Schedule Constrains and Delay Drivers in Nuclear Power Plant Construction

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Abstract

Delays and cost overruns remain a defining challenge of nuclear power plant (NPP) construction, despite nuclear energy's strategic role in low-carbon energy systems. This paper evaluates empirical evidence in order to identify the most influential delay drivers and to critically evaluate how these factors interact across the project life cycle. The analysis incorporates construction and project-management research, risk-register analyses, historical cost-escalation studies, regulatory and institutional research, and recent macroeconomic assessments. Across the literature, the most consistently cited delay drivers include design immaturity and change, weaknesses in project management and interface coordination, regulatory uncertainty, supply-chain and productivity constraints, first-of-a-kind (FOAK) technology challenges, and broader macro-political instability. The review also identifies methodological fragmentation, insufficient integration between project-internal and national-level factors, and limited quantitative evidence on the effectiveness of specific project-control tools. Building on these insights, the paper argues for a layered and integrated approach to schedule-risk assessment and concludes by outlining implications for future research, including recommendations relevant for work on project controls in nuclear construction.

Keywords

nuclear construction; project management; construction delays; nuclear power plant

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Introduction

Nuclear energy is widely regarded as a critical component of national energy transitions due to its ability to produce stable, low-carbon electricity. Nevertheless, new nuclear build projects have historically struggled with prolonged construction durations and significant cost overruns, which undermine investor confidence and complicate the economic viability of nuclear programmes [1]. There are strong indicators that schedule overruns are not isolated occurrences but reoccurring structural features of the global nuclear industry. Their persistence across different countries, reactor designs, and regulatory regimes suggests that delays are systemic rather than project-specific, making their identification and mitigation a central challenge for both policymakers and industry practitioners [2].

The causes of these delays vary significantly. Nuclear construction is characterised by extreme complexity, long lead times, and strict safety standards, placing it within the realm of megaprojects where risks emerge from technical, organisational, regulatory, and political domains. Earlier research has emphasised internal project and regulatory causes such as design immaturity, documentation issues, contractor capability, and licensing bottlenecks [3,4]. More recent work expands this view by considering external institutional and macroeconomic factors, including governance quality, political stability, and financial crises [5,6,7]. This development reflects a growing understanding that nuclear construction outcomes cannot be explained solely by technical or managerial variables but are instead shaped by a multilayered environment. In particular, the intersection of project-internal weaknesses with unstable or uncertain external conditions has been shown to amplify schedule risks, further complicating the delivery of projects that already operate under demanding technical and regulatory requirements [4].

The growing body of research therefore points toward the need for more integrated analytical frameworks—approaches that acknowledge how design maturity, project governance, regulatory systems, and national macro-political environments jointly influence schedule performance. Understanding these interactions is especially important as many countries pursue renewed nuclear expansion to meet climate targets, making timely and predictable project delivery a strategic priority [9].

The purpose of this literature review is therefore twofold: first, to synthesise existing academic research on schedule performance in the nuclear construction sector, and second, to provide a critical evaluation of the dominant delay drivers as reported in the literature. In doing so, the review aims to clarify where scholarly consensus exists, where findings diverge, and where further research is needed to support more effective project-control methodologies for future nuclear programmes.

Major Delay Drivers in Nuclear Construction

Design Immaturity and Documentation Quality

Across the literature, design immaturity and late design changes emerge as some of the most powerful predictors of construction delay. Wright et al. (2014) identify design completeness, constructability, and documentation accuracy as critical determinants of schedule success. Sherman et al. (2017), analysing U.S. nuclear project risk registers, find that design-related risks constitute the dominant class of threats to timely delivery. Similar conclusions arise in Eash-Gates et al. (2020), who attribute much of the observed cost escalation in modern nuclear projects to the disruptive impact of ongoing design modifications and rework.

Design-related issues often originate from insufficient front-end engineering design (FEED), unclear requirements, regulatory interpretation changes, or inadequate coordination between engineering disciplines. These conditions create cascading effects throughout the construction process, manifesting as incompatible drawings, incorrect details, and design clashes. Moreover, in nuclear projects these clashes often occur at the interface of civil, mechanical, electrical and I&C systems, where even minor inconsistencies require extensive redesign and re-approval due to safety implications. Despite its prevalence, the literature frequently treats design change as a symptom rather than interrogating its deeper causes, which limits the development of predictive models and targeted mitigations. Several authors note that without rigorous design-freeze mechanisms, integrated digital platforms, and early involvement of constructors in the design process, design maturity remains difficult to achieve in practice.

