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A BIM-Integrated Stage-Gated Framework for Mitigating Strategic Design Errors in Infrastructure Projects

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Abstract

Design errors remain a persistent challenge in infrastructure delivery, particularly when strategic errors introduced during early design stages propagate into later project phases. This study develops a Building Information Modeling (BIM)-integrated stage-gated framework to mitigate strategic design errors across the infrastructure design lifecycle. The proposed approach embeds interdisciplinary coordination, iterative model federation, and structured verification checkpoints throughout conceptual, preliminary, and detailed design phases. The framework was implemented through a BIM workflow using Civil 3D, Revit, and Navisworks and applied to the Al Najaf Airport Road project in Iraq as a case study. A standards-based geometric and functional assessment was conducted to evaluate both the baseline design and the redesigned solution developed through the proposed framework. The analysis revealed that the baseline design satisfied only 39% of the evaluated design criteria, indicating significant geometric and operational deficiencies. After applying the BIM-integrated framework, the redesigned scheme achieved full compliance with the evaluated standards while eliminating previously undetected coordination conflicts. Model-based analyses also enabled targeted traffic and drainage assessments, helping identify and mitigate potential risks such as flooding susceptibility and unsafe junction configurations prior to construction. The findings demonstrate that early and continuous BIM integration can function as a proactive design assurance and risk management mechanism rather than a late-stage coordination tool. The proposed framework contributes a structured methodology for preventing strategic design errors and improving reliability in BIM-enabled infrastructure projects.

Keywords: BIM; Strategic Design Errors; Design Assurance Framework; Stage-Gated Verification; Multidisciplinary Coordination; Standards Compliance Assessment; Clash Detection and Resolution; Simulation-Supported Validation.

1. Introduction

Infrastructure projects are intrinsically complex and high-risk systems, where decisions made during initiation and early design strongly influence cost, schedule, quality, and long-term performance. Design errors, particularly those originating from strategic or conceptual misjudgements, remain a major driver of rework, delay, and budget escalation during construction [1, 2]. Evidence indicates that rework attributable to design-related errors can increase contract value by up to 16%, and in some cases schedule growth can exceed 50% of the planned duration [1]. Such impacts are rarely explained by isolated drafting mistakes alone. Instead, they often arise from upstream deficiencies that become embedded in requirements interpretation, key assumptions, and discipline interfaces, then propagate through subsequent design development. In this study, the term 'strategic design' errors refers to fundamental deficiencies or omissions

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introduced during early planning and conceptual design that later manifest as significant compliance gaps, constructability constraints, coordination conflicts, or operational limitations.

Root-cause analysis indicates that these errors are frequently linked to limited competence or experience within the design team, combined with ineffective communication and fragmented decision-making among stakeholders [3]. Consequently, systematic detection and mitigation of design-stage errors has become a priority for improving reliability and performance in infrastructure delivery. Over the past two decades, both research and practice have increasingly emphasized proactive design management and early error prevention. Conventional approaches include structured design reviews, peer checking, and stronger interdisciplinary collaboration, supported by effective communication and early stakeholder engagement. Misalignment during early design can generate misunderstandings and omissions that later require expensive redesign and rework [4-6]. Despite these measures, many conflicts and non-compliances remain latent and are detected only late in design coordination or during construction, when corrective actions are costly and disruptive. This persistent pattern has intensified interest in Building Information Modeling (BIM) as a means of improving design quality by strengthening integration, transparency, and coordination. BIM introduces a shared, model-based environment that supports integrated visualization and information exchange across disciplines. A key advantage is the ability to support real-time collaboration among architects, engineers, and stakeholders on a coordinated digital representation, reducing errors that emerge from fragmented information and miscommunication [7-9].

BIM-based coordination also enables earlier identification and resolution of conflicts and inconsistencies during the pre-construction phase, before they become site problems [5]. The rationale is that identifying and resolving design issues earlier is substantially less costly and less disruptive than correcting them during construction, and BIM provides mechanisms to support such collaboration through integrated modeling and early coordination. A substantial body of literature has examined the prevalence, causes, and mitigation of design errors in construction projects. Foundational studies, including those by Love et al. and others in the 2000s–2010s, explored error causation, classification, and rework impacts across different project types [2, 10]. These studies show that design-induced rework is pervasive and can materially degrade project performance when not addressed systematically. Common error types include human mistakes in calculations and drawings, omissions of required information, and coordination conflicts between disciplines. Proposed mitigation strategies include design quality management systems and organizational practices that encourage early issue reporting and learning from repeated mistakes [11-14]. Improving the skills and experience of design personnel and strengthening interdisciplinary communication are also repeatedly identified as essential for preventing errors at the source [3]. In practice, coordination meetings and multidisciplinary workshops remain common tools for aligning stakeholders and reducing discrepancies that later drive rework.

In this context, BIM is often advocated as a powerful technological intervention for reducing design conflicts and rework [14]. By enabling integrated 3D visualization and structured data sharing, BIM can reveal latent clashes and omissions earlier, allowing teams to resolve issues before they escalate [1, 15, 16]. Empirical studies consistently indicate that BIM strengthens design coordination and clash detection, two functions strongly associated with error reduction [16, 17]. Evidence from an infrastructure case study indicates that BIM enabled clash detection can identify hidden interdisciplinary conflicts virtually before site operations, reducing the likelihood of on-site clashes and rework [18]. Other studies also report measurable time and cost savings when clashes are identified and resolved before construction through coordinated BIM use [17, 19]. Beyond clash detection, BIM can strengthen information consistency by providing a shared data environment in which modifications are tracked and disseminated, thereby reducing errors associated with version mismatch and misinterpretation [20]. However, the literature also cautions against treating BIM as a panacea solution. If erroneous data are incorporated into models, if users lack training, or if governance and checking processes are weak, BIM can propagate errors rather than mitigate them, reflecting the well-known ‘garbage in, garbage out’ (GIGO) problem [14]. Therefore, BIM’s effectiveness in error reduction depends not merely on software capability but also on well-defined workflows, verification routines, and organizational support.

Recent studies continue to demonstrate the growing role of BIM in improving design coordination, reducing design errors, and supporting integrated decision-making across the project lifecycle. Das et al. (2025) reported that BIM-enabled coordination can significantly improve project performance by reducing delays and cost overruns associated with design conflicts [21]. Ailem & Boton further demonstrated that machine-learning-supported BIM workflows can enhance multidisciplinary coordination by automatically identifying and prioritizing relevant clashes during design reviews [22]. Similarly, recent review studies emphasize the expanding adoption of BIM across infrastructure projects and highlight the increasing integration of BIM with emerging digital technologies such as digital twins and advanced data analytics to support lifecycle management and decision-making [23, 24]. These developments indicate a growing transition from BIM as a visualization tool to a data-driven platform for proactive design management and risk mitigation in complex infrastructure systems. Notably, much BIM-related research and implementation on design error reduction has been concentrated in building projects, while infrastructure applications have lagged in both adoption and systematic empirical attention [20, 25, 26]. Although BIM has been widely adopted in vertical construction and credited with reducing design mistakes and coordination problems, its use in infrastructure remains comparatively emergent despite substantial potential to address persistent design and delivery challenges [24, 27]. Reviews emphasize a continuing shortage of studies that examine BIM’s specific uses and benefits for infrastructure projects, which often involve distinctive challenges such as large linear geometries, complex ground and utility interfaces, and extensive stakeholder networks [28, 29]. Emerging research in road projects reports benefits including improved design accuracy, facilitated clash checking, and enhanced stakeholder collaboration [7, 18].

Li et al. also reported that BIM contributed to design efficiency and conflict detection in large-scale projects characterized by complex geometry and constrained schedules [24]. However, despite these advances, a comprehensive understanding of how BIM can be structured to mitigate strategic design errors in infrastructure projects, particularly errors introduced early and propagated through later stages, remains limited. Accordingly, a clear research gap exists at the intersection of design error mitigation and BIM-enabled infrastructure delivery. The research problem addressed in this study is the persistent risk of strategic design errors during the design stage of infrastructure projects and how BIM integration can be used to mitigate that risk. While prior studies recognize that design errors drive rework and underperformance and that BIM provides capabilities that can reduce some categories of error, focused investigation of early-stage strategic errors in infrastructure delivery remains insufficient. Existing studies have often prioritized late-stage technical clash detection in detailed models or broad BIM benefit claims rather than systematic prevention of high-level misjudgments and omissions that occur when foundational decisions are made. This study addresses that gap by examining BIM as a risk-mitigation mechanism for strategic design errors in infrastructure projects. It aims to develop a structured approach and best-practice guidance for integrating BIM into early and intermediate design stages to support earlier verification, improved interdisciplinary alignment, and reduced error propagation. The study contributes to both theory and practice by strengthening the linkage between BIM-enabled methods and strategic design error prevention in infrastructure contexts, supporting stakeholders seeking to improve delivery outcomes and reduce the costly consequences of ‘getting it wrong’ at the project outset.

Despite growing interest in BIM-enabled coordination and design quality improvement, much of the existing research focuses primarily on late-stage clash detection or coordination during detailed design. Several studies highlight BIM’s capacity to identify geometric conflicts and information inconsistencies once discipline models have been developed; however, relatively limited attention has been given to the prevention of strategic design errors originating during the early conceptual and planning stages of infrastructure projects. Furthermore, a large proportion of BIM-related research has concentrated on building-sector applications, while infrastructure projects present distinct challenges such as linear geometry, extensive utility interfaces, and broader stakeholder involvement. As a result, there remains a need for structured methodologies that integrate BIM earlier in the project lifecycle to support systematic verification, interdisciplinary coordination, and evidence-based decision-making before strategic assumptions become embedded in later design stages. The proposed framework is conceptually grounded in several complementary theoretical perspectives related to design management and collaborative engineering systems. First, the study builds on the theory of design quality management, which emphasizes the early detection and prevention of design errors through systematic verification and interdisciplinary coordination. Previous research in construction engineering has demonstrated that errors introduced during early design stages often propagate through later project phases, leading to costly rework and performance deficiencies. Second, the framework draws on the stage-gate decision model widely used in project management and product development, where complex processes are structured through sequential decision checkpoints that enable systematic evaluation and risk control before progression to subsequent phases. Third, the framework incorporates the principles of BIM-enabled collaborative design, which conceptualizes digital models as shared information environments that facilitate interdisciplinary coordination, transparency, and evidence-based decision-making. By integrating these theoretical perspectives, the proposed BIM-integrated stage-gated framework provides a structured mechanism for reducing strategic design errors through early verification, coordinated model-based review, and controlled progression across design stages (see Figure 1).

