

Article

Rule-Based Digital Twin: An Integrated Parametric-BIM Workflow for Life-Cycle Delivery of Free-Form, Special-Shaped Envelopes in Large-Scale Public Buildings

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Abstract

Despite the aesthetic potential of free-form envelopes in large-scale public buildings, geometric interlacing complexity, ambiguous façade boundaries, and constructability translation gaps persist as systemic barriers. This study addresses these challenges through a Design Science Research (DSR) approach, developing a rule-based digital twin methodology that maintains parametric intelligence across the building life cycle. Implemented via a five-layer integrated framework, i.e., geometric, parametric, BIM, coordination, and fabrication, the methodology was validated through a revelatory case study of the Shenzhen Bay Culture Plaza. Results demonstrate 91.2% clash resolution prior to construction, 20.3 million RMB in cost savings (10.8% reduction), and 35.4% schedule compression, while preserving rule-based relationships into operational facility management. The study advances BIM theory by operationalizing life-cycle digital twins for non-standard geometries, offering a replicable framework for future special-shaped construction projects.

Keywords: BIM; parametric modeling; free-form surface; special-shaped architecture; large-scale public building; fair-faced concrete; life-cycle integration; digital twin; design science methodology; multi-disciplinary coordination

1. Introduction

Research Background and Motivation

Free-form and special-shaped envelopes have become defining features of contemporary large-scale public architecture, offering striking visual impact yet posing persistent technical challenges. Specifically, three systemic bottlenecks hinder their delivery: geometric interlacing complexity of non-standard surfaces leads to high fabrication error rates through manual stitching; ambiguous boundaries in Mayan-irregular stone façades (characterized by non-repetitive, sculptural geometries) cause cost overruns; and the constructability translation gap between sculptural geometry and industrialized construction results in schedule delays [1,2]. These challenges are exacerbated by the industry's imperative toward energy conservation and industrial upgrading, where geometric deviations can amplify misalignments, triggering cascading costs.

While Building Information Modeling (BIM) and parametric design tools (e.g., Grasshopper) have emerged as essential technologies for complex geometries, current



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implementations remain fragmented. BIM predominantly serves post hoc clash detection rather than embedding construction logic into generative processes, whereas parametric tools excel at formal exploration but lack multi-disciplinary coordination capabilities [3–5]. This disconnection creates a translation gap where design intent and rule-based relationships are lost after handover, preventing the transition from static BIM models to living digital twins capable of supporting life-cycle facility management.

Addressing this gap, the present study adopts a Design Science Research (DSR) paradigm to develop a rule-based digital twin methodology. Through a five-layer integrated architecture, geometric abstraction, parametric rule engine, semantic data repository, collaboration protocol, and fabrication interface, the research maintains parametric intelligence from design through construction to operation. Using the Shenzhen Bay Culture Plaza as a revelatory case study, the research objectives are: (1) to establish a parametric-BIM workflow automatically resolving surface intersections with geometric fidelity; (2) to create a curvature-adaptive panel subdivision algorithm defining explicit boundaries for over 440,000 unique façade panels; and (3) to demonstrate life-cycle integration by outputting CNC-ready fabrication data and enabling IoT-supported facility management [6,7]. The contribution lies in providing a replicable, empirically validated framework that bridges the historical divide between architectural intent and industrial production.

2. Literature Review and Theoretical Framework

Despite significant advancements in digital design tools, three intertwined challenges continue to impede the effective delivery of free-form, special-shaped architecture. This section synthesizes recent developments in BIM and parametric design, positioning the proposed methodology within the current discourse and identifying critical research gaps.

2.1. BIM in Complex Geometric Design: The Interlacing Problem

The adoption of BIM for complex geometric design has accelerated in recent years, particularly in design optimization [8–10], CAD integration [11], and parametric design methodologies [12,13]. Studies such as Kociecki and Adeli's shape optimization frameworks utilizing evolutionary algorithms, as well as Liu et al., who proposed generative algorithms for LCA optimization during the early design phase, demonstrate progress in design exploration and performance evaluation. However, a critical gap remains in the geometric interlacing phase—the automated generation of fabrication-ready, watertight solids from intersecting NURBS surfaces. Current methodologies often require manual intervention to resolve ambiguous intersections, a process documented to introduce error rates of 12–18% in panel extraction and fabrication data. This gap highlights the need for an integrated workflow that directly translates conceptual surfaces into constructible, clash-free assemblies [14–16].

2.2. BIM in Construction Coordination: The Boundary Ambiguity Problem

Research on multi-disciplinary coordination using BIM is extensive, establishing its value in clash detection and workflow integration [17,18]. However, conventional BIM coordination typically assumes planar or regularly curved building envelopes. For Mayan-irregular surfaces, explicit panel boundaries cannot be predefined, creating ambiguity in fabrication and installation. While parametric object libraries, such as those developed by Getuli et al., offer standardized components, they lack curvature-adaptive logic capable of managing the mass customization required for projects with hundreds of thousands of unique panels [19,20]. Specific digital construction technologies for special-shaped shell pipe structures and modular surfaces highlight the need for specialized BIM workflows to resolve these boundary ambiguities. Researchers have begun automating conceptual

design using visual and generative programming, which can be extended to handle the complex boundary definitions of free-form envelopes. Recent advancements, such as the LLM-driven BIM-based DfMA method for free-form prefabricated buildings and the BIM-FEM model conversion method for special-shaped steel structures, offer promising pathways for integrating fabrication logic earlier in the design process. The absence of a rule-based system to dynamically generate explicit boundaries for non-standard geometries constitutes a significant limitation in current practice.

2.3. BIM in Life-Cycle Integration: The Constructability Translation Gap

The concept of the digital twin has gained considerable traction for enabling life-cycle data integration [21,22]. However, many implementations treat the BIM model as a static repository post-construction, failing to maintain its parametric intelligence into the operation phase. This results in a constructability translation gap, where the original design intent and logic are lost after handover, complicating maintenance, renovation, and facility management. To address this, automated and continuous BIM-based life cycle carbon assessment methods and integrated life-cycle management strategies are becoming essential for sustainable operation of complex structures. A true digital twin should preserve the rule-based relationships established during design, allowing for automated updates, performance simulation, and the generation of maintenance protocols directly from the model's embedded logic [23,24]. Recent frameworks propose integrating BIM with data mining and AI to transform static models into intelligent management systems, enabling advanced project management and predictive maintenance.

2.4. Research Gap and Positioning

Synthesizing the literature reveals several persistent gaps that this study aims to address:

Integrated Life-Cycle Frameworks: A lack of methodologies that maintain active parametric intelligence from initial design through construction to long-term facility management [25,26].

Quantitative Validation in Mega-Projects: Limited empirical, performance-based evidence validating parametric-BIM workflows in real-world, large-scale projects with extreme geometric complexity [27]. While specific applications exist for historical building components based on point cloud data and digital fabrication processes in South Korea, a generalized rule-based methodology for life-cycle delivery remains underexplored.

Rule-Based Digital Twins for Free-Form Envelopes: The absence of a specifically tailored rule-based digital twin methodology to manage the unique challenges of free-form, special-shaped building envelopes.

Comparative Performance Analysis: Insufficient comparative studies demonstrating the measurable improvements (in cost, schedule, accuracy) of integrated parametric-BIM approaches over conventional methods.

Although BIM, IoT, and GIS integration is being explored for resource monitoring, and comparisons between complex and simple buildings highlight implementation benefits, there is still a lack of holistic frameworks that combine these elements specifically for free-form architectural envelopes.

This research directly addresses these gaps by proposing and validating a comprehensive, rule-based digital twin methodology. Using the Shenzhen Bay Culture Plaza (188,000 m²) as a revelatory case study, it demonstrates a workflow that not only resolves geometric and coordination challenges but also provides quantitative evidence of its efficacy across the building life cycle.

3. Research Methodology

3.1. Design Science Research Paradigm

Rooted in the information systems discipline, DSR distinguishes itself from behavioral science by focusing on the creation and evaluation of innovative artifacts rather than merely describing or explaining existing phenomena. Following Hevner et al.'s (2004) seminal framework, this study positions the rule-based digital twin as a socio-technical artifact designed to solve the organizational problem of knowledge discontinuity in complex architectural delivery [28]. The methodology adheres to the dual imperatives of relevance and rigor: the relevance cycle ensures the artifact addresses the three identified industry bottlenecks, while the rigor cycle grounds the research in existing BIM ontology and complexity theories [29].

