# From Algorithmic Intent to Accountable Assembly: A Computational Delivery Framework for Digital Architecture

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**Abstract.** Parametric design has transformed architectural authorship from form-making to the orchestration of generative systems governed by performance, structure, and spatial logic. Yet its cultural promise often stalls at the threshold of fabrication and building delivery, where institutional, material, and lifecycle demands remain unresolved. This paper proposes a process-based framework—the Computational Delivery Framework (CDF)—to trace how design intent is encoded, materialized, and validated across the full arc of digital architecture. We first analyze three modes of intent encoding: form-finding strategies, multi-objective optimization, and human–computer co-agency. We then examine how subtractive, additive, and robotic-hybrid fabrication workflows negotiate this intent under real-world constraints of assembly, tolerance, and material behavior. Finally, we address the institutional and technical barriers that limit translation into building-scale delivery, and explore façade and roof systems as performance testbeds where architectural ideas confront regulation, durability, and operational viability. The contribution is a three-phase delivery model that clarifies the tensions between design freedom, fabrication logic, and institutional accountability. We conclude with an agenda for evidence-based digital architecture—where generative complexity is evaluated not by novelty alone, but by its capacity to produce certifiable, maintainable, and insurable systems.

## 1 Introduction

Parametric design has redefined architectural authorship, shifting focus from the composition of discrete forms to the orchestration of generative systems governed by structural, environmental, and spatial criteria[1]. Over the past two decades, this evolution has enabled architects to move beyond intuition-based decisions, embedding optimization, simulation, and algorithmic negotiation into the design process[2].

Yet despite its computational sophistication, a systemic gap persists between design exploration and architectural delivery. Generative workflows often stall at the boundaries of fabrication, certification, and lifecycle operation—where institutions, materials, and performance standards constrain what architecture can actually become[3-5]. Much of the literature privileges formal novelty or technical ingenuity, while offering limited insight into how digitally authored systems survive contact with regulation, insurance, or durability over time.

To address this, the paper introduces the Computational Delivery Framework (CDF)—a three-phase model that maps how design intent is encoded, materialized, and validated across architectural scales. This framework constitutes the paper's central methodological contribution, offering a structured approach for tracing the survival of computational form from simulation to real-world accountability.

We begin by analyzing how computational authorship encodes design intent across form-finding, optimization, and co-agency (Section 2). Section 3 examines how subtractive, additive, and robotic-hybrid workflows materialize those intentions through fabrication. Section 4 traces how such systems are tested—first against systemic barriers (4.1), then through façade and roof prototypes that enact performance accountability (4.2). Section 5 synthesizes and extends this trajectory toward a practice of validated digital architecture.

## 2 Parametric Design Logics

Parametric design has redefined architectural practice by shifting emphasis from the invention of discrete forms to the orchestration of rule-based generative systems. This section analyzes how computational authorship encodes design intent across three interrelated trajectories—form-finding strategies, multi-objective optimization, and human–computer co-agency. These trajectories constitute the first phase of the Computational Delivery Framework (CDF), where design intelligence is formalized before it encounters material and institutional constraints.

First, generative and form-finding logics extend the analogue experiments of Otto and Isler into digital environments, treating form not as a preconception but as the emergent outcome of material and structural

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interaction. This approach repositions the designer as a calibrator of forces, geometries, and rules, initiating a shift from composition to orchestration.

Second, multi-objective optimization embeds environmental, structural, and spatial performance criteria directly into algorithmic workflows. Through evolutionary solvers and performance simulation, conflicting goals are negotiated to produce Pareto-optimal design sets—exposing latent trade-offs and expanding the space of informed decisions[2].

Third, human–computer co-agency reframes authorship itself. Here, the designer engages computational systems not only to generate, but to curate: selecting among algorithmic proposals, adjusting priorities, and incorporating qualitative criteria otherwise excluded by formalized optimization. This mode reclaims architectural judgment within increasingly automated workflows[6].

Together, these three modes outline a shift in design epistemology—from intuition-driven composition to system-guided negotiation and curatorial agency. The following section explores how this encoded intent confronts physical constraints in fabrication, where geometric freedom, constructability, and material anisotropy are tested in full-scale realization.

## 2.1 Generative and Form-Finding Strategies

Generative and form-finding strategies constitute the foundational layer of computational authorship within the Computational Delivery Framework (CDF)—the phase where design intent is first encoded as a system of geometric and structural logics. These approaches mark an epistemological departure from prescriptive "form-making," reframing architecture as the orchestration of self-organizing systems rather than top-down composition.