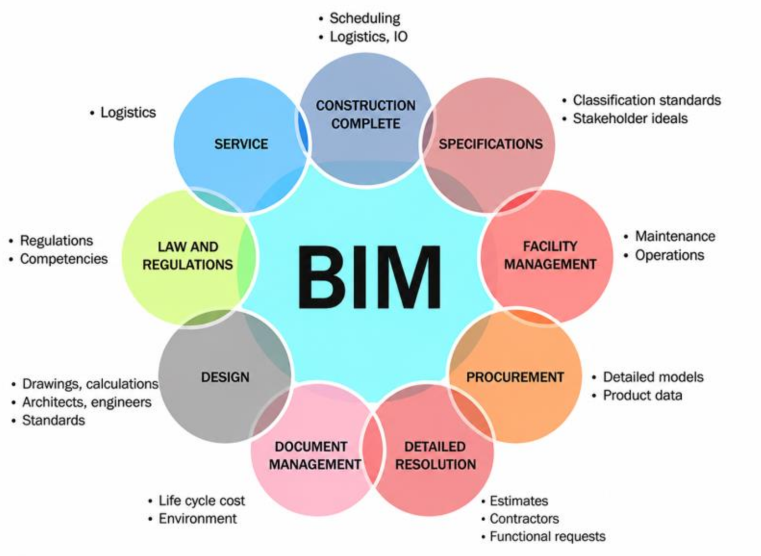

Figure 1. BIM integration for enhanced structure / infrastructure design and construction; modified from Montenegro [30]

1.1. Research Gap Analysis

To further clarify the research gap addressed in this study, Table 1 synthesises representative studies related to design error mitigation and BIM-enabled coordination in construction and infrastructure projects. The table summarizes the primary focus of previous research and highlights the limitations that remain insufficiently addressed in existing literature. While prior studies demonstrate the benefits of BIM for clash detection, coordination, and design efficiency, comparatively limited research has focused on systematic mitigation of strategic design errors during early design stages in infrastructure projects. The proposed BIM-integrated stage-gated framework aims to address this gap by embedding structured verification checkpoints and interdisciplinary coordination throughout the design lifecycle.

Table 1. Literature synthesis and research gap analysis

Study	Research focus	Key contribution	Identified limitation
Love et al. [14]	Design error reduction in construction	Demonstrates how BIM can reduce design-related errors through improved coordination	Focus mainly on building projects and design-stage coordination
Bryde et al. [17]	Benefits of BIM in project management	Identifies productivity and cost benefits of BIM adoption	Limited focus on early-stage design decision errors
Chahrour et al. [18]	BIM-enabled clash detection	Shows cost-benefit advantages of clash detection workflows	Emphasis on late-stage coordination rather than early design
Sampaio et al. [7]	BIM design coordination and simulation	Demonstrates improved interdisciplinary collaboration	Focus on building-sector design coordination
Li et al. [24]	BIM applications in civil infrastructure	Highlights growing BIM adoption in infrastructure projects	Limited investigation of strategic design error mitigation
This study	BIM-integrated stage-gated framework	Introduces structured BIM workflow for early identification and mitigation of strategic design errors	Addresses early-stage strategic errors in infrastructure projects

2. Project Life Cycle and Design Process

Infrastructure projects progress through a structured life cycle in which decisions and deliverables evolve from problem definition to long-term asset performance. In practice, this cycle is commonly described through initiation and feasibility, planning and conceptual design, design development and documentation, construction implementation, and operation with eventual renewal or closure. For infrastructure, the design process is particularly consequential because early assumptions about site conditions, standards, interfaces, and system requirements often become embedded in later documentation and are difficult to reverse once scope, approvals, and procurement commitments are in place. This section summarizes the lifecycle stages with an emphasis on the design phases, where strategic errors are typically introduced and preventive controls can reduce downstream impacts.

2.1. Initiation and Feasibility Analysis

The lifecycle begins with initiation, where the project need is established and viability is assessed. For infrastructure, feasibility studies commonly act as a decision gate by evaluating whether the project is deliverable and justified, considering technical requirements, cost implications, regulatory conditions, and socio-environmental constraints. A central activity is site analysis, which determines whether the physical and environmental conditions can support the project and what type and scale of solution is realistic. This frequently requires preliminary investigations such as geotechnical surveys and environmental assessments and early engineering studies that define constraints and risks. By the end of initiation, the feasibility case should define a preferred solution concept suitable for development and approval [31, 32]. Strategic design errors can originate at this stage when baseline information is incomplete, assumptions are weak, or stakeholder objectives are misaligned. These errors may remain latent while subsequent design work elaborates the chosen concept, then reappear later as major redesign, permitting difficulty, constructability constraints, or operational inefficiencies. Strengthening analytical rigor and improving early integration of baseline data are therefore critical controls for reducing strategic design risk before it becomes embedded in design decisions.

2.2. Planning and Conceptual Design

During planning, the project is developed into an implementable roadmap, including scope definition, scheduling, cost and resource estimates, and early risk identification [33, 34]. In infrastructure projects, planning and conceptual design are closely linked because early design options must be tested against feasibility, budget, and regulatory requirements. Conceptual design translates the project idea into an outline of form and function, often using concept layouts and initial configurations that allow stakeholders to compare alternatives and make key decisions before committing major resources [35]. A preliminary cost estimate is typically derived from concept outputs to verify budget feasibility and to support option selection [36]. Strategic design errors commonly arise here through incomplete evaluation of alternatives, inadequate interpretation of constraints and standards, and weak interdisciplinary alignment. A concept that appears feasible in fragmented drawings may later prove incompatible with site realities, utility constraints, or system interfaces. For this reason, conceptual design benefits from structured decision-making routines that make assumptions explicit, document rationale for selection, and force early alignment across disciplines and stakeholders. The objective is to prevent early misjudgements from becoming the baseline for detailed engineering and downstream documentation. Within the proposed BIM-integrated framework, this phase includes an initial model-based coordination stage and an early verification checkpoint that allows major strategic decisions, such as alignment configuration and functional design parameters, to be evaluated collaboratively before they propagate into downstream design stages.

2.3. Design Development, Technical Documentation and Approvals

The detailed design phase of an infrastructure project is commonly delivered in two sub-stages: preliminary design followed by detailed design, which together translate the selected concept into buildable specifications. In preliminary design, engineers develop the concept in three dimensions to demonstrate technical feasibility and to establish the main layout and interface requirements [37]. Through the integration of BIM-based model verification and coordinated design review cycles, the framework helps identify inconsistencies, coordination conflicts, and standards non-compliance during design development rather than during construction or late-stage design revisions. This refinement is inherently multidisciplinary and requires collaboration among various disciplines. The principal challenge is maintaining alignment across specialties as each discipline advances its analyses and outputs. Without continuous coordination, interface inconsistencies and clashes can remain hidden. Effective practice therefore relies on regular cross-disciplinary reviews and iterative adjustments to ensure that system components fit together coherently. By the end of preliminary design, the major decisions are typically settled, and the project's viability is confirmed in sufficient detail to proceed to final design development [38].

Next, the detailed design concentrates on creating documentation that is ready for construction. Engineers and architects finalize calculations, material selections, dimensions, and specifications and generate the drawings and schedules needed for contractors to execute the work as intended. The project team simultaneously performs compliance verification to ensure that the design satisfies applicable standards, safety requirements, environmental regulations, and permitting conditions prior to construction. Securing approvals and permits is therefore a central milestone in this phase, and the outcome is an authorized documentation set that governs subsequent implementation. Strategic design errors introduced during earlier phases, or coordination weaknesses that remain unresolved, are particularly costly at this stage because they become embedded in technical documents and can trigger change orders and site-based redesign once construction begins. Therefore, disciplined coordination, systematic checking, and clear accountability for interfaces and requirements closure are essential for effective practice before issuing final deliverables. Within the proposed framework, the design development stage integrates iterative model federations, interdisciplinary coordination reviews, and structured verification checkpoints to ensure that evolving design solutions remain consistent across disciplines and compliant with applicable standards before the technical documentation is finalized.

2.4. Construction, Operation and Closure

Once the design is approved, construction implements the project through mobilization of resources and execution in accordance with the design documents. Construction management focuses on productivity, quality, safety, and schedule control, and it represents the primary capital expenditure period in the lifecycle [39]. Although construction is frequently treated as 'execution', design support remains essential because unforeseen site conditions, interpretation issues, and design changes must be resolved rapidly to avoid disruption. Handover typically marks the transition to operations, including the transfer of as-built documentation and maintenance information to the operating entity [40, 41]. Operation and maintenance is the longest stage in the lifecycle and strongly determines realized value, safety performance, and lifecycle cost [42]. Major infrastructure assets are expected to function for decades, and typical lifespans of 60 to 80 years are frequently reported for infrastructure systems [43, 44]. Design decisions made in earlier phases directly influence maintainability, inspection access, durability, and operational efficiency. Finally, closure or renewal involves decommissioning, site restoration, and administrative close-out, including documentation of lessons learned and contractual closure [45]. Strategic design errors that escape early detection can therefore impose long-lived impacts, including persistent operational inefficiency, elevated maintenance burden, premature deterioration, and increased lifecycle risk exposure.

In summary, the lifecycle perspective highlights a consistent pattern: strategic design errors are most predominantly introduced early, but their largest consequences are typically realized later, during construction and operation when change is costly. This observation motivates the need for structured early verification, strong interdisciplinary coordination, and traceable decision-making across design development, particularly for infrastructure where interface complexity and long service lives amplify the consequences of early misjudgements.

3. Types and Sources of Design Errors

Design errors in infrastructure projects can be classified according to (i) their root sources, (ii) the design phase in which they originate, and (iii) their consequences for project outcomes. This multidimensional view is important because design errors are rarely isolated technical mistakes. They typically emerge from interacting human, organizational, technical, and contextual conditions that influence how design information is produced, communicated, checked, and revised.

3.1. Source-Based Typology

To further clarify the concept used in this study, strategic design errors can be distinguished from conventional drafting or coordination errors based on their origin, scope, and impact on the project lifecycle. Strategic design errors are high-level deficiencies introduced during early planning or conceptual design decisions that influence the overall system configuration or design assumptions. Unlike conventional design errors, which typically involve calculation mistakes, drawing inconsistencies, or discipline coordination conflicts, strategic design errors affect fundamental project parameters such as alignment selection, functional classification, design standards, or system integration decisions. Because these errors originate at an early stage, they often propagate through later design phases and become embedded in subsequent documentation and construction processes. In the context of infrastructure projects, strategic design errors can therefore be conceptualized as early-stage decision deficiencies with system-level consequences for design compliance, constructability, and operational performance (see Table 2).