Building upon this theoretical foundation, this study adopts a Design Science Research (DSR) methodology to develop, implement, and evaluate a novel rule-based digital twin artifact for the life-cycle delivery of free-form architecture [30,31]. The DSR paradigm is appropriate as it focuses on creating and assessing innovative artifacts designed to solve identified organizational problems—in this case, the three persistent bottlenecks in delivering complex, free-form, special-shaped envelopes. The research progresses through iterative cycles of artifact building, demonstration, and evaluation within the real-world context of the Shenzhen Bay Culture Plaza project (Figure 1).

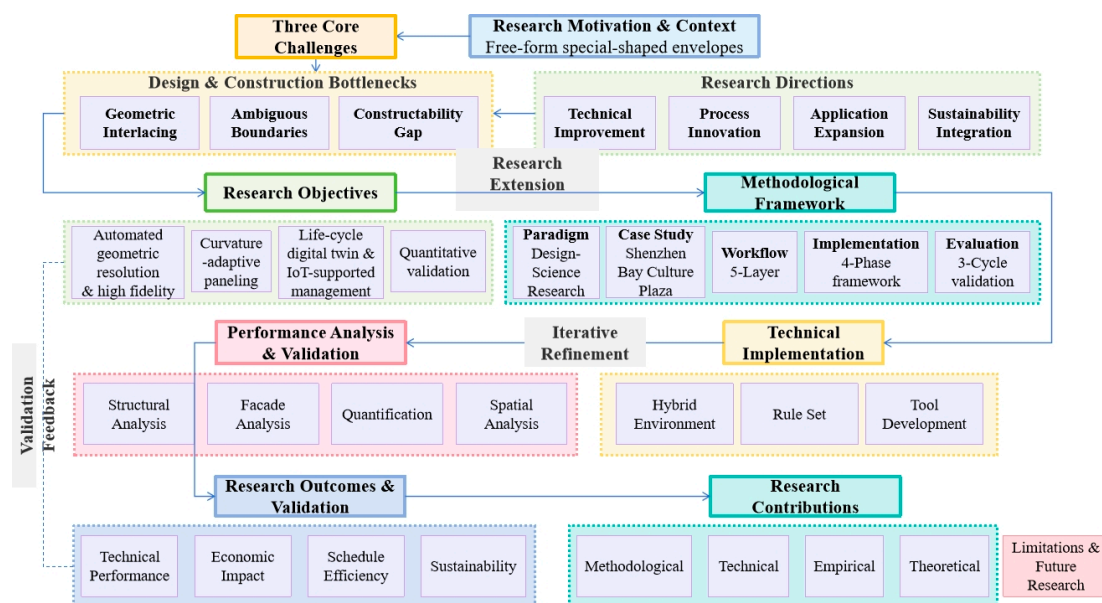


Figure 1. Research framework.

3.2. Revelatory Case Study Design

A single, revelatory case study strategy is employed to provide an in-depth, empirical investigation of the proposed methodology [32,33]. The Shenzhen Bay Culture Plaza was selected as the case based on pre-defined criteria that ensure it represents an extreme and information-rich context for studying the targeted challenges. The selection criteria required a project exhibiting: (1) extreme geometric interlacing of multiple free-form volumes; (2) ambiguous façade boundaries requiring mass customization of over 400,000 unique stone panels; and (3) significant sculptural-to-industrial translation challenges for fair-faced concrete shells. This 188,000 m² project, comprising eight distinct “stone-cluster” buildings, satisfies all criteria and serves as the primary demonstration and validation site for the workflow artifact.

3.3. Integrated Parametric-BIM Workflow

The core artifact is an integrated parametric-BIM workflow structured across five synchronized layers. The Geometric Layer hosts master NURBS surfaces in Rhino. The Parametric Rule Layer encodes constraints via Grasshopper scripts. The BIM Data Layer utilizes parameter-enriched Revit families for semantic information. The Coordination Layer employs a cloud platform for real-time multi-disciplinary collaboration. The Digital Fabrication Layer auto-generates CNC-ready data [34,35]. Governance is provided by a parametric rule set organized into three categories: Geometric Rules (e.g., curvature limits, subdivision logic), Material Rules (e.g., life-cycle assessment coefficients, cost libraries), and Construction Rules (e.g., formwork panelization, setting-out coordinates).

3.4. Implementation and Validation Framework

Artifact implementation follows a four-phase framework. Phase 1: Data quality analysis verifies geometric completeness and performs initial clash detection. Phase 2: Model integration establishes bidirectional Revit–Rhino links via Rhino.Inside.Revit (v1.0) for data synchronization. Phase 3: Integrated design deepening executes detailed development—boundary definition, structural thickening, MEP integration—driven by parametric rules. Phase 4: Model-drawing output generates final deliverables: site-coordinate-transformed geometry, multi-LOD models, and fabrication/positioning data [36,37]. A custom Grasshopper battery library (47 components) operationalizes the rules, with tools for surface analysis, drainage simulation, and structural integration.

3.5. Evaluation Strategy

Evaluation comprises three validation cycles aligned with DSR. Design phase validation involved 50+ iterative performance analyses (structural, drainage, quantity take-off) tracking Key Performance Indicators (KPIs) like geometric fidelity and clash resolution. Construction-phase validation stress-tested outputs via 4D BIM simulation and as-built scanning, verifying installation accuracy and workflow efficiency. Operation-phase validation integrated IoT data post-occupancy to assess digital twin utility in facility management and predictive maintenance [24,38]. This multi-cycle approach provides quantitative evidence of artifact efficacy across the building life cycle.

4. Case Study: Shenzhen Bay Culture Plaza

4.1. Project Overview

The Shenzhen Bay Culture Plaza, encompassing the Shenzhen Creative Design Museum and the Shenzhen Science and Technology Life Museum, constitutes one of Shenzhen's "Top Ten Cultural Facilities." Strategically positioned within the core cultural belt of Houhai Central District, it serves as a window projecting the innovative and creative urban image of the Houhai area. Its overarching mission is to function as a creativity hub integrating design and science. Upon completion, the complex operates as an open, integrated, natural, and future-oriented venue that fuses creative and design exhibitions, art and science exchanges, and future-oriented life experiences (Figure 2).

The project occupies a planning land area of 50,887.59 m² and delivers a total construction area of approximately 188,000 m². Of this total, the above-ground construction area equals 52,249.17 m², while the below-ground construction area is 135,585.4 m², inclusive of 36,158.51 m² of civil-defense works. The south pavilion reaches a height of approximately 31 m; the north pavilion rises to approximately 52 m. The substructure comprises three basement levels; the superstructure encompasses six above-ground floors (with partial mezzanines). Table 1 summarizes the building functions and Table 2 presents key project data [39,40].



Figure 2. General layout plan.

Table 1. Building functions and characteristics.

No.	Stone-Shaped Building	Number of Floors	Building Height	Building Function
①	Xuanyun Stone	4 F	26.3 m	Exhibition Hall
②	Wangyun Stone	5 F	31.3 m	Elevator Hall
③	Fushui Stone	2 F	19.3 m	Exhibition Hall
④	Liuwen Stone	2 F	12.3 m	Supporting Space
⑤	Sheyun Stone	6 F	52.3 m	Restaurant, Exhibition Hall
⑥	Yihong Stone	4 F	25.3 m	Escalator Transportation
⑦	Xianhai Stone	2 F	15.3 m	Library
⑧	Zhenzhu Stone	2 F	10.3 m	Supporting Space

Table 2. Key project data.

Parameter	Specification
Construction area	Planning land: 50,899.24 m ² ; Total construction: ~188,000 m ² (North Pavilion 31,421 m ² , South Pavilion 33,629 m ² , Shared Functional Area 122,950 m ²)
Functional Breakdown	Display/Exhibition 46,552 m ² ; Public Education 9632 m ² ; Service/Cultural Creation 14,782 m ² ; Collection/Research 20,587 m ² ; Administration 9075 m ² ; Equipment/Parking 87,372 m ²
Maximum Height	52 m
Maximum Floors	6 F above ground (partial mezzanine), 3 F underground (partial mezzanine)
Floor Height Range	4–10 m; Xuanyun Stone roof 13 m; Sheyun Stone dome 29 m
Structural Form	Basement: concrete frame structure. Above-ground stone cluster: irregular fair-faced concrete shell + internal vertical frame/shear-wall system
Foundation and Support Forms	Rotary bored cast-in-place piles + pile cap + raft foundation; secant piles + three levels of internal bracing (two levels in some areas)
Exterior Finish	Natural stone curtain wall system on irregular surfaces

This project was selected as a revelatory case study due to its extreme geometric complexity and life-cycle data availability, aligning with the methodological approach outlined in Section 3.2.