Project Management Capability and Interface Coordination

Weaknesses in project management practice represent another consistent contributor to schedule slippage (Alsharif & Karatas, 2019). Several studies show that deficiencies in planning accuracy, interface coordination, progress monitoring, and change control tend to amplify technical challenges and create systemic disruptions. Wright et al. (2014) argue that managerial competence and clarity of communication are as influential as technical parameters. Sovacool et al. (2014) extend this observation by showing that managerial and productivity issues explain a substantial portion of cost overruns historically attributed to technology itself.

Interface management between civil contractors, mechanical suppliers, I&C specialists, regulators, and owner teams is particularly problematic. Megaproject literature (e.g., Ahiaga-Dagbui et al., 2017; Locatelli et al.,2017; Wuni, 2025) highlights that fragmented contracting structures, mismatched incentives, and insufficient integration between stakeholders often generate schedule disruption, even when technical execution is competent. In nuclear construction, multi-national consortia and complex supply contracts frequently lead to communication barriers and unclear responsibility boundaries, making timely resolution of interface issues extremely challenging. The reviewed studies agree that better project-governance structures and more rigorous progress-control systems could mitigate many of these delays, although quantitative evaluations of specific tools remain scarce. There is growing interest in integrated master schedules (IMS), earned value management (EVM), and digital collaboration platforms, yet empirical evidence on their real-world effectiveness in nuclear megaprojects remains limited.

Regulatory and Licencing Dynamics

The regulatory environment exerts a substantial influence on nuclear construction timelines. Nuclear power plants undergo complex, multi-stage licensing processes that involve extensive documentation, safety demonstrations, and iterative design reviews. Kessides (2012) observes that regulatory stringency and post-accident rule changes have historically extended project durations, although such changes are often intertwined with political responses and public pressure. Escobar-Rangel and Lévêque (2015) similarly argue that evolving safety requirements materially shape project scope and cost structures.

Regulatory delays arise through several mechanisms. Some are predictable, stemming from inherently lengthy and resource-intensive licensing processes. Others are driven by mid-project regulatory revision, inconsistent interpretation of codes, insufficient regulatory capacity, or misaligned expectations between licensee and regulator. Kim et al. (2017) and Hossen et al. (2015) both place regulatory uncertainty among the highest-ranked schedule risks. Despite this emphasis, the literature rarely differentiates between the types of regulatory delay, limiting its ability to support targeted improvement measures such as early regulator engagement, pre-licensing of standard designs, or harmonisation of regulatory approaches. A further complication is that regulatory agencies themselves may face resource constraints, staff turnover, or shifting political priorities, which indirectly influence review speed and predictability. This dynamic interplay between regulatory practices and political context is often acknowledged qualitatively but remains insufficiently explored in quantitative terms.

Supply Chain and Construction Productivity

A further delay driver concerns supply-chain readiness and construction productivity. Studies by Sovacool et al. (2014) and Lovering et al. (2016) document how limited capacity in heavy-component manufacturing, variations in labour productivity, and quality-control deficiencies significantly influence construction duration. Nuclear projects often require highly specialised materials and components available only from a limited number of suppliers; any disruption, delay, or nonconformance in this chain can propagate directly to the critical path.

Eash-Gates et al. (2020) argue that the absence of standardisation in nuclear engineering prevents learning and productivity gains typically observed in repetitive construction. FOAK projects in particular, face immature manufacturing processes and untested vendor capabilities. Quality failures in the supply chain—such as welding non-conformances, incorrect material specifications, or inadequate documentation—can require extensive investigation, repair, and re-certification, often halting downstream construction activities. While these dynamics are well described conceptually, the literature still lacks quantitatively robust benchmarking of nuclear construction productivity, which would be essential for more realistic scheduling. This absence of reliable productivity data also limits the industry's ability to perform probabilistic schedule risk analyses or to calibrate productivity assumptions across different reactor types and construction cultures.