Table 2. Typology of strategic design errors in infrastructure design

Category	Description	Example in infrastructure design
Conceptual configuration errors	Incorrect high-level system configuration or alignment decisions	Inappropriate corridor alignment or route selection
Functional classification errors	Mismatch between road function and design parameters	Road classified incorrectly for urban context
Standards interpretation errors	Misapplication or omission of required engineering standards	Insufficient curve radius or missing design elements
Context integration errors	Failure to consider site, environmental, or network constraints	Ignoring terrain conditions or drainage impacts
Interface planning errors	Inadequate consideration of infrastructure interfaces	Poor integration with utilities or future structures

Prior research commonly groups error sources into four interrelated categories:

- ***Human factors:*** These include calculation mistakes, misapplication of engineering principles, oversight of requirements, and inappropriate selection of parameters. Risk increases when designers are inexperienced or unfamiliar with project-specific standards and constraints, leading to incorrect assumptions or design approaches [46]. Human lapses have also been highlighted as a major contributor to safety-critical failures, with some studies associating ‘gross errors’ by designers with a high proportion of structural failures [12].
- ***Communication and coordination failures:*** Many design errors arise from poor information exchange and fragmented understanding among participants. In multidisciplinary environments, inadequate coordination between disciplines can create inconsistencies across drawings, specifications, and interface assumptions. Ambiguous or missing documents and weak interdisciplinary coordination are repeatedly identified as major contributors to design-induced rework in complex projects [47].
- ***Tools and process limitations:*** Errors may be triggered or left undetected when teams use inadequate or outdated tools, or when checking and verification routines are weak. Examples include insufficient survey support for alignment decisions, reliance on manual calculations without cross-checking, and inconsistent use of review checklists. These issues are often organizational in nature because they reflect the robustness of the firm’s quality processes and its ability to detect errors before the issue of deliverables [14].
- ***Project constraints and change dynamics:*** External pressures such as tight deadlines, budget constraints, limited site investigation, and frequent scope changes can precipitate errors. Under schedule or cost pressure, verification may be reduced, and incomplete baseline data can force incorrect assumptions, particularly regarding ground and utility conditions. Change orders and client-driven revisions also introduce repeated opportunities for inconsistency unless change management and communication are disciplined [48, 49].

These categories are not independent. A human error, such as an incorrect calculation, may persist because peer checking is weak (process limitation) and because the team is operating under time pressure (project environment). Accordingly, reviews of design errors emphasize that people, methods, tools, information quality, and environment contribute jointly to error generation and persistence.

3.2. Phase of Origin and Propagation

Design errors can occur across the full design process, but their characteristics differ by phase, and this strongly influences severity and propagation. In conceptual planning, decisions about layout, capacity, feasibility, and key assumptions set the trajectory for subsequent design. Errors at this stage frequently take the form of incorrect high-level assumptions or neglected constraints. Because conceptual choices guide downstream development, early errors, such as flawed route alignment, can propagate through preliminary and detailed design and create substantial rework when discovered late. During preliminary/schematic design, the selected concept is developed into coordinated discipline solutions. Errors at this stage frequently arise at interfaces, including inconsistent interpretation of requirements, ambiguous responsibility boundaries, and misaligned assumptions between disciplines. Such coordination failures can result in omissions or incompatible designs that may only become visible during later reviews or during construction [50].

In detailed design, errors are typically more precise and technical because the phase produces the definitive drawings and specifications for construction. Common problems include inaccurate dimensions, specification inconsistencies, and calculation errors. Dosumu & Aigbavboa identified issues such as incorrect dimensions in plans and errors in structural calculations as recurrent detailed-design faults [51]. Detailed-phase errors can also include inappropriate material or component specifications that are not compatible with local conditions and may only be detected during construction or operation. A key implication is that errors introduced early can become embedded in later deliverables, making detection more difficult and remediation more expensive. By contrast, many detailed-design errors are more localized but still costly if they escape review and reach construction. This interaction between source, phase, and propagation provides the basis for targeted prevention measures and motivates verification and coordination controls that operate early and repeatedly during design.

3.3. Impacts of Design Errors

Design errors in infrastructure projects produce multi-dimensional consequences that undermine cost, schedule, quality, and safety objectives. The most common impact pathways include cost overruns, schedule delay, rework and wasted effort, safety risk, and reduced performance and stakeholder confidence.

4. Cost and Schedule Impacts

Design errors almost invariably increase project cost through redesign effort, change orders, disruption to construction sequencing, and physical rework of incorrectly executed work. Empirical studies attribute a significant share of cost overruns to design-related issues in infrastructure projects [52]. Barber et al. found that in civil engineering projects design errors accounted for approximately half of the costs of quality failures, including rework and defect remediation [53]. Lopez & Love estimated that direct costs associated with design errors average about 6 to 7% of contract value, with indirect costs of comparable magnitude when broader disruption effects are included [54]. In highway contexts, late detection of omissions or noncompliance can be particularly expensive because corrective action may involve re-approvals, traffic management, and extensive rework. A case study of a Spanish highway project reported a significant cost overrun driven by rework resulting from design deficiencies [55]. Schedule impacts follow similar mechanisms. When errors are detected late, corrective actions require redesign, approvals, procurement adjustment, and resequencing of site activities, all of which extend duration. Research consistently identifies design errors and subsequent corrections as a major driver of schedule growth in construction [6, 52].

4.1. Rework and Productivity Losses

Rework is the operational manifestation of design error and is a direct linkage between cost escalation and time growth. Design deficiencies are widely reported as a dominant contributor to rework, particularly in complex projects where interfaces are numerous and documentation is extensive. Robinson Fayek et al. reported that approximately 68% of total rework costs in an engineering project were linked to design errors [56]. In highway projects, rework associated with design omissions, revisions, and poorly coordinated changes is frequently identified as a driver of budget escalation and loss of productivity [47]. Beyond direct rework, error-driven disruption can reduce labor efficiency, increase idle time, and trigger cascading delays when critical path activities must be revisited.

4.2. Safety Risks, Quality Failures, and Reputational Consequences

The most critical impacts relate to safety and quality failures. Design errors can embed hazards that become visible only during construction or in service, potentially leading to serious incidents. The collapse of the I-35W Mississippi River Bridge in 2007 was traced to a design error involving undersized gusset plates, demonstrating how a design deficiency can lead to catastrophic failure under load [57]. Even where failures are not catastrophic, design errors can create code violations, unsafe operating conditions, and accelerated deterioration that require urgent rectification and costly retrofit. Corrective interventions implemented after the asset is built are typically far more expensive than preventing the deficiency through robust early verification and coordinated design assurance [58]. Design errors also affect quality perception and stakeholder confidence. Assets delivered with design deficiencies can damage the reputations of designers and owners and may lead to claims, disputes, or regulatory sanctions. Taken together, the evidence indicates that design errors degrade infrastructure delivery not only through cost and schedule consequences, but also through elevated safety exposure and reduced lifecycle performance.

4.3. Interactions Between Source, Phase and Impact

The consequences of design errors are shaped by the interaction of the source, phase of origin, and point of detection. Certain sources are more prevalent in specific phases. Conceptual design is vulnerable to cognitive bias, incomplete information, and inexperience, and mistakes introduced at this stage can have disproportionate consequences because conceptual decisions set the trajectory for later design development. Preliminary and detailed design, by contrast, are often dominated by coordination and communication challenges because multiple specialist contributions must be integrated into consistent interfaces and documents. Project pressures also vary by phase; schedule compression in detailed design may increase drafting and documentation mistakes, while schedule compression in conceptual work may lead to inadequate option evaluation or superficial risk analysis. A well-established principle in engineering management is that the later an error is detected, the more expensive it is to correct [59]. A conceptual error that persists into construction can trigger extensive redesign and high-impact rework, whereas detection during design review can substantially reduce downstream consequences. This is the rationale for stage-gate review processes intended to intercept errors before they propagate.

Burati et al. reported that design changes and errors accounted for approximately 79% of the costs associated with quality deviations, reflecting the heavy penalty of late discovery and correction [60]. Real incidents illustrate how interacting factors amplify consequences. The Boston Central Artery tunnel (Big Dig) ceiling collapse demonstrates how design shortcomings and weaknesses in oversight can combine, producing severe safety consequences alongside costly emergency response and disruption [61, 62]. The I-35W gusset-plate error (Bridge Failure in Minnesota) also illustrates long latency; a design calculation error introduced decades earlier remained embedded until operational conditions exposed the deficiency [63]. Even when outcomes are less dramatic, professional evidence indicates that design errors prolong construction, disrupt workflows, and increase costs [6]. Overall, these interactions reinforce the need for preventive controls that operate early, repeatedly, and with clear accountability, particularly during stages where strategic assumptions and cross-disciplinary interfaces are established.

5. Conventional BIM Deployment vs. Early Stage-Gated BIM Integration

Design errors are shaped not only by technical decisions but also by how design information is created, exchanged, checked, and controlled across disciplines. In many infrastructure projects, BIM is adopted as an overlay for conventional document-centered workflows and introduced primarily in later design stages for coordination and clash detection. This late and narrow deployment leaves strategic errors introduced during initiation and conceptual design insufficiently controlled and allows misaligned assumptions to persist into detailed design and construction. The following comparison therefore focuses on the timing and purpose of BIM use, namely late-stage BIM coordination versus early, stage-gated BIM integration, which motivates the methodology presented in Section 6. The coordination workflow and review process implemented within the proposed framework are illustrated in Figure 2.

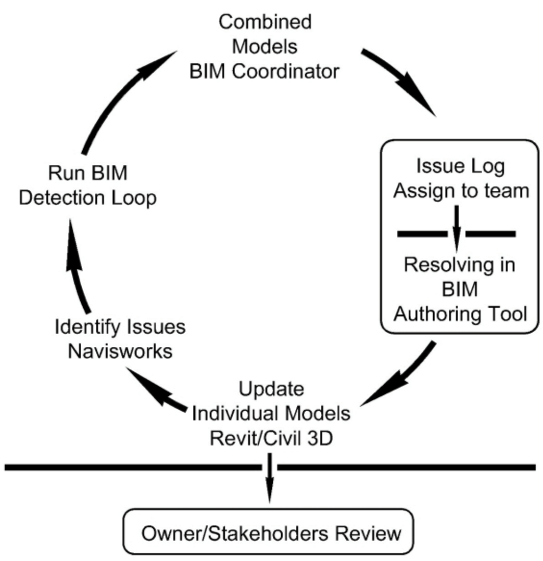

Figure 2. Workflow of BIM coordination and review process

5.1. Conventional Practice: Late-Stage BIM Coordination

In conventional practice, design development remains discipline-siloed and document-driven. Each discipline produces separate drawings and reports that are coordinated through periodic reviews and manual cross-checking. This environment is vulnerable to omissions, inconsistent assumptions, and interface conflicts, particularly as project complexity increases [64, 65]. Where BIM is used, it is regularly introduced after major decisions have been fixed, commonly during later preliminary or detailed designs, with the primary objective of identifying geometric clashes and producing coordinated deliverables. Although this method can reduce some downstream conflicts, it does not systematically control strategic errors established earlier, such as incorrect baseline assumptions, misaligned functional requirements, or incomplete consideration of constraints [48, 66]. Late-stage coordination also tends to concentrate stakeholder input at milestone reviews. When significant issues are exposed at this point, revisions must be executed under time pressure, increasing the risk of incomplete updates and inconsistent documentation [62]. As a result, many projects still experience design-induced rework and disruption during construction, even when BIM is applied, because the underlying information flows and checking routines remain reactive rather than preventive [16, 67].