This shift traces back to the analogue experiments of pioneers such as Frei Otto and Heinz Isler, who modeled structural efficiency using material media—hanging chains, soap films, and thin shells—as analogue computers. These systems optimized for force flow under gravity, typically in pursuit of minimal surfaces or pure compression geometries[7].

Digital environments extended these principles beyond the constraints of physical modeling. Tools like Kangaroo enabled real-time sculpting with force fields, while agent-based modeling and computational morphogenesis supported emergent forms based on local interaction rules[8]. In these systems, fabrication constraints and material properties increasingly act as generative drivers, embedding tectonic logics directly into the morphogenetic process[9].

This transition reframes the designer's role—from a "form-giver" to a "system-designer"—but introduces a new dilemma: when systems yield an abundance of formal possibilities, how are decisions made? The need to embed and negotiate multiple, often conflicting, performance criteria within generative logic leads directly to the next phase of computational authorship: multi-objective optimization[10].

## 2.2 Multi-Objective Optimization and Performance Integration

As generative systems produce increasingly complex geometries, the challenge shifts to evaluating those forms against competing goals. Multi-Objective Optimization (MOO) addresses this need by embedding performance negotiation directly into the design process[10]. Within the Computational Delivery Framework (CDF), this phase marks the intensification of design intent—where objectives are formalized, prioritized, and computationally balanced.

Unlike single-objective methods, MOO employs Evolutionary Algorithms (EAs) to generate Pareto-optimal solutions, revealing trade-offs among spatial quality, environmental performance, and structural feasibility. These approaches range from early genetic algorithms for façade articulation to dedicated solver plug-ins like Octopus and Wallacei in Grasshopper[11]. Simulation-Based Optimization (SBO) offers tighter integration of performance metrics but at high computational cost[12]. Topology Optimization, meanwhile, pushes structural efficiency but raises questions about constructability and manufacturability[13].

Projects such as the BUGA Wood Pavilion and the HiLo Solar Facade illustrate successful integration, balancing energy use, material efficiency, and actuation logic[14]. Yet these examples also expose persistent gaps: most MOO applications are project-specific and lack generalizability; simulations struggle to capture non-linear material behavior; and physical validation of digital predictions remains limited.

Beyond technical limitations, MOO raises deeper epistemological questions. Optimization routines often encode assumptions as neutral logics, masking cultural or institutional biases[6]. More critically, they struggle to account for qualitative values—atmosphere, ritual, meaning—resistant to numerical formulation. This tension reframes the role of the architect: if algorithms navigate the quantitative, who curates the qualitative? That negotiation defines the next phase of computational authorship—human–computer co-agency.

## 2.3 Human – Computer Collaboration in Architectural Design

The final mode of design intent encoding within the Computational Delivery Framework (CDF) is human–computer co-agency, which addresses the qualitative limitations of optimization frameworks. Here, design is reframed not as a deterministic output of algorithms, but as an interactive negotiation between computational processes and architectural judgment[6].

This negotiation manifests along a continuum between two paradigms. In the augmentation model, the computer acts as a decision-support system, extending human cognition without displacing authorship[15]. Tools such as real-time physics simulators allow designers to intuitively shape force-driven geometries while preserving agency[8]. In contrast, the co-creation model positions the computer as an active collaborator. Through methods like

Interactive Evolutionary Algorithms, expansive design spaces are algorithmically generated, with architects serving as curators who steer the system by selecting, weighting, and redirecting outputs.

Both models offer creative leverage but also introduce tensions. Over-reliance on automation risks deskilling, stylistic convergence, and the erosion of embodied expertise. To counter this, emerging practices integrate inverse workflows—such as physical prototyping and digital twin validation—to align simulated outputs with real-world performance metrics.

Human–computer collaboration thus becomes both operational and epistemological: it redistributes authorship, challenges conventional notions of expertise, and produces design not as a fixed object but as a modifiable process model embedded with material and performance logic[10]. Yet this model remains provisional until it is tested through fabrication. The next section explores how subtractive, additive, and robotic hybrid workflows enact—or compromise—computational intent at full scale, where questions of tolerance, anisotropy, and joinery transform algorithms into architecture.

