistently observed, Conditional: Holds under specific project or organizational conditions, Diverges: Stakeholder perspectives differ or contradict

10.5 Cross-Phase Pattern Validation of Model Outputs

Output	Early design (0–30%)	Schematic design (30–60%)	Design development (60–100%)	Construction (mid–late)
Innovation (CCA vs. typical)	Model: low adoption; coordination inactive. *"Trade engagement not*	Model: gradual increase as coordination activates. *"Activation is*	Model: smooth plateau as decisions stabilize. *"Stabilization occurs via*	—

	yet triggered; minimal coordination influence." Strong alignment.	*discrete, triggered by specific trade engagement events."* Simplified.	*discrete decision-closure events, not smoothly."* Simplified	
Redesign (Timing shift)	Model: early redesign concentrated in CCA *"Early engagement surfaces constructability issues before propagation"* Strong alignment	Model: continued early iteration in CCA; accumulation begins in typical *"Episodic bursts (MEP routing, façade), not smooth"* Simplified	Model: late-stage rework peaks in typical *"Disruptive cross-system rework; some still in CCA due to client changes"* Strong alignment	—
RFI volume (CCA vs. typical)	—	—	—	Model: mid-phase escalation in typical; lower sustained level in CCA. *"Early coordinated engagement reduces downstream RFIs; limited RFIs during key trade interactions are manageable through coordination."* Strong alignment
Capacity utilization (Workflow stability)	—	—	Model: stable high utilization in CCA; decline begins in typical *"CCA supports stable workflow, but sustained high utilization is overstated; variability exists due to trade interdependencies"* Simplified	Model: smooth productivity decline in typical; stable in CCA *"Stop–start conditions, out-of-sequence work, and rework; drops are event-driven, not gradual"* Simplified

10.6 Synthesis of Pattern Validation Results for ICF and Typical Scenarios

Output	ICF Model Pattern	ICF Real-World Alignment	ICF Limitation	Typical Model Pattern	Typical Real-World Alignment	Typical Limitation
Innovation Adoption	Slow early phase → rapid mid-phase acceleration →	Matches expert input, timing, and progression consistent with	Smooth curve; practice is event-driven with	Fast early progression → early low plateau (~25%) with no	Strongly confirmed experts validated that the typical model constrains innovation	Plateau in practice may be even lower on highly fragmented projects; the model

	high stabilization (~75%)	coordinated procurement experience	discrete system decisions	further growth once major design decisions are fixed	to post-design substitutions; early speed masks lost opportunity	does not capture the opportunity cost of skipped early engagement
Redesign	Early moderate increase → gradual stabilization (~50%)	Strong alignment, early coordination shifts, and redesign to flexible stages	Episodic in reality; concentrated bursts around specific decisions rather than a smooth curve	Continuous steep rise from early phases → no stabilization → ~80% cumulative	Strongly confirmed experts described non-coordinated redesign as never stabilizing; late iterations propagate across systems	Real-world accumulation is more uneven and trigger-driven than a smooth curve
RFIs	Low and controlled throughout → gradual minor increase → stabilization (~20% normalized)	Strong alignment and early coordination prevent escalation; minor RFIs represent field clarifications, not coordination failures.	Real-world peaks are sharper and more concentrated around specific trade interaction events.	Slow early growth → sharp mid-construction acceleration → continuous rise to end (100% normalized)	Strongly confirmed: experts described compounding RFI cycles in mid-to-late construction; RFIs generate further RFIs rather than clean resolution.	The model's smooth acceleration understates the spike intensity around specific trigger events such as MEP installation and façade coordination.
Capacity Utilization	Starts ~95% → moderate decline → stabilizes ~88% through late construction	Matches field behavior, supports early coordination to maintain workflow continuity, and limits mid-phase disruption.	Over-smooth trends; real disruptions are sharp and event-driven rather than gradual	Starts ~95% → tracks ICF to ~40% timeline → continuous decline → reaches ~75% with no recovery	Strongly confirmed experts validated the decline as characteristic of fragmented procurement.	A 75% model endpoint may be optimistic for typical projects; cascade failures across trades can push utilization lower.