5.2. BIM-Based Design Approach

The proposed approach advanced in this study reframes BIM from a late-stage coordination tool into an early-stage design assurance workflow. The key change is not the presence of BIM software, but the disciplined integration of BIM processes from initiation onwards. This includes establishing a Common Data Environment (CDE) and BIM execution rules early, maintaining a federated model through design development, and implementing repeatable verification routines and decision gates to prevent unresolved issues from propagating downstream. Instead of using clash detection as a one-time inspection near design completion, coordination and checking are performed iteratively through the conceptual, preliminary, and detailed stages. Issues are recorded, assigned, and resolved in the authoring environment and rechecked until closure or agreed-upon tolerance, creating traceability and accountability. Early federation and review also enable option evaluation and stakeholder alignment at the stage when design changes are least disruptive, reducing the likelihood that strategic errors become embedded in later documentation (see Figure 2). Evidence from BIM-based design review studies indicates that model-based checking can reveal latent design conflicts that may be missed in conventional review processes, supporting earlier correction and reduced downstream rework [21, 68, 69].

Empirical evidence from previous studies also supports the advantages of integrating BIM earlier in the design process. Several case studies have demonstrated that early BIM implementation significantly improves coordination efficiency and reduces downstream design conflicts. For example, Bryde et al. reported that BIM adoption across project phases improved design coordination and reduced rework in infrastructure and building projects [17]. Similarly, Chahrour et al. analyzed BIM-based clash detection workflows and found that early model integration can reduce coordination conflicts and improve overall project performance [18]. More recent studies such as Sampaio et al. further highlight that early BIM-supported collaboration improves interdisciplinary decision-making and enables design issues to be identified before they propagate into detailed documentation and construction stages [7]. These findings reinforce the rationale for embedding BIM coordination within structured stage-gated design workflows, as proposed in the present study. In short, the distinction addressed in this section is late-stage BIM coordination versus early, stage-gated BIM integration. A comparison between traditional design workflows and the proposed BIM-integrated stage-gated process is presented in Figure 3. The proposed framework operationalizes early integration through defined checkpoints, iterative checking loops, and evidence-based decision gates (see Figure 3).

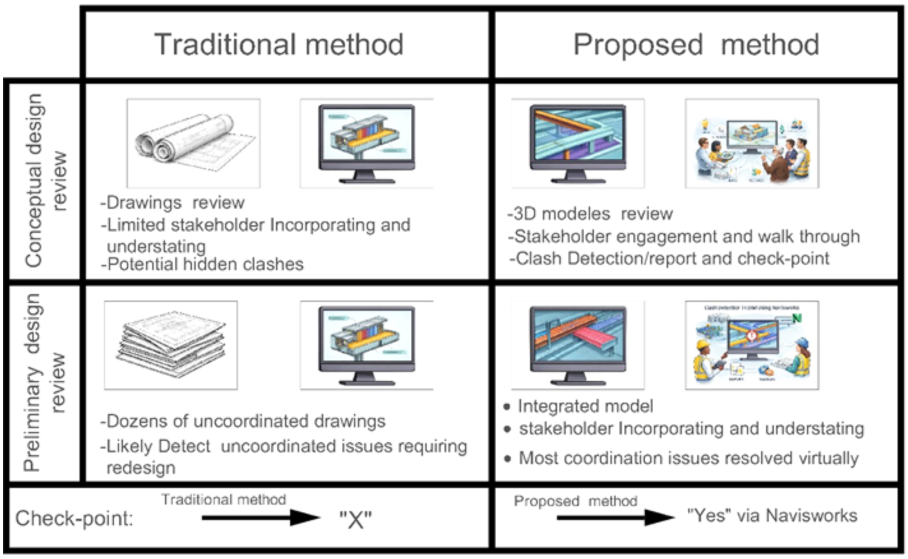

Figure 3. Comparison of design review checkpoints in traditional and BIM-based workflows

6. BIM-Integrated Design Methodology

This study develops a BIM-integrated, stage-gated framework that spans the full project (infrastructure) design lifecycle, from initiation through conceptual, preliminary, and detailed design. The overall structure of the proposed BIM-integrated framework is illustrated in Figure 4. As illustrated in Figure 4, the framework structures design development as a repeatable cycle of model authoring, federation into a federated model, verification, issue register management, and formal decision gates. The objective is to mitigate strategic, conceptual, coordination, and constructability errors before construction by embedding multidisciplinary coordination and systematic checking routines at each stage. In contrast to conventional workflows and late-stage BIM deployment, where coordination and clash detection are introduced after key decisions have been fixed, the proposed approach uses a shared digital project model and continuous verification to identify high-impact issues early and prevent error propagation (see Figure 5).

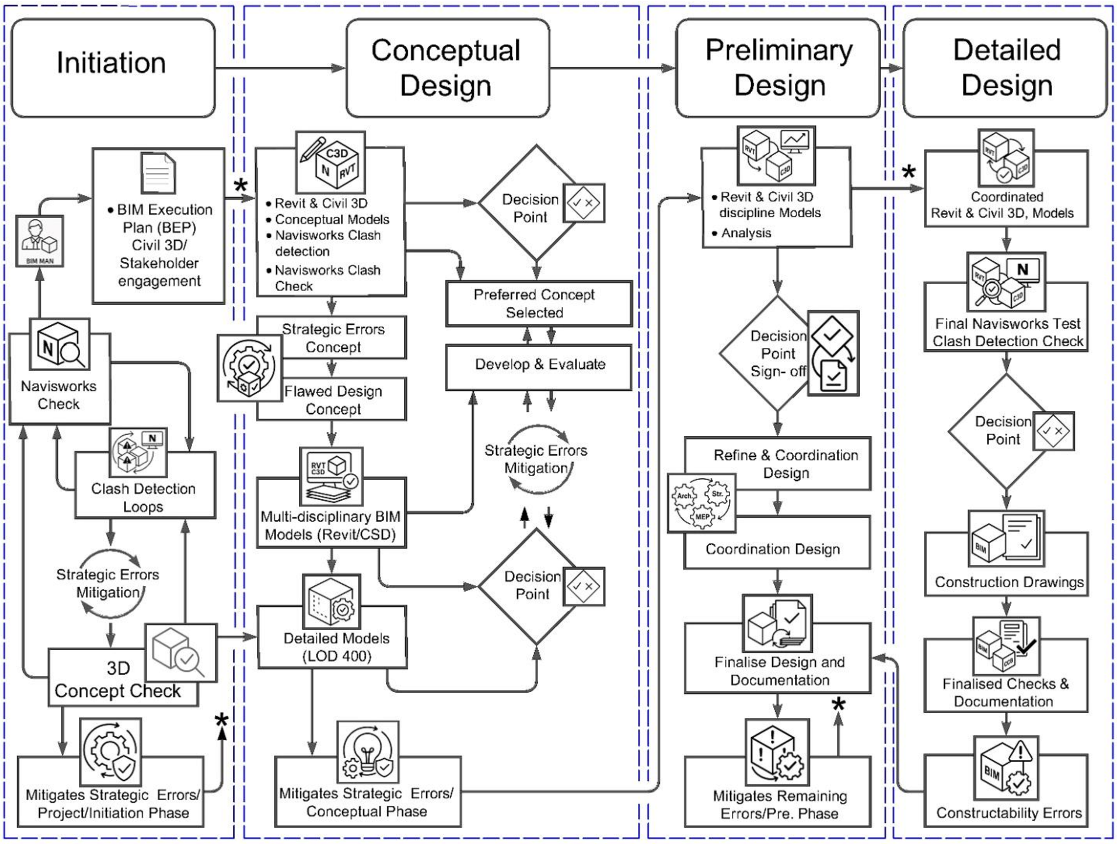

Figure 4. Proposed BIM-based framework for mitigating project design errors across all design phases

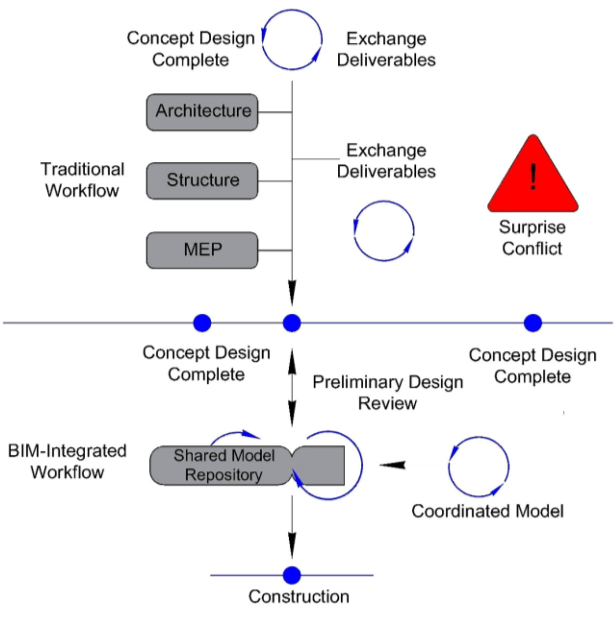

Figure 5. Comparison of traditional and proposed BIM-based workflows during the design phase of the project lifecycle

The framework is operationalized through four implementation elements. First, a BIM Execution Plan (BEP) defines modeling standards, roles and responsibilities, exchange formats, verification requirements, and acceptance criteria for each decision gate. Second, a Common Data Environment (CDE) provides controlled access, versioning, and an audit trail so that the federated model and related decisions are traceable. Third, discipline models are periodically federated for coordination review and clash detection using consistent rule sets appropriate to model maturity. Fourth, issues are managed through an explicit workflow supported by the issue register: issues are detected, classified, assigned to owners/stakeholders, resolved in the authoring environment, and rechecked in the federated model until closure or agreed tolerance. The framework is tool-agnostic in principle and can be implemented using common infrastructure BIM toolchains that combine authoring platforms for civil geometry and structures with coordination platforms for federation, review, and reporting. In this study, Autodesk Civil 3D, Revit, and Navisworks are referenced as representative tools for these functions.