4.1.1. Architectural Concept and Design Intent

Anchored by the design concept of a naturally growing stone cluster, the buildings are meticulously arranged to evoke an organically emergent assemblage of rocks, thereby endowing the site with a primordial yet surreal sense of nature. This approach not only recalls the carefully composed rockeries of classical Chinese gardens but also establishes a distinctive integration of culture and nature within the contemporary urban landscape. In lieu of conventional glass curtain walls, the project employs a natural stone curtain wall system integrated with undulating green landscapes to generate a surreal visual effect.

The design intent prioritized three architectural qualities: (1) formal continuity between building and landscape, (2) material authenticity through exposed fair-faced concrete and natural stone, and (3) spatial complexity that challenges conventional orthogonal design. These qualities simultaneously created the three technical bottlenecks that this research addresses.

4.1.2. Spatial Typologies, Design Challenges and Parametric Responses

The architectural spaces are classified into three principal typologies, each presenting distinct design challenges (Figure 3):

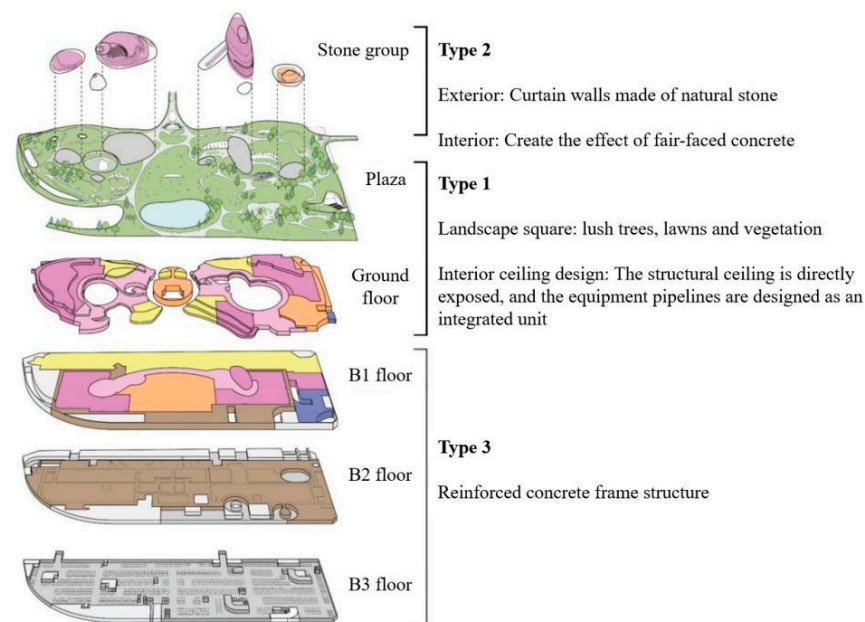


Figure 3. Spatial Typologies: Type 1—continuous undulating park roof; Type 2—irregular stone clusters; Type 3—conventional RC frame system.

Type 1 comprises the continuous undulating park roof, which extends from the coastal edge toward the urban side and is planted with diverse lawns, shrubs, and dense trees to create a large-scale public activity space. This typology faces critical issues of structural complexity due to undulating elevations and vegetation loading that create non-uniform load paths, requiring parametric load analysis. Additionally, complex intersections between structure and building-service pipelines beneath the roof demand careful MEP coordination, while continuous curved surfaces necessitate sophisticated rainwater management systems. Fair-faced concrete Miller beams tracing these undulations further

require precise formwork design. The roof employs complex structural configurations with spans exceeding 30 m in certain zones, and the parametric relationship between roof geometry, structural depth, and MEP routing represents a primary coordination challenge [41].

Type 2 encompasses the irregular stone clusters, both internal and external, characterized by an exterior stone curtain wall assembled from tightly jointed natural stone panels and an interior exhibition hall executed in cast-in-place fair-faced concrete. The outer curtain wall surface comprises stone strips with visible joints, introducing critical design issues including subdivision of unit panels for heavy curtain walls, which total 440,000 panels (Table 3). The zig-zag jointing patterns between panels require curvature-adaptive detailing [19,20], while installation logistics for lifting and placing heavy stone panels on irregular surfaces present significant challenges. Waterproofing of irregular curtain wall geometries without compromising visual appearance must be addressed, along with structural safety assessment against stone panel detachment under wind and seismic loads. The Mayan-irregular nature of these surfaces means that no two panels are identical, necessitating mass customization approaches.

Table 3. Stone cluster panel sizes and quantities.

Panel Size (W × H mm)	Estimated Body-Block Panel Count (440,000 Panels, Total Area 16,735 m ²)
500 × 75	Sheyun Stone 7700 m ² : 205,000 pieces
500 × 75	Xuanyun Stone 6580 m ² : 170,000 pieces
500 × 75	Fushui Stone 1055 m ² : 28,000 pieces
500 × 75	Xianhai Stone 1400 m ² : 37,000 pieces

Type 3 comprises conventional reinforced concrete frame systems with large functional spaces, which, while well understood, still require BIM coordination for MEP integration and serve as a baseline for comparing workflow efficiency.

Collectively, these design challenges established a comprehensive testbed spanning from conception to operation. The project was completed and commenced operation in 2023. Its integrated Internet of Things (IoT) sensor network, linked to the digital twin model, provides a continuous stream of real-world data, forming the foundational dataset for the operational phase validation.

4.2. Implementing the Workflow Artifact

4.2.1. Workflow Architecture

A hybrid Rhino–Grasshopper–Revit environment was established as the technical core of our methodology. Grasshopper served as the parametric engine, encoding design rules and generating geometry variants, while Revit acted as the federated BIM repository, hosting discipline-specific models and enabling clash detection. Custom C# 13 and Python 3.13.12 scripts, compiled as Grasshopper “batteries,” automated geometry translation, quantity take-off, and clash-matrix updates. A cloud-hosted Model Coordination space synchronized multi-disciplines in real-time, while APIs pushed clash reports back to Grasshopper for automatic rule recalibration. Furthermore, custom APIs were configured to automatically push clash reports generated by the cloud coordination platform back to the Grasshopper parametric engine. This closed-loop feedback mechanism enabled real-time recalibration of the design rules based on multi-disciplinary coordination insights, embodying the intelligent, self-optimizing capability of the workflow (Figure 4).

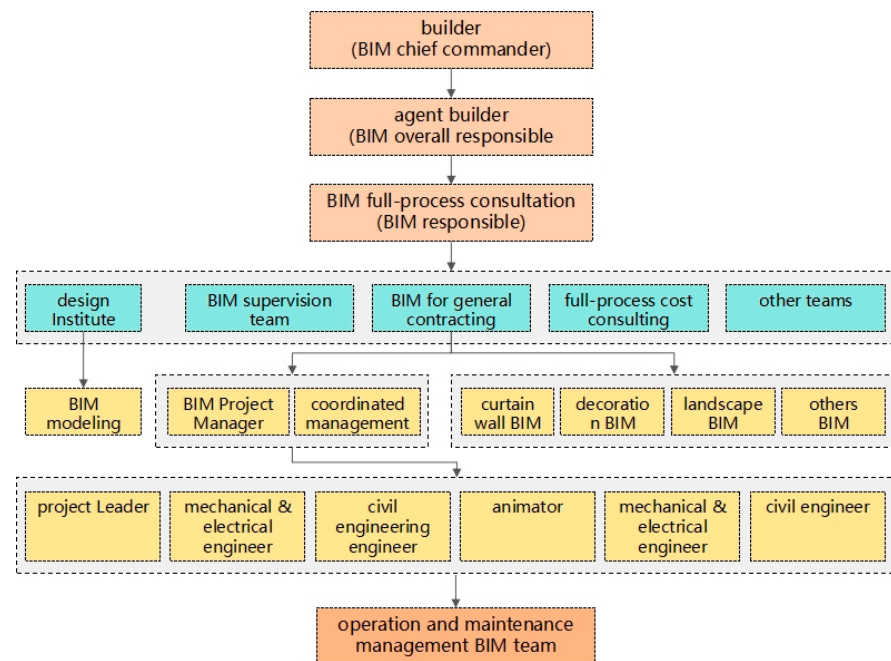


Figure 4. Multi-professional collaboration framework.