FOAK Status and Technological Complexity

First of a kind (FOAK) designs introduce uncertainties that extend beyond design maturity issues. Sovacool et al. (2014) demonstrate that novel reactor technologies entail heightened risk due to unfamiliar supply chains, limited workforce experience, and unforeseen interactions between design and construction. Escobar-Rangel and Lévêque (2015) show how new technologies and new safety requirements evolve together, creating feedback loops between innovation and regulation. Although series effects appear to reduce durations in certain countries (Lovering et al., 2016; Carajilescov & Moreira, 2011; Ho et al., 2019), these benefits are fragile and can be reversed by programme interruptions or political interventions.

Despite widespread recognition of FOAK risk, many studies use it as a broad descriptive category rather than analysing which specific technological features (e.g., modularisation degree, safety-system architecture, containment complexity) most strongly influence schedule performance. This lack of granularity limits the transferability of lessons learned between projects, as the term FOAK may obscure substantial variation in technological complexity, design philosophy, and construction methodology. Future research could benefit from more systematic classification of reactor technologies according to constructability characteristics, modularity potential, and integration requirements.

Macroeconomic and Political Context

In addition to internal and regulatory factors, national macroeconomic and political conditions represent a significant, yet often underexamined, source of schedule risk. Comparative studies such as those by Kim et al. (2017), Portugal-Pereira et al. (2018), and Benson (2022) demonstrate that political instability, policy discontinuity, and macroeconomic shocks can materially extend construction durations. These effects operate through multiple channels, including interruptions in financing, supply-chain stress, labour-market volatility, or the politicisation of project oversight (Spirkova, 2014).

Macroeconomic downturns, such as recessions or periods of high inflation, can directly influence project timelines by restricting available capital, increasing material costs, and undermining supplier solvency (Adepu, 2023). During such periods, governments may also shift budgetary priorities away from large infrastructure investments, further delaying project progress. Similarly, political instability—manifested through frequent government changes, policy reversals, or governance disputes—creates uncertainty regarding long-term energy strategy and regulatory consistency. For nuclear projects, which rely on stable multi-decade commitments, such instability increases the likelihood of schedule disruptions or extended approval timelines.

The literature also indicates that broader institutional quality plays an important role in project performance. Countries with transparent governance, consistent policy frameworks, and robust public institutions typically exhibit shorter and more predictable construction timelines. Conversely, weak institutional environments may suffer from administrative bottlenecks, inconsistent regulatory enforcement, or reduced oversight capacity, all of which contribute to delays.

Despite the recognised importance of macro-level conditions, there remains a notable gap in integrating these factors with project-level analyses. Most studies treat political and economic instability as contextual conditions rather than as variables that actively interact with internal project vulnerabilities. As a result, the mechanisms by which national-level shocks propagate into project schedules remain insufficiently quantified, leaving important questions unanswered regarding how external risks should be incorporated into schedule planning and project-control methodologies.

Discussion

The findings of this literature review indicate that schedule delays in nuclear power plant construction arise from a constellation of interconnected factors rather than from isolated technical or managerial shortcomings. Design immaturity, project-management capability, regulatory dynamics, and supply-chain limitations stand out as the most consistently identified drivers, yet the evidence shows that these do not operate independently. Instead, they interact with broader technological, institutional, and macro-political conditions in ways that amplify their effects. This reinforces the interpretation that nuclear construction delays are fundamentally systemic phenomena, shaped by the interaction of project-internal vulnerabilities and the external environment in which the project is delivered.

A central insight emerging from the analysis is that design immaturity frequently acts as the initiating factor that triggers downstream disruptions across construction, licensing, and supplier coordination. This aligns with earlier findings from Wright et al. (2014), Sherman et al. (2017), and Eash-Gates et al. (2020), who similarly identify design completeness and documentation quality as primary determinants of schedule performance. However, the present review highlights that design issues rarely occur alone—they often arise in conjunction with managerial weaknesses, such as insufficient interface coordination, ineffective change control, and fragmented communication structures. This observation supports the argument made by Sovacool et al. (2014) that managerial and organisational factors are as influential as purely technical ones.