To support interdisciplinary coordination, the BIM workflow implemented in this study relied on structured data exchange procedures between the primary authoring and coordination platforms. Civil 3D was used to develop the road alignment, terrain modeling, and corridor geometry, while Revit was used to model the associated structures and infrastructure components. Discipline models were periodically exported to interoperable formats such as IFC and NWC and aggregated within Navisworks to create a federated coordination model. This federated model enabled systematic clash detection, visual review, and issue tracking during each stage-gated verification cycle. Model updates were performed iteratively in the authoring environments, and revised models were re-exported and rechecked to confirm issue resolution. Coordination reviews were conducted only after discipline models reached an appropriate Level of Development (LOD) for the corresponding design stage, ensuring that model maturity was sufficient to support reliable verification and decision-making during conceptual, preliminary, and detailed design reviews. The framework is applied and evaluated in Section 7 through a real case study (Al Najaf Airport Road), where baseline performance is assessed and compared with BIM-enabled redesign outcomes.

6.1. Initiation Phase

The initiation phase establishes the governance, baseline information, and coordination routines required to prevent strategic errors from propagating into later design deliverables. The primary deliverable is the BIM Execution Plan (BEP), which defines project objectives, modeling scope by phase, roles and responsibilities, naming and classification conventions, exchange formats, and acceptance criteria for each decision gate. The BEP also defines the framework's iteration logic, including the frequency of coordination cycles, clash detection rule sets to be applied by stage, severity classification, and acceptance thresholds (for example, no major clashes at gate approval). Stakeholder engagement is formalized at the initiation stage by documenting requirements, decision criteria, review participants, and the sign-off process that will govern option selection and subsequent design development.

A Common Data Environment (CDE) is configured to control access, manage versioning, and retain an audit trail for model exchanges, review comments, and decisions. In parallel, the team compiles an existing conditions model using available site datasets (for example, surveys, terrain surfaces, GIS layers, known utilities, and preliminary geotechnical information). This baseline model provides a reliable spatial reference for feasibility and early optioneering and reduces the likelihood that concept decisions are made on incomplete or inconsistent assumptions. Where major structures or constrained interfaces are anticipated, preliminary 3D representations can be developed to support an initial 3D concept check. Although model detail is limited at initiation, the framework introduces early verification by federating baseline and concept representations for a coordination review (for example, using Navisworks) and running coarse clash screening to identify fatal constraints and high-severity inconsistencies, such as obvious utility conflicts, corridor infeasibility, clearance constraints, or missing baseline information that would undermine concept evaluation. Issues identified at this stage are recorded in the issue register, assigned to the owners/task owners, and either resolved through data correction or carried forward as defined information gaps with deadlines. The initiation decision gate confirms readiness to proceed to conceptual design. Approval requires an agreed BEP, a functioning CDE, a validated existing conditions model, a defined issue register workflow, and evidence that high-severity baseline constraints have been identified and managed before optioneering begins.

6.2. Conceptual Design Phase

The conceptual design phase develops and evaluates high-level alternatives while establishing the foundation for "zero major clashes at 100% design" through early coordination and stakeholder review. Conventional practice often progresses conceptual design largely as a standalone activity, with limited continuity from initiation datasets and interdisciplinary checking to later stages. In the proposed framework, conceptual modeling builds directly on the initiation baseline and is treated as the first stage, where multidisciplinary verification is performed in structured cycles. During this phase, preliminary 3D concept models are authored to represent alternative options. For linear infrastructure, civil engineers can develop alternative alignments and corridor envelopes in Autodesk Civil 3D, including initial profiles and earthworks implications, while structural or architectural teams can model key structures in Revit at a level sufficient to test major interfaces and constraints. Discipline models are then combined into a federated model for coordination review, either through direct linking workflows or through exchange formats suitable for multidisciplinary coordination (for instance, IFC or Navisworks). Navisworks can be introduced at this early stage as the federation and review environment, enabling the design team to compile concept models into a single coordination view and to run an initial clash screening cycle. Although model fidelity is limited, early clash screening is valuable because it targets high-severity conflicts that can invalidate an option, for example, incompatibility between bridge geometry and roadway profile, clashes between excavation envelopes and known utilities, or corridor configurations that violate fixed site constraints. Identifying such conflicts at the concept stage reduces the risk of pursuing a geometrically infeasible or strategically flawed option.

The conceptual phase also supports structured optioneering through model-based interrogation rather than drawing-based interpretation alone. Concept alternatives can be compared using model-derived indicators, such as preliminary quantities (for example, earthworks volumes) and their implications for cost and constructability, and, where relevant, preliminary simulations or performance checks. Importantly, stakeholder engagement is formalized through model-based reviews. The federated concept model enables clear communication of design intent through coordinated 3D visualizations and walkthroughs, supporting client and authority feedback while changes remain inexpensive. This creates a continuous feedback loop in which modeling, federation, clash screening, stakeholder reviews, and refinements are repeated until major conflicts are closed or explicitly managed. All identified issues are documented in the issue register, and clash reports can be generated at the concept stage to record issue type, severity, and resolution status. Tracking these early issues provides an evidence base for concept selection and establishes baseline metrics for subsequent stages. The conceptual decision gate (approve, revise, or reject) selects the preferred concept only after high-severity conflicts are resolved or controlled and after key assumptions and constraints are recorded for preliminary design. In this way, concept selection is evidence-informed, comparing alternatives not only through drawings but also through model-derived quantities, conflict severity and counts, and stakeholder review outcomes, reducing the likelihood that strategic design errors are embedded and carried forward.

6.3. Preliminary Design Phase

The preliminary design phase develops the ideal concept into a coordinated multidisciplinary design suitable for formal review and sign-off. This stage advances discipline models from the concept level to a coordination-ready level of development. Civil geometry is refined in Autodesk Civil 3D to finalize horizontal and vertical alignments, corridor configurations, and related design elements in accordance with relevant standards and project constraints. Simultaneously, structures and systems are developed in Revit to stabilize interfaces and define key dimensions, clearances, and connection requirements. All models are exchanged through the Common Data Environment (CDE) to maintain version control and ensure that coordination is performed using current model states rather than outdated drawings. Coordination is executed as an iterative cycle embedded within routine design management. At planned intervals, for example, biweekly coordination meetings or milestone reviews (such as 30% and 60% development), discipline models are federated in Navisworks for multidisciplinary review and clash detection using consistent rulesets. Detected clashes and interface issues are classified by severity, recorded in the issue register, and assigned to responsible owners. Owners resolve issues in the native authoring environment (Civil 3D or Revit) and republish updated models to the CDE, and the federated model is refreshed so that clashes can be rechecked. This coordination cycle continues until the agreed threshold is achieved, which includes the closure of high-severity issues and the absence of major clashes, while any remaining minor issues are managed within defined tolerance levels.

Compared with conventional workflows where cross-discipline conflicts often remain latent until late stages, this structured coordination cycle functions as a form of virtual integration, reducing the likelihood that one discipline's updates introduce downstream conflicts for another. Beyond geometric coordination, the framework embeds preliminary validation activities that reduce performance and compliance-related errors before detailed documentation commences. Structural teams can verify key performance requirements through analysis workflows supported by the model, either within the authoring environment or through export to analysis tools. Civil teams can use model-derived quantities to confirm that evolving design choices remain consistent with budget, environmental constraints, and constructability assumptions. Where rule-based checks are available, standards compliance or design rule violations can be extracted as actionable lists and managed in the same way as clashes, recorded in the issue register, assigned, corrected, and revalidated. Because updates are managed through the CDE, all participants view revisions and decisions consistently, reducing the risk of errors caused by fragmented communication or inconsistent assumptions. The preliminary design decision gate provides multidisciplinary sign-off supported by evidence. Typical outputs include a coordinated federated model, a clash and issue summary demonstrating closure rates and residual risks, documented validation checks performed, and an agreed-upon carry-over list for a detailed design where necessary. If high-risk issues remain unresolved, the gate triggers targeted redesigns or further coordination cycles before the project proceeds to documentation-level modeling.

6.4. Detailed Design Phase

The detailed design phase finalizes the coordinated design at the construction documentation level and aims to eliminate constructability and documentation errors before issuance. In this stage, discipline models are developed to full documentation-level detail, typically corresponding to LOD 350–400, depending on project requirements. Revit is used to complete the modeling of structures and systems, while Civil 3D is used to finalize civil elements, including alignment, corridors, elevations, and associated design components. The discipline models are maintained within the CDE and integrated into a documentation-level federated model for final coordination and verification. Coordination continues through an iterative cycle, but at a higher level of granularity than in the preliminary design stage. Navisworks is used to iteratively perform clash detection on high-fidelity components, with rulesets refined to identify fine-scale clashes, clearance infringements, and tolerance-related conflicts that emerge as the level of detail increases. Detailed-stage coordination focuses on resolving residual issues introduced by specification-level modeling rather than fundamental interface misalignments, enabling earlier resolution of high-severity coordination issues. The outputs of each coordination cycle are recorded in the issue register, assigned to responsible parties, resolved within the authoring environment, and rechecked in the federated model until closure or agreement within acceptable tolerances. A final coordination report provides evidence of the resolution of high-severity issues prior to documentation issuance.

At this point, one of the main benefits of the BIM-integrated workflow is that it keeps documents consistent. Drawings, schedules, and quantity outputs are generated directly from the coordinated models, reducing the risk of internal inconsistency that can arise when drawings and schedules are updated manually or independently. Where late design changes are unavoidable, revisions are applied at the model level and propagated automatically to dependent views and outputs, reducing the likelihood of issuing mismatched plans, profiles, details, and schedules. The framework also allows for final model-based validation that fits the needs of the project. This may include compliance checks against relevant standards and regulatory requirements, the export of Civil 3D or federated outputs to operational assessment tools (for example, traffic or safety evaluation), and constructability review through sequencing simulation where feasible. For example, a 4D simulation linking model elements to the construction program can function as a design-stage constructability review, revealing sequencing constraints, access conflicts, or temporary work issues that may otherwise arise during construction. Final quantity take-offs provide an additional cross-check for scope completeness and anomalies that can indicate missing elements or residual design errors. Where cost integration is undertaken, the model can support final reconciliation against budget expectations and provide early warning of cost-driven risks prior to issue. Stakeholder involvement is formalized through a documentation-level model review. Clients and relevant authorities can review the coordinated model to support final approval, and where contractor input is available, constructability feedback can be incorporated before issuance. The detailed design decision gate gives formal approval based on evidence, such as a final coordination report showing that high-severity issues have been resolved or that agreed tolerances have been met, confirmation that all necessary checks have been done, and approval of the documentation package. The phase concludes with the handover of the coordinated model and supporting information as a design deliverable to support construction implementation and potential downstream asset information use.

7. Framework Application, Results and Discussion

7.1. Framework Application

The proposed BIM-integrated, stage-gated framework was applied to the case study from initiation through detailed design to identify, document, and mitigate strategic design errors before construction. Strategic error control was operationalized through coordinated model authoring, model federation, iterative clash screening and resolution, and stakeholder decision gates at defined design maturity points. The comparison between the baseline design and the BIM-enabled redesign, therefore, provides direct evidence of the framework's ability to prevent error propagation across phases.