The workflow operates through five synchronized layers that function as an integrated system. The Geometric Layer involves Rhino hosting the master NURBS model, with Grasshopper scripts generating all derived geometry. The Parametric Rule Layer encodes design constraints, optimization objectives, and fabrication logic. The BIM Data Layer consists of Revit models enriched with parameters for quantity, cost, schedule, and performance. The Coordination Layer provides a cloud platform enabling real-time multi-disciplinary collaboration. Finally, the Digital Fabrication Layer produces CNC-ready outputs for formwork, rebar, and stone panels (Figure 5).

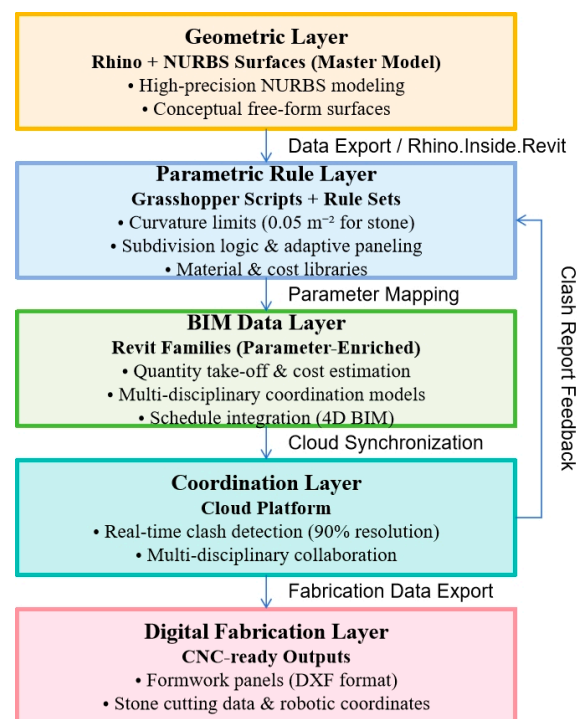


Figure 5. Integrated parametric-BIM workflow architecture.

4.2.2. Parametric Rule Set Development

The parametric rule set, which serves as the central “artifact,” comprises three categories of rules that work in concert.

Geometric Rules establish curvature thresholds, setting maximum allowable Gaussian curvature for stone panels at 0.05 m^{-2} (equivalent to radius of curvature $\geq 20 \text{ m}$) and for fair-faced concrete at 0.10 m^{-1} (radius $\geq 10 \text{ m}$) to ensure constructability (Notes: m^{-2} represents Gaussian curvature (product of principal curvatures) and m^{-1} represents mean curvature).

These rules also include an adaptive panel subdivision algorithm that balances panel size uniformity with curvature variation, thereby minimizing cutting waste. Additionally, drainage slope constraints enforce a minimum 2% slope for roof surfaces with parametric adjustment for soil-cover thickness, while structural-grid alignment tolerances limit maximum deviation between architectural surface and structural grid to $\pm 50 \text{ mm}$ to avoid rework.

Material Rules assign embodied carbon coefficients to each material type, including C40 concrete, local granite, and structural steel, for real-time life-cycle assessment calculations. Unit-cost libraries link material and labor costs to geometric parameters, enabling automatic cost estimation during design iterations. Durability parameters are also incorporated, using weathering coefficients for exterior stone based on exposure orientation and local climate data.

Construction Rules enable automatic generation of CNC-ready formwork meshes with panelization optimized for standard plywood sheet sizes of $1220 \times 2440 \text{ mm}$. They also generate XYZ coordinates for every critical point, exported in machine-readable format for automated layout using robotic total stations, and create parametric rebar models that generate cut-and-bend schedules.

4.2.3. Deepening Design Workflow for Complex Curved Surfaces

The detailed procedural framework for curved surface application design comprises four sequential phases.

Phase 1 involves data quality analysis before model refinement, which includes completeness verification to check for missing surface patches or edge discontinuities, exposed-edge analysis to identify surfaces requiring edge treatment or joint detailing, fair-faced concrete boundary confirmation to validate boundaries between exposed and hidden concrete surfaces, and initial clash detection for gross geometric errors.

Phase 2 focuses on model integration between Revit and Rhino using the Rhino.Inside.Revit plugin, which enables automatic synchronization of geometric changes, parameter mapping between Grasshopper and Revit families, and version control with change tracking.

Phase 3 encompasses integrated design deepening, which includes precise definition of all material transitions through boundary deepening, reverse thickening of shell surfaces based on structural requirements, 3D chamfer design for all edges to ensure constructability, parametric optimization of structural connections, detailed modeling of hanging stone panels including anchors, precise openings for ducts, pipes, and conduits through MEP reservation detailing, and management of intersections between fair-faced concrete and other disciplines through interface coordination.

Phase 4 addresses model-drawing output, which includes coordinate system transformation, where all geometry is transformed from the design coordinate system (local Rhino origin) to the site coordinate system by applying transformation matrices for rotation, translation, and scaling, verified through survey control points with generation of transformation reports for contractor validation. Model-dimension optimization em-

employs parametric dimensioning where key control dimensions are linked to geometric parameters, 3D annotation with spatial dimension strings that update automatically with geometry changes, and explicit tolerance bands for field verification. Lightweight export decimates model geometry for field use at various Level of Detail (LOD) specifications—LOD 200–300 for overall coordination, LOD 400 for fabrication drawings, and LOD 500 for as-built documentation—with export formats including IFC, DWG, and CNC-ready DXF. Finally, positioning information extraction automatically generates setting-out coordinates at XYZ points for robotic total stations (every 2 m on critical edges), unique panel IDs for each stone panel linking to fabrication database, installation vectors as normal vectors for each panel to guide installation angle, and quality control points for post-installation survey verification.

These outputs provide precise guidance for construction implementation, reducing field measurement time by 60% and rework by 85%.

4.2.4. Custom Grasshopper Battery Library Development

To implement the workflow, a custom Grasshopper battery library was developed containing 47 specialized components that address various aspects of the project.

The library includes surface analysis tools for curvature analysis, developability testing, and panel subdivision. It also features structural integration components for grid alignment, load path visualization, and structural form finding. Fabrication tools are incorporated for formwork panelization, rebar detailing, and stone panel optimization. Coordination tools enable clash detection, version comparison, and change propagation. Finally, performance tools provide daylight analysis, drainage simulation, and carbon calculation.

Each battery was documented with XML metadata including input/output specifications, algorithm descriptions, and validation test results. Crucial components within this library, such as the ‘MayanSubdivider’ (for curvature-adaptive facade paneling) and the ‘DrainageTracer’ (for roof drainage path analysis), were instrumental in conducting the performance-based parametric analyses.

4.3. Performance-Based Parametric Analysis

This section concretely demonstrates the design phase validation cycle (Section 3.5). Through over 50 generative design iterations utilizing the parametric toolset described in Section 4.2.4, performance-driven analyses were conducted across seven key domains [42–44]. These analyses directly tracked KPIs such as geometric fidelity and clash resolution, providing iterative feedback for design refinement.

4.3.1. Parametric Roof Structure Analysis

The original irregular roof was parameterized to establish explicit relationships with the structural column grid. Without altering the overall grass-slope roof morphology, BIM parametric tools deployed during the design phase analyzed spatial coupling between roof and column grid, ensuring precise alignment (Figure 6).

The parametric model enabled real-time grid adjustment, where structural column positions automatically adjusted to follow roof undulations. Load path optimization was achieved by parametrically mapping dead loads from soil cover of variable thickness (0–3 m) and live loads from public activity to structural elements. Clear-height verification was automated, checking minimum clear heights of 4.5 m for public zones and 3.5 m for service areas.