The findings also corroborate previous studies (e.g., Kim et al., 2017; Escobar-Rangel & Lévêque, 2015) regarding the central role of regulatory complexity in shaping nuclear construction timelines. However, unlike many earlier works that treat regulatory delay as a standalone category, this review reveals how regulatory processes are themselves sensitive to project-internal and contextual conditions. For example, design immaturity increases regulatory review workload, supply-chain deficiencies generate extra inspections and re-certifications, and political instability may influence regulatory priorities or capacity. This suggests a more dynamic and reciprocal relationship between project performance and regulatory behaviour than what is typically acknowledged.

Likewise, the evidence on FOAK projects confirms long-established assumptions—namely, that technological novelty increases uncertainty, complicates supply-chain readiness, and reduces workforce familiarity. Yet this review identifies a gap in the granularity with which FOAK drivers are classified. Most studies treat FOAK status as a broad category without specifying which technological or design features drive delay. This limits comparability between reactor types and reduces the transferability of lessons learned across programmes.

On a broader level, the findings are in strong agreement with political-economy research (e.g., Portugal-Pereira et al., 2018; Benson, 2022) showing that macroeconomic and political instability can exacerbate internal project risks. Economic shocks influence financing and material availability, while political volatility can lead to changes in regulatory expectations or national energy policy. This external instability interacts with internal vulnerabilities—for example, projects with immature designs or weak project governance are less capable of absorbing such shocks. The literature therefore suggests that nuclear construction performance depends not only on organisational capability but also on the stability and predictability of the institutional environment.

Despite these coherent trends, the review also identifies important limitations in the current body of evidence. Data availability remains limited and often inconsistent. Many studies rely on case studies, expert elicitation, or historical compilations that lack methodological transparency or standardised metrics. Cross-country comparisons are particularly challenging because definitions of "construction start," "completion," and "delay" vary widely. Furthermore, nuclear-specific research often neglects relevant concepts from general megaproject management—such as optimism bias, strategic misrepresentation, and incentive misalignment—while general megaproject literature rarely incorporates the unique regulatory, technological, and safety characteristics of nuclear plants. Together, these limitations restrict the ability to derive robust comparative conclusions or to quantify the relative influence of each delay driver.

The implications of these findings are significant for both scholars and practitioners. Conceptually, they indicate that improving schedule performance in nuclear construction requires integrated project-control strategies that address design maturity, managerial capability, regulatory alignment, and supply-chain readiness simultaneously. Focusing on isolated drivers—such as design freeze, EVM, or standardisation—may yield only partial improvements if systemic interactions are not considered. At the policy level, the results show that institutional stability, regulatory capacity, and long-term political commitment are essential prerequisites for predictable delivery of nuclear megaprojects.

Conclusion

Schedule overruns in nuclear power plant construction arise from a multifaceted interplay of design immaturity, managerial weaknesses, regulatory complexity, technological novelty, supply-chain constraints, and macro-political instability. While design-related deficiencies and shortcomings in project management consistently emerge as the most influential delay drivers, the literature increasingly emphasises that these factors do not operate in isolation. Instead, they interact with broader institutional and national-level dynamics, creating layered and often mutually reinforcing sources of schedule risk. Despite extensive research spanning several decades, the field still lacks a unified analytical framework capable of integrating these diverse factors, limiting the accuracy of delay predictions and the effectiveness of mitigation strategies.

Improving schedule reliability in nuclear construction therefore requires an approach that moves beyond isolated risk identification. A more holistic perspective—one that recognises how technical, managerial, regulatory, and macro-political conditions converge to shape project performance—is essential for understanding why delays persist and how they can be prevented. Such an approach would also better reflect the realities of nuclear megaprojects, where changes in national policy, regulatory expectations, or supply-chain stability can have effects equal to, or greater than, internal project shortcomings.

Future research should prioritise the development of integrated models that capture these cross-cutting interactions and support more targeted project-control methodologies. Efforts to combine design maturity assessments, organisational capability metrics, regulatory-process mapping, and indicators of institutional stability would provide a more comprehensive basis for forecasting construction timelines and strengthening project resilience. As many countries revisit nuclear energy as part of their long-term decarbonisation strategies, the need for such integrated, evidence-based approaches will only become more pressing.

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