7.1.1. Framework-Guided BIM Process and Toolchain

Implementation began at project initiation with the development of a BIM Execution Plan (BEP), agreed upon by key stakeholders, to confirm assumptions and define modeling rules, responsibilities, and verification expectations. Early stakeholder engagement enabled review of high-consequence decisions (for example, alignment placement and road classification) before they became embedded in downstream deliverables. During conceptual design, preliminary 3D models were developed in Civil 3D and Revit to support concept evaluation within the real site context, including topography and surrounding urban features. The discipline models were federated for review, and early clash detection was executed in Navisworks to identify high-severity feasibility conflicts that can invalidate options (for example, misalignment between structural elements and corridor geometry or conflicts with identified constraints). Although conceptual models are low-detail, iterative clash detection cycles were used to refine the concept and eliminate critical strategic errors before concept selection. A formal decision gate was then used to confirm that the preferred option was free of critical conflicts prior to progressing.

In the preliminary design, the selected concept was developed into higher-detail multidisciplinary models (road geometry, drainage systems, utilities, and structures), enabling coordinated federation and targeted verification. Model-based checks (for instance, earthworks quantities and drainage system capacity) supported compliance review and reduced reliance on manual recalculation. A preliminary-design decision gate was used to confirm standards compliance and close residual strategic issues before committing to detailed design. In detailed design, discipline models were developed to a high level of detail (approaching LOD 400 for critical components) and federated for comprehensive coordination. Navisworks clash testing acted as the final validation layer, with clash detection and resolution loops driving successive refinements until conflicts were cleared. Construction documentation (plans, profiles, cross-sections, schedules, and quantity take-offs) was generated directly from the coordinated model to improve internal consistency. A final constructability review, supported by stakeholder walkthroughs of the coordinated model, was used to confirm that the design can be executed without avoidable sequencing, access, or interpretation issues.

7.1.2. Data and Implementation Assumptions

Effective application of the framework depends on the availability and usability of reliable baseline datasets, including survey measurements, terrain models, geotechnical information, and utility records, so that modeling decisions reflect actual site conditions rather than unverified assumptions. For the case study, an accurate digital terrain model and GIS context were necessary to represent the corridor environment consistently. Where information gaps existed, they were addressed through documented engineering assumptions, with the expectation that real-world deployment would strengthen inputs through additional site investigation. A (BEP) is required to define modeling standards (for example, coordinate systems, phase-specific detail expectations, and naming conventions), as well as roles for model authoring, federation, and clash detection cycles. Implementation used an interoperable toolchain, with Civil 3D supporting parametric roadway geometry (alignments, profiles, and coordination), Revit supporting structural elements, and Navisworks providing federation, review, and clash reporting. Interoperability is essential, with exchanges supported through common formats and link workflows (such as IFC, DWG, and native RVT linkages). The framework also assumes that the design team has adequate BIM competence or that training and configuration time is explicitly allocated. The iterative coordination and clash-resolution cycles require planned time allowances during design, but the intent is to reduce downstream rework that would otherwise arise during construction. Finally, stakeholder participation is treated as an operational requirement, supported by accessible model-based outputs (for instance, walkthroughs, fly-throughs, and simplified model-derived extracts) to ensure that design decisions are understood and validated beyond the technical design team.

7.1.3. Coordination and Risk Mitigation Outcomes

The primary performance benefit observed in the application of the framework is improved design accuracy through data-grounded modeling and disciplined coordination. High-resolution survey and imagery inputs enabled precise representation of existing ground conditions, reducing the likelihood of vertical alignment and interface errors that regularly arise when design development proceeds with fragmented or inconsistent base information. Model-derived quantities and measurements were extracted directly from the digital model, reducing manual recalculation and associated human error. Coordination performance improved because discipline models were integrated into a unified federated environment with iterative clash detection loops. Detected clashes were treated as managed issues, resolved in authoring models, then rechecked until closure. The coordination and model-checking feedback loop implemented during the framework application is illustrated in Figure 6. This systematic closure process reduced the likelihood that unresolved conflicts would surface later as change orders. Figure 6 summarizes the coordination feedback loop enabled by model checking and clash detection. Risk mitigation was strengthened by moving detection and resolution upstream. Strategic errors in the baseline design that would have translated into construction-phase risks were addressed in the virtual environment, including flooding risk associated with inadequate elevation and drainage capacity and safety risks arising from junction configuration and access provision.

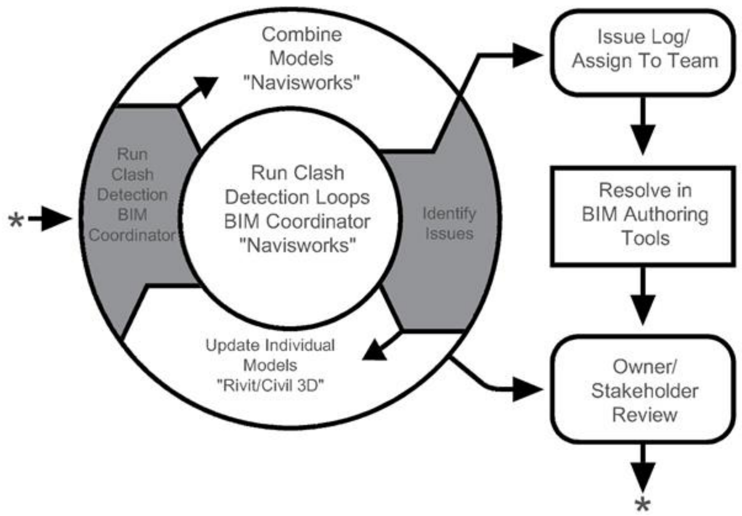

Figure 6. Clash Detection and Model Checking, Coordination Feedback Loop

The coordinated model also enabled targeted simulations and scenario testing, including drainage assessment to confirm performance under heavy rainfall conditions and traffic evaluation (for example, using InfraWorks) to test intersection performance against anticipated demand. Formal sign-offs at the concept, preliminary, and detailed stages functioned as risk checkpoints, ensuring that high-impact uncertainties were progressively closed rather than deferred.

7.1.4. Collaboration, Documentation, and Constructability

The framework materially strengthened collaboration by making stakeholder engagement a structured input to design development rather than a late-stage review activity. In conventional practice, external stakeholders such as local authorities, utility agencies, and community representatives may have limited visibility of design intent until drawings are substantially complete, which increases the likelihood that local constraints or operational concerns are identified too late to influence strategic decisions. Previous research has also emphasized that early stakeholder engagement improves decision transparency, reduces coordination risks, and supports informed infrastructure planning [70, 71]. The proposed approach embeds stakeholder involvement from inception through the BEP and concept-stage model reviews. Model-based visualization, including 3D renderings and walkthroughs, supported clearer communication about alignment, junction configurations, and interface constraints. This allowed non-technical stakeholders to interrogate the scheme more effectively and to provide early feedback on route logic, access provisions, and coordination with existing assets. As a result, the decision gates were supported by shared understanding and documented stakeholder inputs, reducing the likelihood of disruptive late changes driven by misinterpretation or omitted local knowledge. The direct generation of construction deliverables from the coordinated BIM environment also enhanced the quality of the documentation. Plans, profiles, cross-sections, schedules, and quantity outputs were derived from the model, so revisions were reflected consistently across drawings and reports once updates were made in the authoring models. This model-driven workflow reduces internal inconsistencies that commonly arise when documentation is revised manually across disciplines. In addition to conventional drawing packages, the coordinated model can also be issued in review-friendly formats (for example, Navisworks files or cloud-based model viewers), enabling contractors and reviewers to query geometry, evaluate clearances, and visualize complex junctions directly. These outputs improve interpretability and reduce the risk of site-based misinterpretation that often triggers RFIs and corrective work.

Constructability was addressed explicitly during detailed design through model-based review and, where feasible, sequencing simulation. A 4D simulation was developed in Navisworks by linking model elements to a construction program, enabling the virtual rehearsal of major construction stages and the identification of practical constraints. This type of review can reveal issues such as access limitations, temporary work requirements, or sequencing conflicts and provide actionable feedback to refine the design prior to resolution. The ability to test 'what-if' construction scenarios within the coordinated model supports the selection of construction logic that minimizes disruption and improves safety and efficiency. Overall, the case study indicates that embedding collaboration, documentation control, and constructability review within a stage-gated BIM workflow improves design robustness and reduces the probability that strategic design errors translate into construction-phase disruption or safety exposure.

7.2. Strategic Design Error Mitigation

Application of the proposed BIM integrated, stage-gated framework enabled the systematic identification and mitigation of the strategic design errors embedded in the baseline project for the case study (Figures 7 and 8; Table 3). The case study focuses on the Al Najaf Airport Road corridor located in the city of Al Najaf, Iraq, a rapidly developing urban area where increasing transportation demand has created significant pressure on existing road infrastructure. The Al Najaf Airport Road project was selected as the case study for two main reasons. First, the project is representative of many rapidly developing urban infrastructure projects in emerging metropolitan areas, where increasing transportation demand requires the expansion and redesign of major road corridors under complex technical and operational constraints. The project therefore provides a realistic context in which strategic design decisions related to alignment configuration, intersection design, and infrastructure integration must be evaluated across multiple disciplines. Second, the project offered access to the detailed design documentation, survey data, and digital modeling resources necessary to implement the BIM-integrated workflow and conduct a comprehensive validation of the baseline and redesigned solutions. This combination of practical representativeness and data availability makes the project a suitable case study for evaluating the proposed framework. In this application, strategic risks were treated as 'upstream design decisions' requiring evidence-based validation through iterative modeling, multidisciplinary review, and stakeholder engagement, rather than as downstream issues to be corrected during late coordination or construction.

- Corridor alignment and flood risk. The baseline alignment generated adverse community and hydrologic outcomes by severing neighborhoods and increasing runoff-related flooding risk in adjacent areas. The redesign relocated the corridor to a less hazardous route and re-established the vertical profile against an accurate digital terrain model (DTM) in Civil 3D. This removed the unjustified elevation discontinuity (approximately 0.5–1.5 m) and supported the development of an integrated drainage strategy aligned with the updated topographic conditions. Critically, these interventions were initiated during conceptual-stage BIM workshops, where early stakeholder review helped surface location and elevation constraints while design flexibility remained high.