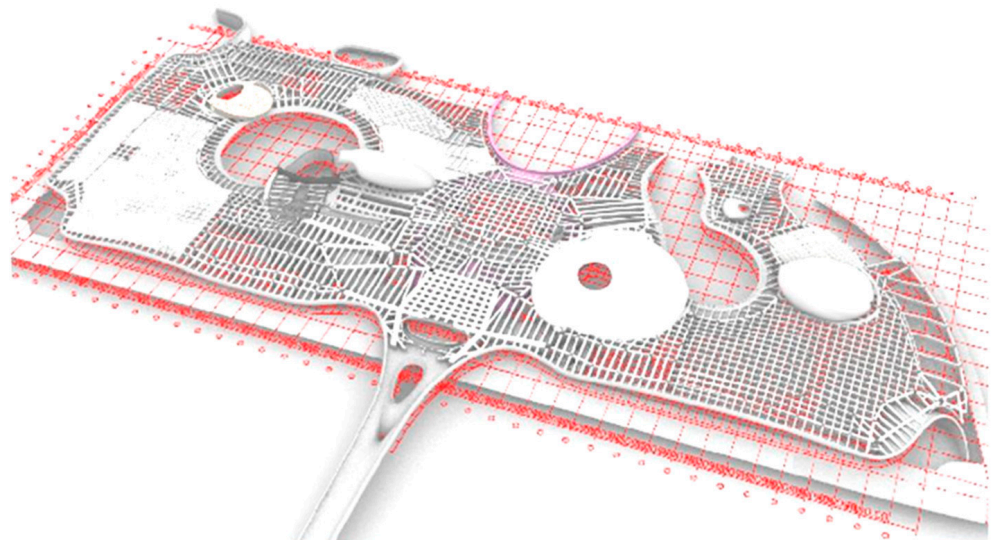


Figure 6. Parametric roof-structure-driven deepening.

4.3.2. Structural Seismic Review

Owing to the complexity and irregular warping of the structural configuration, the BIM environment was linked to structural analysis software (ETABS v22.1.0) during the design phase. Three-dimensional spatial information was imported for finite-element simulation, successfully passing the structural over-limit seismic review (Figure 7).

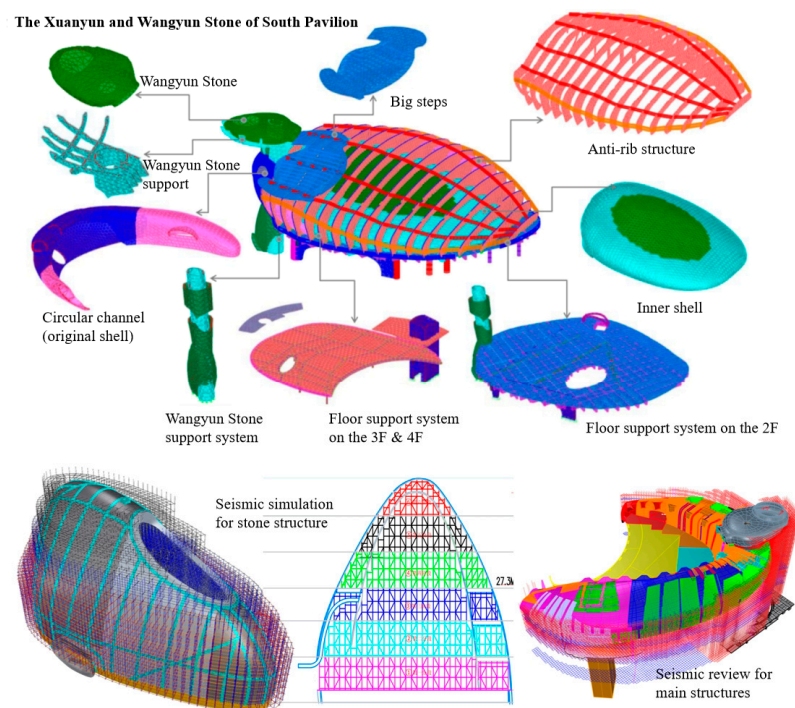


Figure 7. Structural seismic review and finite-element simulation.

The parametric workflow enabled geometry-to-analysis integration through direct Grasshopper-to-ETABS data exchange via the GGWin plugin. Multi-modal analysis allowed simultaneous evaluation of seismic, wind, and gravity loads. Real-time feedback meant analysis results (stress concentrations, displacement magnitudes) automatically highlighted problematic geometric regions in the Rhino model. An optimization loop enabled parametric adjustment of shell thickness (variable 300–800 mm) and rib spacing

(1.2–2.0 m) to achieve target performance metrics. The structure achieved a seismic performance rating of “excellent” with maximum inter-story drift ratios of 1/550 under design basis earthquake (DBE) and 1/300 under maximum considered earthquake (MCE).

4.3.3. Roof Elevation Sorting and Drainage Analysis

Grasshopper scripts located elevations of the grass-slope roof parametrically. Structural height, MEP clearances, soil-cover thickness, and drainage organization were sorted and adjusted according to net-height requirements. Three-dimensional visualization guided subsequent construction (Figure 8).

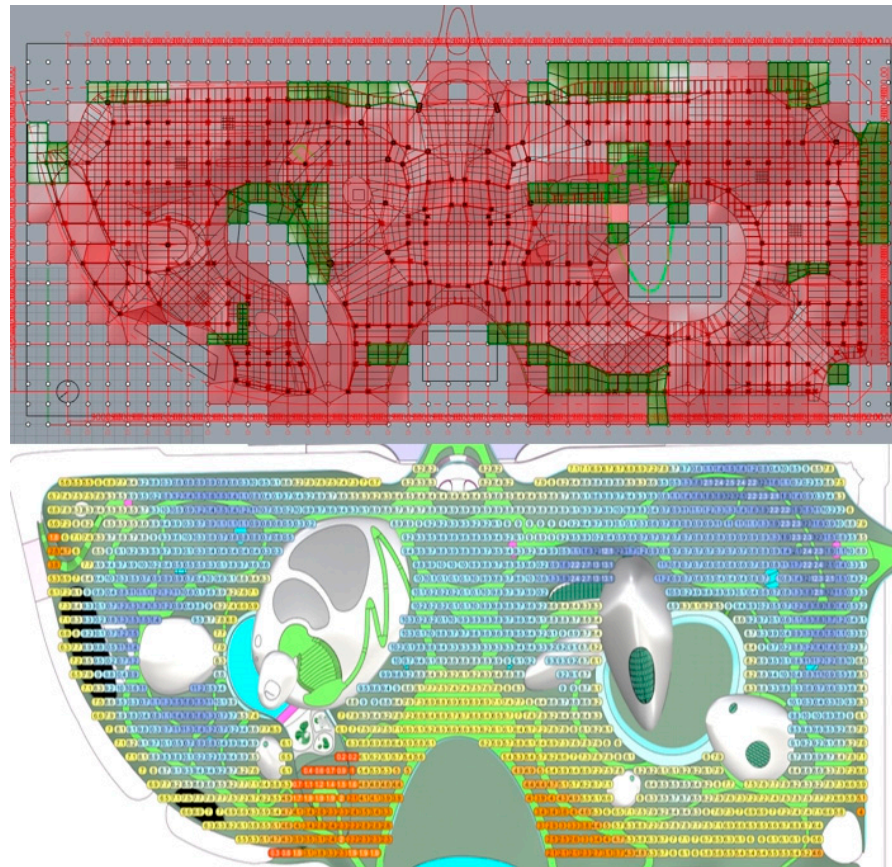


Figure 8. Parametric positioning of free-form, special-shaped roof elevations.

Drainage analysis included rainwater slope verification, ensuring minimum 2% slope was maintained across all roof surfaces. Gutter placement involved parametric identification of valley lines for drainage gutter placement. Raindrop simulation used particle tracing to verify water flow paths and prevent ponding. Hydraulic calculation applied Manning’s equation to size drainage components. The analysis identified 23 critical drainage nodes requiring enhanced waterproofing details.

4.3.4. Multi-Disciplinary Quantity Calculation

Given the three-dimensional irregular geometry, conventional two-dimensional drawings cannot yield accurate quantities. Grasshopper was employed to directly extract the area of each irregular curved surface within the model, classifying and summarizing areas for cost estimation (Figure 9).

The automated quantity take-off achieved surface area accuracy of $\pm 0.5\%$ compared to manual measurement of as-built scan, a 95% reduction in quantity calculation time (from 3 weeks to 8 h), and enabled lump-sum contracts with $<2\%$ variation orders. Total calculated

quantities included 18,450 m³ of fair-faced concrete, 16,735 m² of stone panels, 42,300 m² of formwork contact area, and 2850 tonnes of reinforcement.