- Functional classification and urban fit. The framework also revealed a functional mismatch between the road's baseline classification and its urban service role. Early-stage reviews supported by stakeholder input and network-level traffic considerations, led to reclassifying the corridor as an urban arterial/major collector, with corresponding updates to key design parameters. These updates included context-appropriate operating assumptions (e.g., design speed and junction form) and incorporation of pedestrian provisions to better align the system with urban mobility requirements and planning intent.
- Terrain-integrated vertical design and earthworks balance. In the baseline design, vertical geometry decisions were not adequately integrated with terrain conditions. In the redesign, high-resolution survey/GIS terrain data were incorporated to align the profile with natural ground levels. This reduced unnecessary fill, improved earthworks balance, and increased confidence in the constructability of the proposed levels. The BIM environment also enabled rapid quantification and targeted checks (e.g., earthworks and drainage-related assessments), replacing coarse estimation with model-derived evidence to support profile optimization.
- Connectivity, junction strategy, and operational performance. Limited junctions and access points in the baseline layout constrained local accessibility and weakened network connectivity. The redesign integrated the corridor model with the surrounding urban network and introduced additional intersections and access connections where justified. Junction geometries were then validated using swept path checks and 3D coordination review to confirm turning performance, reduce conflict risk, and improve operational robustness.
- Standards compliance as an iterative control. In the proposed framework, compliance was managed as a staged and iterative control activity rather than a late audit. Geometric and safety requirements were verified through stage-gated reviews and repeated coordination cycles, with corrections implemented in the authoring models and rechecked in the federated environment. By the final design iteration, the road model satisfied the required geometric and safety parameters (Table 3), addressing the baseline noncompliance observed across multiple criteria.
- Integration with utilities and future infrastructure. Finally, the redesign corrected the baseline tendency to treat the road as an isolated asset. Existing utilities, drainage systems, and planned structures were incorporated into a federated model (Civil 3D and Revit, coordinated in Navisworks) to support multidisciplinary planning and reduce retrofit risk. This integration enabled earlier provision for interface requirements (e.g., utility crossings and allowances for future grade separation), improving resilience and reducing the likelihood of disruptive changes after design issues.

Overall, the results demonstrate that embedding structured decision gates, iterative coordination, and stakeholder review throughout design development can convert an initially fragmented scheme into a context-responsive, coordinated, and verifiable infrastructure design (see Table 3).

Figure 7. Aerial imagery of the study area

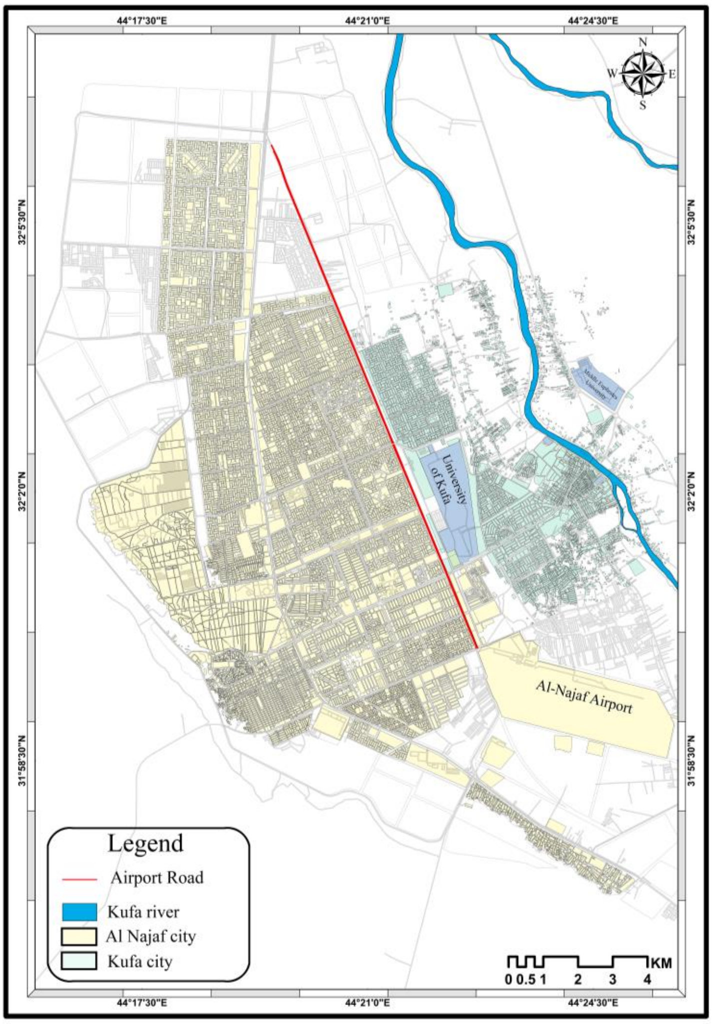

Figure 8. GIS map of the case study

Table 3. Strategic design errors in the baseline Airport Road design and corresponding BIM-framework mitigation actions

Baseline strategic issue	Baseline compliant?	BIM mitigation action	Redesign compliant?
Alignment drives severance and flood risk	✗	Context-based realignment, and integrated drainage system.	✓
Functional class inconsistent with urban context	✗	Reclassify road, update standards and parameters	✓
Vertical design not terrain-informed	✗	DTM-based vertical alignment refinement	✓
Insufficient junctions and access control	✗	Add access points and junctions, validate via swept-path and coordination	✓
Noncompliance with key engineering provisions	✗	Standards-based checks embedded by phase, iterative closure	✓
Isolated road design, weak integration with utilities and network	✗	Federated infrastructure model, coordinated interfaces and constraints	✓

Note: ✗ = noncompliant in baseline; ✓ = compliant after redesign; DTM = digital terrain model

7.3. Geometric Compliance Assessment

The geometric compliance assessment was conducted using a structured evaluation framework derived from established roadway design standards, primarily AASHTO guidelines and related engineering references. Each criterion listed in Table 4 represents a specific measurable design requirement associated with alignment geometry, vertical design, cross-sectional configuration, or safety-related roadway elements. Compliance was evaluated using a binary approach in which each parameter was assessed as either compliant or non-compliant based on measurable values obtained from the project drawings and BIM models. No weighting was applied to individual criteria; instead, all parameters were treated equally to ensure transparency and avoid subjective scoring. The resulting compliance percentage therefore represents the proportion of design requirements satisfied relative to the total number of evaluated criteria. This approach ensures that the evaluation reflects objective engineering standards and provides a consistent basis for comparing the baseline and redesigned solutions.

Table 4. The case study geometric design compliance check, baseline versus proposed framework application (AASHTO-related criteria)

Criterion	Desirable	Minimum	Baseline	Pass	Redesign
Design speed, V (km/h)	60.0	40.0	60.0	✓	60.0
Horizontal curve radius, R (m)	≥ 500.0	230	15.0	✗	230.0
Maximum Grade, G_{max} (%)	6.0	5.0	None	✗	6.0
Stopping sight distance, SSD (m)	150.0-170.0	85.0	85.0	✓	150.0
Width of travel lanes (m)	3.6	3.3	3.3	✓	3.3
kerbside parking lane Width (m)	2.4	2.1	Non	✗	2.4
Speed-change Lane width (m)	3.6	3.3	3.3	✓	3.3
Median Width (m)	15.0	14.0	4.0	✗	15.0
Lanes (total, per direction)	(4–6, 2–3)	(4–6, 2–3)	(6, 3)	✓	(6, 3)
Right-of-way, ROW (m)	30–45	24.0	21.0	✗	35.0
Shoulder width (m)	2.5	1.5	None	✗	2.1
Clear sidewalk width (m)	1.8–2.5	1.5	2.0	✓	2.5
On-street bicycle lane width	1.8	1.5	None	✗	1.8
Superelevation, e (%)	6%	4.0	None	✗	4.0
Vertical clearance (m)	5.0	4.5	4.0	✗	5.0
Clear zone width (m)	3–9	1.5	2.0	✓	2.5
Median U-turn radius (m)	15–25	14.0	5.0	✗	15.0
Total paved width (m)	-	-	25.0	✗	50.0

Note: ✓ indicates criterion satisfied, ✗ indicates criterion not satisfied. "None" denotes element not provided in the baseline design.

The evaluation of the existing arterial road geometry against established standards revealed numerous non-compliant design elements. As summarized in Table 4, several key geometric criteria for the original design failed to meet the minimum values recommended by AASHTO and related guidelines [72]. Deficiencies are identified in the horizontal alignment (curve radius and superelevation), vertical alignment (grade and vertical clearance), and various cross-sectional dimensions (median width, right-of-way, shoulders, parking lanes, and bicycle lanes). The original horizontal curve radius was only 15 m, which is far below the minimum requirement of 230 m for the specified design speed. Similarly, the median measured merely 4 m in width (compared to a conventional minimum of 14 m), and the right-of-way was only 21 m (rather than the minimum of 24 m), signifying a significantly restricted cross-section. Each deficiency is marked with a '✗' to show that it is not compliant, along with the relevant specification values [72-74]. Several features were completely omitted in the original layout, further underscoring the compliance gap. The original road lacked any superelevation on its curve, and it provided no dedicated road shoulder, parking lane, or bicycle lane (each marked as 'Non' in Table 4).

However, AASHTO provisions consider shoulder width a controlling criterion; shoulders serve as emergency refuge and recovery areas, and eliminating them without justification requires a formal design exception. In the original design, the shoulder was eliminated, which necessitates such an exception and might compromise safety and operations. Similarly, omitting the bicycle lane contradicts modern urban street design guidance that recommends ≥1.5 m bike lanes to safely accommodate cyclists, and a parking lane should be provided to prevent informal parking that encroaches on travel lanes. Certain parameters that satisfied basic standards were at the lowest permissible thresholds, resulting in a minimal safety margin. The design speed was set at an appropriate value of 60 km/h, and the stopping sight distance (SSD) provided (85 m) was just equal to the minimum value for lower speeds. The through lane width of 3.3 m met the minimum standard, and the clear sidewalk width of 2.0 m satisfied the basic ADA guideline (1.5 m). Designing to mere minimums can reduce comfort and operational efficiency; for instance, a 3.3 m lane on a busy road is passable but offers less lateral clearance for large vehicles than the recommended 3.6 m, potentially affecting driver confidence and capacity at high flows. This recurring tendency to ignore some elements or adhere only to baseline thresholds, rather than optimize for safety and functional resilience, reflects a broader strategic error in the design philosophy. It suggests that the project lacked a performance-orientated approach, treating compliance as a checkbox exercise rather than a means to achieve safe and efficient operations. In summary, while a few aspects of the original road were nominally within specifications (marked "✓" in Table 4), many critical geometric elements fell short of AASHTO-compliant criteria, indicating the original arterial design is geometrically substandard in several respects. The assessment shows that the baseline met 7 of 18 criteria (39%), with noncompliance concentrated in controlling geometric elements and several omitted cross‑ section components (see Table 4).