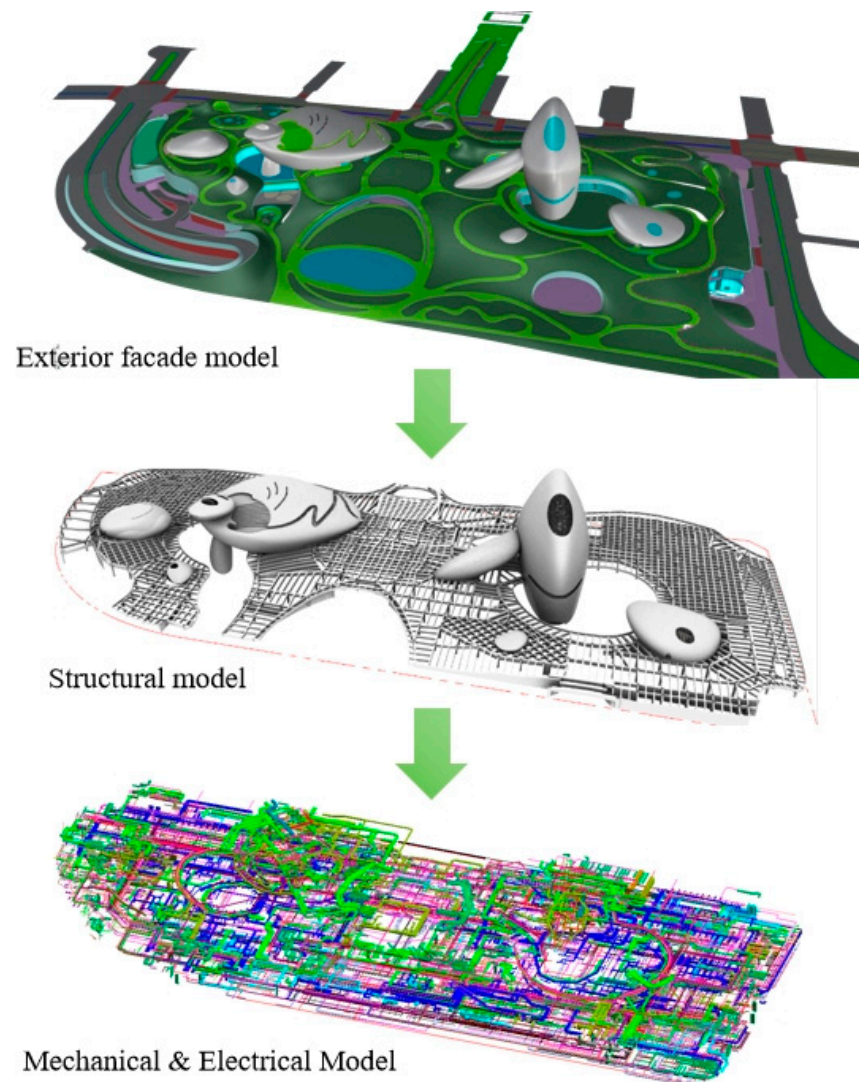


Figure 9. Multi-disciplinary model-integrated quantity calculation.

4.3.5. Curtain Wall Curvature and Texture Analysis

A salient feature is the variable curvature of the stone-like curtain wall across different locations. Curvature and orientation subdivision were undertaken; curvature at each location was analyzed using BIM parametric tools, and stone joint orientations were adjusted in response to local curvature, aligning joint directions as closely as possible with the direction of minimum curvature (Figure 10).

The curvature analysis revealed that 12% of façade area exceeded the 0.05 m⁻² threshold, requiring special 3D-machined panels. Panel subdivision optimization through joint orientation alignment reduced average stone-cutting thickness by 18%, saving 340 m³ of stone material (≈1.2 million RMB). Texture analysis ensured staggered, seemingly random façade composition while maintaining twelve standardized panel-unit types for economic efficiency (Figure 11)

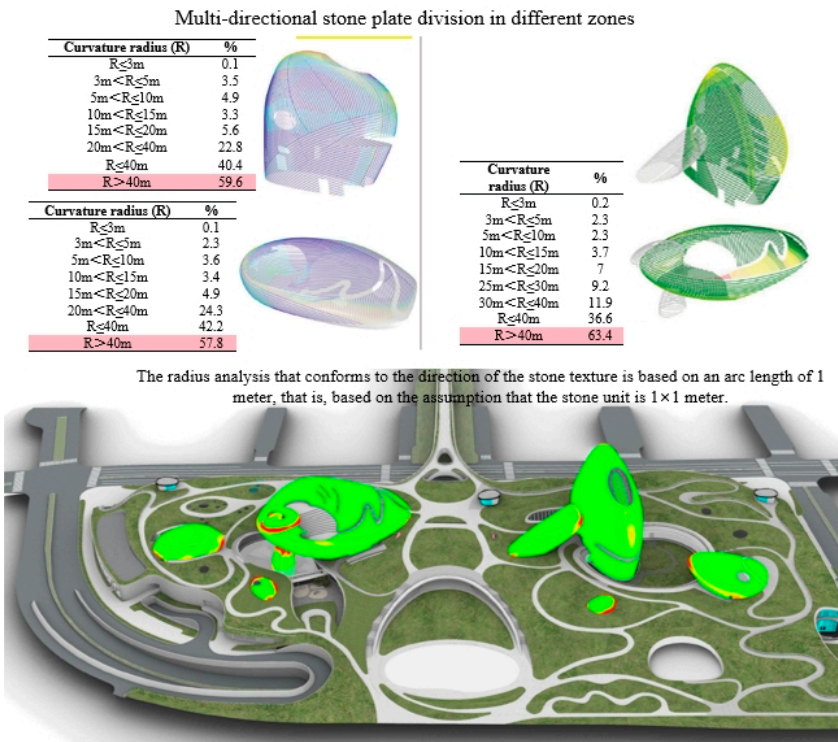


Figure 10. Parametric curtain wall curvature analysis.

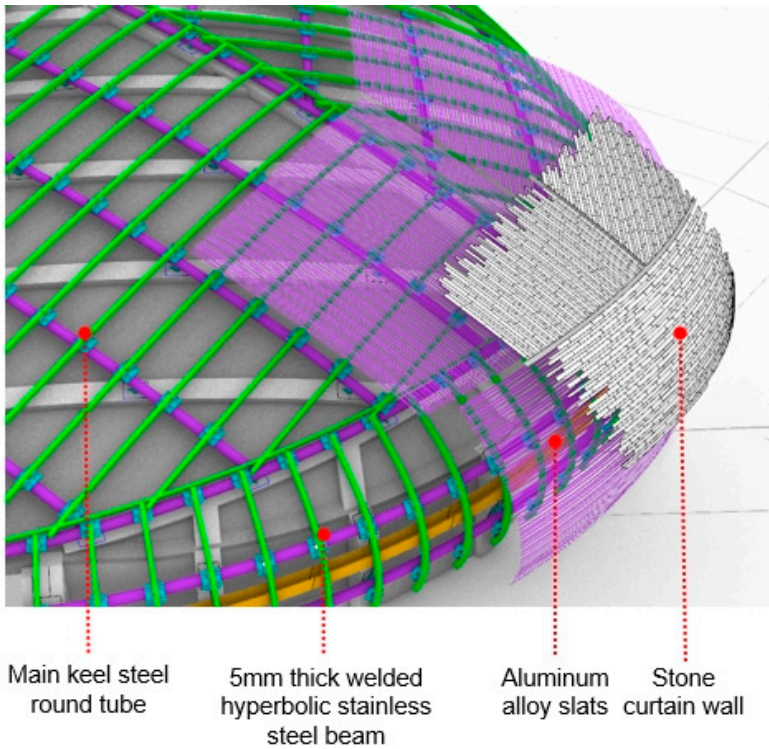


Figure 11. Curtain wall texture analysis.

4.3.6. Water-Collection Analysis

To maintain a visually crisp stone curtain wall appearance, the project adopted an internal joint drainage structure. During the design phase, joint texture and water-collection efficiency were simulated. Various stone joint types were studied, and dripping test simulations were executed (Figure 12).