Although a limited number of baseline parameters satisfied minimum thresholds (e.g., design speed, lane width, sidewalk width, and stopping sight distance), these values were generally at the lower bound of recommended practice, providing limited operational margin. In combination, the results indicate that the baseline design was not only geometrically constrained but also incomplete as an urban arterial cross‑section, with several missing components that normally support incident recovery, kerbside management, and multimodal accommodation. Application of the proposed BIM‑integrated framework enabled targeted redesign and iterative verification of each deficient criterion. As summarized in Table 4, the horizontal alignment was corrected by increasing the curve radius to 230 m and applying 4% superelevation, aligning the controlling curve with the design speed assumption. The redesign uses the enlarged median to incorporate properly designed turning provisions. Specifically, the median openings for U-turns were redesigned to a 15 m radius, up from the unacceptable 5 m radius of the original design. The original 5 m radius was so tight; thus, the traffic police attempted to use plastic barriers to reduce the significant influence of this strategic error (see Figure 9). By correcting the median geometry, the redesign guarantees that vehicles can safely perform U-turns without impeding through traffic and with significantly less risk. The vertical geometry was rationalized by introducing a consistent grade of 6% and increasing the vertical clearance at the proposed structure's location to 5.0 m, exceeding the minimum requirement of 4.5 m. Cross‑sectional elements were also brought into compliance through coordinated model development: the right‑of‑way increased to 35 m. Shoulders of 2.1 m width, kerbside parking lanes of 2.4 m, and a continuous bicycle lane of 1.8 m width were incorporated in addition to widening the sidewalk to 2.5 m. These corrections were validated through the stage‑gated coordination process, where revisions were implemented in authoring models and rechecked within the federated environment. Overall, the redesign achieved full compliance (18 of 18 criteria, 100%), demonstrating that the framework can systematically surface, track, and resolve geometric nonconformities that typically persist when verification is deferred to late design stages (Figures 10 and 11).

Figure 9. Unacceptable U-turns radius of the original design, using plastic barriers to reduce the significant influence

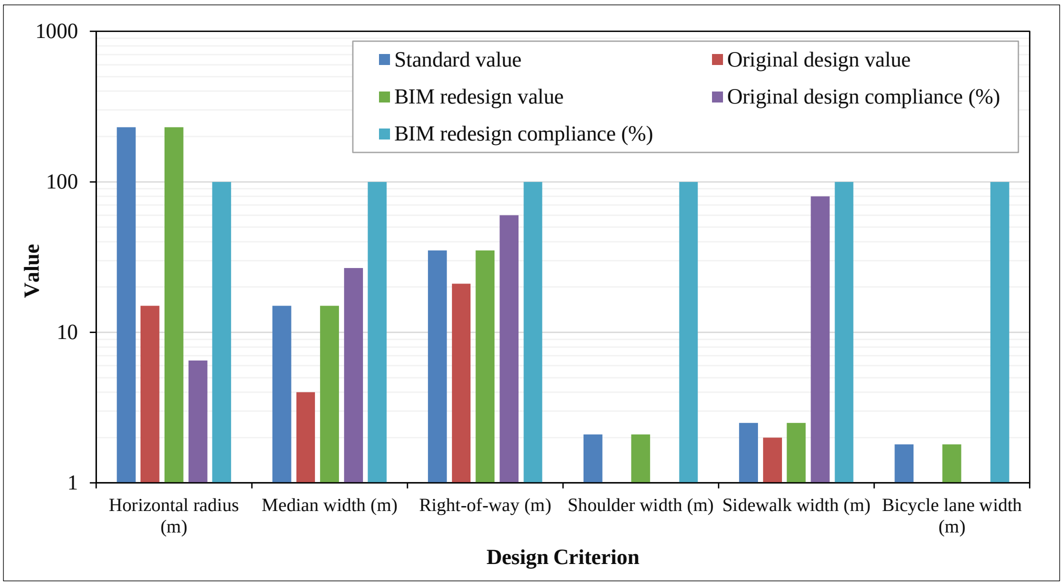

Figure 10. Comparison of Design Criteria and Geometric Compliance (Values/%); Original Design Vs. BIM-Based Redesign

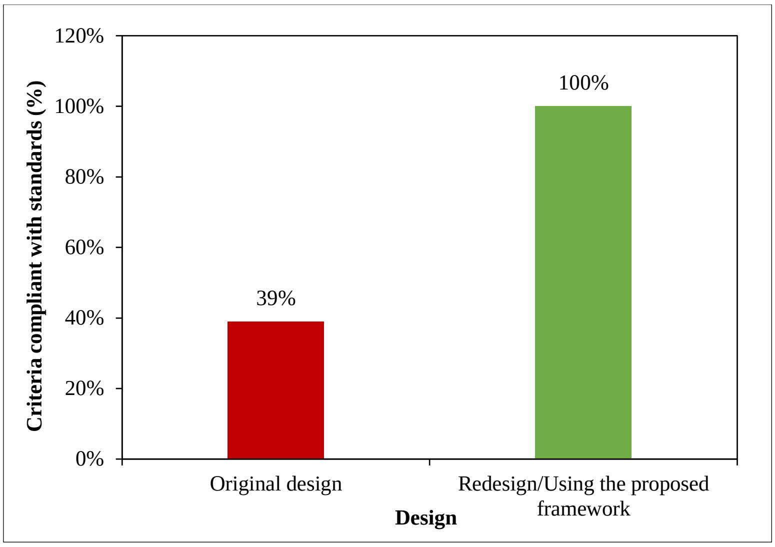

Figure 11. Comparison of Standards Compliance Between Original Design and BIM-Based Redesign

The results also demonstrate the practical implications of integrating BIM with a stage-gated verification process during early design development. Rather than relying on late-stage design reviews or construction-stage corrections, the framework enables systematic identification of strategic deficiencies while design flexibility remains high. The transition from 39% baseline compliance to full standards compliance illustrates how early interdisciplinary coordination, model-based validation, and iterative verification cycles can significantly improve design quality before construction begins. This finding supports previous research indicating that early detection of design inconsistencies substantially reduces downstream rework, schedule disruption, and cost escalation in infrastructure projects. The findings of this study align with previous research demonstrating the benefits of BIM-enabled coordination for improving design quality and reducing interdisciplinary conflicts. Earlier studies have shown that BIM-supported coordination can facilitate the early detection of design inconsistencies and enhance project efficiency. For example, Bryde et al. [17] and Chahrour et al. [18] reported that BIM-based coordination workflows improve multidisciplinary collaboration and reduce design conflicts during project development. Similarly, Sampaio et al. [7] highlighted the value of BIM-supported coordination processes for improving design integration and communication among project stakeholders. The results of the present study extend these findings by demonstrating that when BIM coordination is integrated within a structured stage-gated verification framework, it can also address strategic design errors originating in early conceptual stages. Unlike many previous studies that primarily focus on clash detection during later design phases, the proposed framework illustrates how early BIM integration can prevent high-impact design deficiencies before they propagate into detailed design and construction stages.

7.4. Functional Justification

The redesign measures are functionally justified because they directly reduce safety and operability risks created by the original geometric omissions and inconsistencies. Correcting the extreme horizontal curvature and introducing superelevation improves vehicle stability and speed consistency, reducing loss of control exposure and improving network reliability. Increasing vertical clearance removes constraints on freight and transit operation and reduces strike risk at structures, improving corridor functionality. Cross-section upgrades improve safety, resilience, and multimodal performance. A wider median increases separation and supports safer turning movements, while shoulders provide recovery and refuge space that improves incident management and reduces disruption from breakdowns. Formal parking lanes reduce unmanaged stopping within travel lanes, improving flow and lowering conflict potential in an urban setting. Bicycle lanes and widened sidewalks provide dedicated space for active modes, improving separation and supporting safer multimodal operation. In combination, these interventions demonstrate that standards compliance functions as a practical risk control mechanism, linking geometric design choices to safety, constructability, and long-term operational performance.

Taken together, the results highlight the importance of addressing strategic design decisions during the early stages of infrastructure development. The case study demonstrates that many critical deficiencies in the baseline design were not isolated drafting errors but rather systemic issues related to incomplete coordination, insufficient consideration of contextual constraints, and delayed verification processes. By embedding stage-gated checkpoints and iterative model-based review within the design workflow, the proposed framework provides a structured mechanism for identifying and resolving these issues before they propagate into later project phases. This outcome reinforces the role of BIM as a proactive decision-support environment capable of improving design robustness and reducing risk exposure in complex infrastructure projects.

8. Conclusion

This study developed and demonstrated a BIM-integrated stage-gated framework for identifying and mitigating strategic design errors across the infrastructure design lifecycle. In contrast to conventional workflows that frequently detect critical issues during late-stage coordination or construction, the framework embeds multidisciplinary model federation, stage-gated verification, and simulation-supported validation from project initiation through detailed design. Application to the Al Najaf Airport Road case study illustrates how early deficiencies can persist and amplify when not systematically controlled. A standards-based assessment showed that the baseline design satisfied only 39% of the evaluated criteria and contained significant geometric and operational shortcomings. Following implementation of the proposed framework, the redesigned solution achieved 100% compliance while resolving previously undetected coordination conflicts. The coordinated model also enabled targeted traffic and drainage analyses that helped address high-impact risk configurations, including flooding susceptibility and unsafe junction conditions, before construction release.

The results highlight two principal contributions. First, the study demonstrates that BIM can function as a proactive design assurance and risk management approach rather than merely a late-stage clash detection tool when verification routines and accountability mechanisms are embedded throughout conceptual and preliminary design stages. Second, integrating structured decision checkpoints with iterative simulation and issue-resolution cycles helps reduce uncertainty and limit the propagation of strategic design errors, thereby lowering exposure to downstream rework, schedule disruption, and operational safety risks. More broadly, the findings support a shift toward early digital integration in infrastructure design, where key decisions are validated in a coordinated, data-rich virtual environment before documentation is finalized and construction begins.

The proposed framework is transferable and can be adapted to other infrastructure contexts where multidisciplinary interfaces, standards compliance, and constructability constraints are prominent. Future research should extend the methodology through automated rule-based compliance checking, deeper integration with digital-twin workflows, and probabilistic risk modeling to improve predictive capabilities and quantify residual risk under uncertainty. Overall, the study underscores the value of lifecycle BIM integration for improving design integrity, enhancing constructability, and supporting more reliable and resilient infrastructure delivery outcomes.

9. Declarations

9.1. Author Contributions

Conceptualization, A.T.A., P.E.F.C., and R.F.A.; methodology, A.T.A.; software, A.T.A. and R.F.A.; validation, A.T.A., P.E.F.C., and R.F.A.; formal analysis, A.T.A. and P.E.F.C.; investigation, A.T.A. and R.F.A.; resources, A.T.A., P.E.F.C., and R.F.A.; data curation, A.T.A., P.E.F.C., and R.F.A.; writing—original draft preparation, A.T.A.; writing—review and editing, P.E.F.C.; visualization, A.T.A. and R.F.A.; supervision, A.T.A. and P.E.F.C. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are contained within the article.

9.3. Funding

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9.4. Acknowledgments

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9.5. Conflicts of Interest

The authors declare no conflict of interest.

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