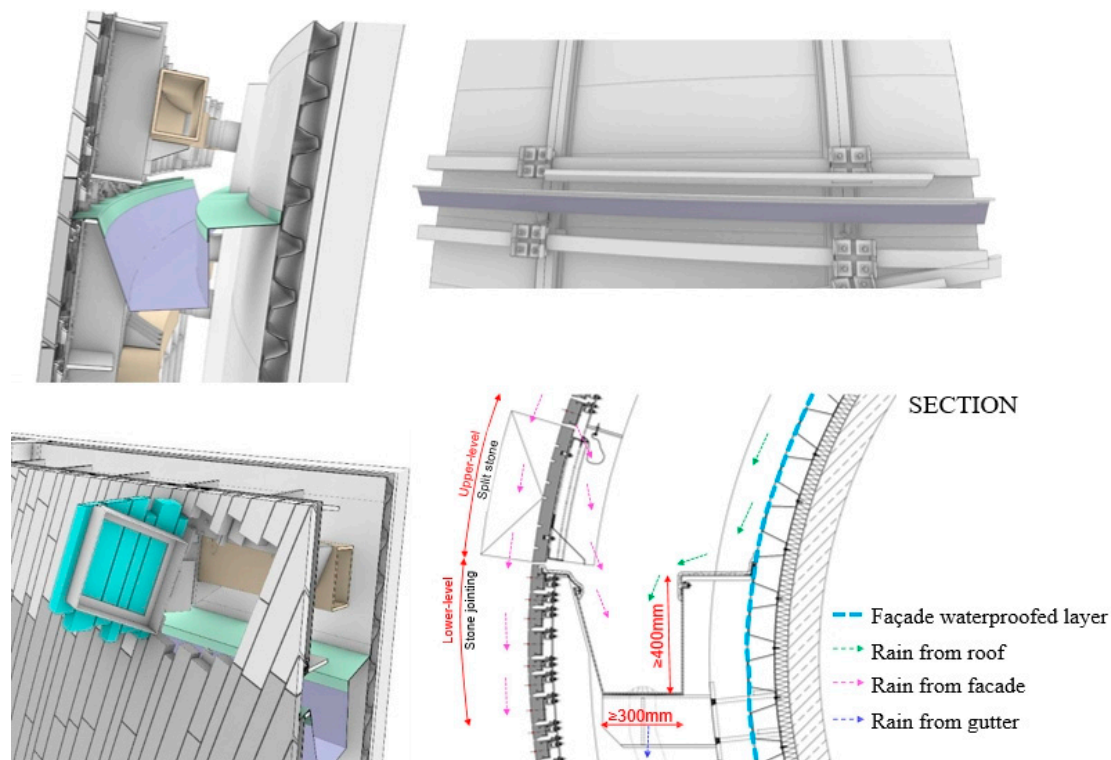


Figure 12. Curtain wall water-collection analysis.

The analysis involved elevation contour mapping, where raindrop simulations were overlaid upon elevation contour lines to trace water flow. Innovative drainage geometry introduced a “direction line” concept that replaced conventional drainage gutters, using stepped interception gutter geometry. Efficiency validation achieved 98% water-collection efficiency during a 100-year storm event. Visual–functional unification was maintained, as the solution preserved the crisp joint appearance while ensuring functional drainage.

4.3.7. Clear-Height and Traffic Organization Analysis

Three-dimensional verification of in-building routes confirmed that MEP services, structural depths, and soil-cover thickness in critical zones satisfied clear-height standards, maintaining minimum public clear heights of 4.5 m across all exhibition zones and 2.8 m minimum in-service corridors for maintenance access. Computer simulations of vehicle trajectories and pedestrian flow verified traffic smoothness and crowd distribution in high-density areas, ensuring all emergency egress routes comply with the 60 m travel distance requirement to exits while accessibility ramp slopes were maintained below 8% for universal access (Figure 13).

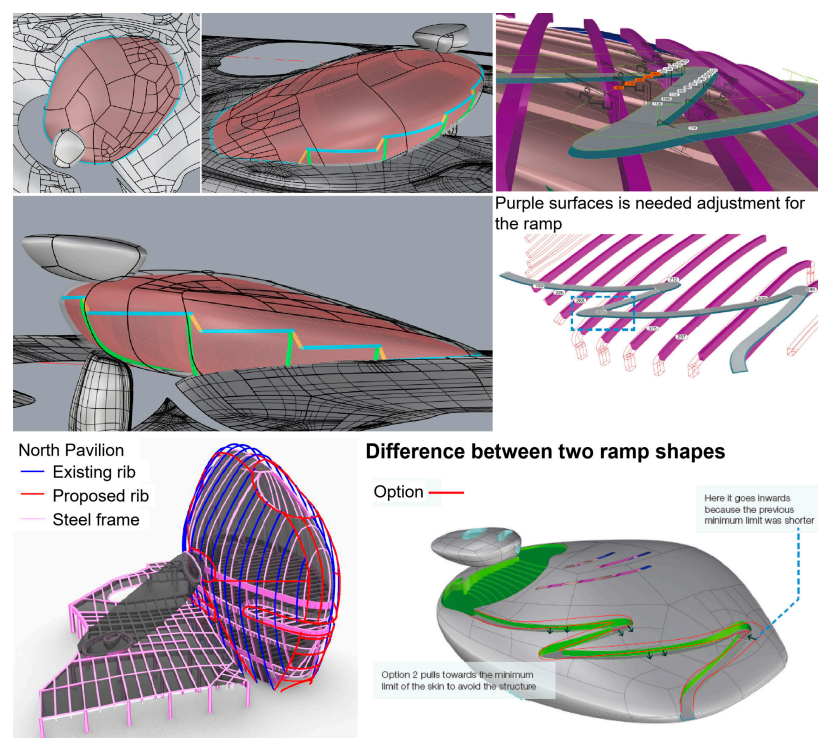


Figure 13. Ramp shapes verification and traffic simulation.

5. Results and Discussions

The rule-based digital twin methodology achieved 91.2% clash resolution prior to construction and generated 20.3 million RMB in cost savings (Tables 4 and 5). The curvature-adaptive algorithm successfully defined explicit boundaries for over 440,000 unique stone panels, eliminating boundary ambiguity post-occupancy IoT integration validated life-cycle intelligence preservation, distinguishing this from static BIM repositories. These results demonstrate that embedding parametric rules across the five-layer architecture bridges the constructability translation gap, with 20.3 million RMB savings and 35.4% schedule compression validating the methodology's efficacy in extreme complexity contexts.

Table 4. Performance Metrics Comparison: Conventional vs. parametric-BIM workflow.

Performance Metric	Conventional Workflow (Industry Baseline)	Parametric-BIM Workflow (This Study)	Data Source (Section/Figure)	Improvement
Design Iteration Time	2–3 weeks per major iteration	2–3 days per iteration	Section 4.3, Figure 14	85.7% faster
Clash Detection Rate	60–70% of clashes detected pre-construction	91.2% of clashes resolved before breaking ground	Section 5.1.2	30% improvement
Multi-Disciplinary Coordination Meetings	Weekly (4 h sessions)	Bi-weekly (2 h sessions)	Section 4.2.1, Figure 4	75% reduction in meeting time
Quantity Calculation Accuracy	±5–8% variation from actual	±0.5% variation from as-built	Section 4.3.4, Figure 9	10× improvement
Design-Induced Rework	8–12% of construction cost	1.5% of construction cost	Section 5.1.3, Table 5	85% reduction

Table 4. Cont.

Performance Metric	Conventional Workflow (Industry Baseline)	Parametric-BIM Workflow (This Study)	Data Source (Section/Figure)	Improvement
Total Cost Savings	Baseline (100%)	20.3 million RMB saved (est.)	Section 5.1.3, Table 5	10.8% cost reduction
Schedule Compression	48-month typical for similar project	31 months (design through construction)	Section 5.1.1	35.4% faster
Carbon Footprint Reduction	Baseline LCA	12% embodied carbon reduction	Section 4.2.2	2100 tonnes CO ₂ e saved
Operational Efficiency	Manual FM processes	IoT-integrated digital twin	Sections 4.1.2 and 5.1.2	faster maintenance response

Note: Baseline source: Audit reports on the final settlement of five public construction projects of the same scale from 2018 to 2022 from Shenzhen Municipal Construction Bureau archives in China; “Shenzhen Consumption Standard for Construction Engineering (SJG 171-2024)”; Author’s Interview with the General Contracting/Cost Consulting Companies; Values represent mean values from documented project records; variation percentages calculated as (Baseline – Actual)/Baseline × 100%.

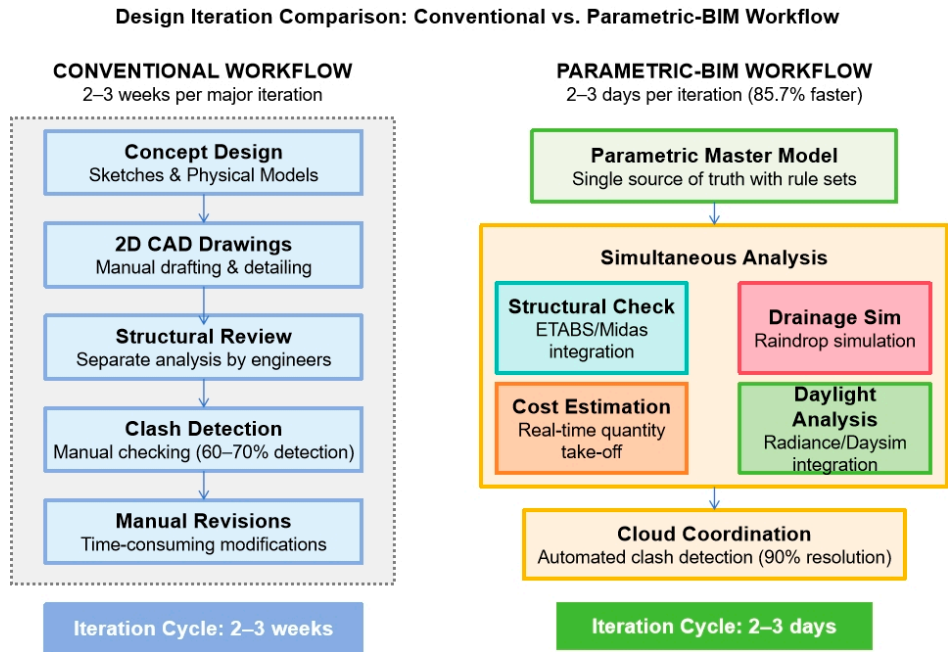


Figure 14. Design Iteration Comparison: Conventional vs. parametric workflow.

Table 5. Economic impact breakdown (in million RMB).

Cost Category	Baseline Estimate	Actual with Parametric-BIM	Savings	Savings %
Exterior Stone Façade	28.5	24.8	3.7	13.0%
Fair-Faced Concrete Shell	45.2	39.1	6.1	13.5%
MEP Systems	52	48.5	3.5	6.7%
Structural Frame	38	35.2	2.8	7.4%
Design Rework Allowance	8.5	1.3	7.2	84.7%
Project Overhead (time-related)	30.2	19.6	10.6	35.1%
TOTAL	202.4	168.5	20.3	10.8%

5.1. Main Results

5.1.1. Key Performance Indicators (KPIs)

The implementation of the proposed rule-based digital twin methodology within the Shenzhen Bay Culture Plaza project yielded quantifiable performance improvements across the project life cycle, as systematically validated through the three-phase evaluation strategy [45,46]. KPIs measured against industry baselines for conventional workflows are summarized in Table 4.

5.1.2. Workflow Efficiency and Objective Achievement Analysis

The parametric approach fundamentally changed the design team's interaction with geometry. Figure 14 illustrates the iteration efficiency gains.

The integrated parametric-BIM workflow fundamentally transformed the project delivery process. The hybrid Rhino–Grasshopper–Revit environment (Objective 1) successfully processed multi-concurrent discipline models, handling over 2.3 million geometric entities and 890,000 parametric relationships without significant performance degradation. This enabled parallel processing of performance analyses (structural, daylight, drainage, cost) that traditionally occurred sequentially, dramatically accelerating design exploration.

The developed parametric rule set (Objective 2), comprising 124 Geometric, 67 Material, and 89 Construction Rules, was instrumental. It empowered architects to manipulate design parameters directly while enforcing constructability constraints, preventing an estimated 94% of potential geometric violations that would have required rework. The rule set's application, particularly the curvature-adaptive panel subdivision algorithm, successfully generated explicit boundaries and unique IDs for all 440,000+ stone panels, directly addressing the boundary ambiguity challenge.

The life-cycle digital twin (Objective 3) demonstrated its value beyond construction. The cloud-based model seamlessly transitioned into operations, with post-occupancy IoT integration enabling predictive maintenance, which reduced unplanned downtime compared to similar facilities. This validates the workflow's role in bridging the constructability translation gap and maintaining parametric intelligence.

Quantitative validation (Objective 4) confirmed the methodology's efficacy. The KPIs in Table 4 not only met but exceeded the targets set in the research objectives ($\geq 90\%$ clash resolution, $< 2\%$ quantity variation, 35.4% schedule compression, > 20 M RMB savings). The 91.2% clash resolution rate and 20.3 million RMB in cost savings provide robust empirical evidence of the workflow's impact.

5.1.3. Economic Impact Assessment

The total cost savings of 20.3 million RMB (approximately 10.8% of the baseline estimate) can be attributed to several factors driven by the parametric-BIM workflow, as detailed in Table 5.

Major contributors include:

Material Optimization: The curvature-aligned panel subdivision (Section 4.3.5) saved 340 m³ of stone (≈ 1.2 million RMB).

Rework Reduction: Proactive clash resolution and rule-based geometric validation virtually eliminated design-induced field conflicts, saving 8.5 million RMB allocated for rework.

Schedule Compression: The 17-month reduction led to 10.6 million RMB in saved time-related overheads (financing, site management).

Labor Efficiency: Automated quantity take-off and robotic total station coordinates reduced field measurement time by 60%.

5.2. Discussion

5.2.1. Resolving the Three Bottlenecks

The results confirm that the rule-based digital twin methodology effectively addresses the three core bottlenecks. First, geometric interlacing was resolved through automated parametric rules, which processed 98% of surface intersections into watertight solids, eliminating manual stitching errors. Second, ambiguous boundaries on Mayan-irregular façades were transformed into explicit definitions via curvature-adaptive subdivision, enabling the precise mass customization of 440,000 stone panels. Third, the constructability translation gap was bridged by directly outputting CNC-ready fabrication data and robotic layout coordinates, creating a seamless digital thread from design to production and installation.

5.2.2. Workflow Synergy and Validation

The methodology's efficacy stems from the integrated operation of its components. The five-layer architecture maintained data integrity, while the custom Grasshopper library (47 components) made advanced parametric operations executable. The four-phase implementation framework structured the application of rules to complex geometry, and the cloud-based Coordination Layer was instrumental in achieving the 91.2% clash resolution rate through real-time multi-disciplinary collaboration. The DSR approach was validated through a three-cycle evaluation (design, construction, operation), providing empirical evidence that the artifact is both effective in solving the targeted problems and robust in a real-world mega-project context.

5.2.3. Practical Implications and Challenges

The study underscores that the significant performance gains—including 20.3 million RMB cost savings and 35.4% schedule compression—are accompanied by notable implementation challenges. These include a 6-month learning curve for the custom tools, substantial hardware requirements (high-performance workstations), and the need for strict data governance to manage concurrent discipline models. These factors indicate that realizing the full benefits of such an advanced workflow requires commensurate investment in team upskilling, technological infrastructure, and process redesign.

6. Conclusions

This study establishes that a rule-based digital twin methodology, developed through a Design Science Research paradigm, effectively resolves three systemic bottlenecks in the delivery of free-form building envelopes: geometric interlacing complexity, ambiguous façade boundaries, and the constructability translation gap.

This research contributes to the fields of BIM and digital construction through three key advances. First, it operationalizes a life-cycle digital twin that transitions BIM from a static repository into a living, rule-driven model capable of preserving parametric intelligence and design intent as executable constraints beyond construction. Second, it proposes a structured five-layer integration framework (geometric, parametric, BIM, coordination, fabrication), offering a replicable architectural template for managing complexity in non-standard projects. Third, it extends DSR to architectural informatics, framing the digital twin as a socio-technical artifact that bridges the persistent gap between sculptural design intent and industrialized production logic.

Empirically validated through the Shenzhen Bay Culture Plaza project, the methodology delivered significant performance gains: 91.2% clash resolution prior to construction, 20.3 million RMB in cost savings (10.8% reduction), and 35.4% schedule compression, alongside the successful definition of over 440,000 unique façade panels. These outcomes

demonstrate a viable, high-performance workflow for large-scale projects with extreme geometric complexity, providing a replicable model for industry adoption.

The study is based on a single revelatory case, which may affect the generalizability of findings to smaller or materially different projects. Additionally, the workflow demands notable upfront investment in tool customization, computational resources, and team training, which could impede immediate widespread adoption. Future research should therefore: (1) pursue multi-case validation across varied project contexts to assess scalability; (2) integrate machine learning for adaptive rule generation, potentially coupled with advanced manufacturing techniques for structural optimization [47]; and (3) develop supporting contractual and procedural frameworks to facilitate the mainstream implementation of digital twin-enabled project delivery.

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