## 3 Digital and Robotic Fabrication Workflows

Within the Computational Delivery Framework (CDF), digital and robotic fabrication workflows represent the phase where encoded design intent encounters the constraints of materialization. This section examines how computational models are enacted—negotiated, adapted, or compromised—through subtractive, additive, and robotic-hybrid processes.

These workflows form the operative core of the file-to-factory paradigm, not only producing architectural geometries but also translating them into tectonic assemblies, structural systems, and performative surfaces[16]. Subtractive CNC machining, additive manufacturing (AM), and robotically choreographed forming or assembly each articulate a distinct logic of making, with corresponding capacities and limitations.

Together, these methods reveal the friction points between geometric ambition and physical execution—highlighting issues of tool access, tolerance budgets, deposition anisotropy, and material behavior[17]. When scaled to architectural applications, they expose how design excellence becomes inseparable from fabrication intelligence, and how "optimal form" must be redefined through the lens of constructability, economy, and institutional viability[5].

### 3.1 CNC-based and Subtractive Processes

Subtractive manufacturing (SM), most commonly implemented through Computer Numerical Control (CNC) technologies, represents the foundational material logic of digital fabrication. Within the Computational Delivery Framework (CDF), SM embodies a form of "intent erosion"—where geometry is realized through removal, and design intelligence must negotiate the limitations of tool access, waste, and tolerance stacking.

CNC-based 2D and 2.5D workflows, such as laser cutting and 3-axis routing of plywood, CLT, or sheet metal, shift authorship toward the assembly phase, where joint articulation becomes both structural mechanism and architectural expression. Timber plate constructions like the BUGA Pavilion exemplify how algorithmic nesting and CNC notching elevate the joint from fabrication constraint to compositional element[10].

Multi-axis CNC milling extends SM to volumetric stock, enabling the production of bespoke, doubly curved components with tight tolerances. Examples include the Urbach Tower and digital stereotomy research[18], while robotic hot-wire cutting of EPS foam has become prevalent for formwork fabrication in complex concrete casting. Across these applications, tectonic identity emerges directly from the logic of removal.

Yet the subtractive paradigm carries systemic limitations. Material blanks are often carved down with significant waste, particularly in one-off or disposable formwork contexts[19]. Even with co-design and nesting strategies, shaping by removal cannot overcome essential constraints: limited tool access, lack of internal geometry, and inefficiency at large scale. These limitations point toward additive manufacturing, which inverts the process by depositing rather than removing—reshaping not only form, but the very premise of material economy and fabrication logic.

### 3.2 Additive Manufacturing and 3D Printing

Additive manufacturing (AM), or 3D printing, offers an inverse logic to subtractive workflows by constructing rather than carving—materializing design intent through controlled deposition. Within the Computational Delivery Framework (CDF), AM represents a shift from "intent erosion" to "intent accumulation"—where the design is not revealed by carving away excess, but progressively built through additive placement. This distinction reframes materialization as the accumulation of intention, not its reduction.

Layer-by-layer fabrication—often termed "layered materiality"—eliminates the need for formwork and repositions the designer as a choreographer of deposition paths. At the component scale, polymer and powder-based techniques such as FDM, SLS, and binder jetting enable the production of lightweight, topology-optimized elements—facade panels, structural nodes, or high-performance connectors—unattainable via CNC milling. At the building scale, extrusion-based methods like 3D concrete printing and Wire Arc Additive Manufacturing (WAAM) pursue monolithic walls and shells with embedded thermal and structural logic[20].

However, these formal freedoms are counterbalanced by systemic limitations. Layered deposition introduces anisotropy—strength varies across axes—compromising structural performance[17]. Scalability remains constrained by slow print speeds, dimensional accuracy, and post-processing demands. Claims of sustainability are likewise complicated by high energy use and feedstock preparation; while recycled aggregates and bio-based geopolymers are

under development, codified standards and certification pathways remain nascent.

AM undoubtedly expands architectural agency by linking generative geometry with fabrication precision. Yet its partial maturation and unresolved material liabilities signal the need for hybrid workflows—systems that combine additive freedom with subtractive control and robotic assembly. These integrated processes form the next stage of negotiation between digital design and buildable matter.

### 3.3 Robotic Forming, Assembly, and Hybrid Workflows

Robotic fabrication extends digital construction beyond the paradigms of removal and deposition, foregrounding forming, assembly, and hybridization as material logics in their own right. Within the Computational Delivery Framework (CDF), these approaches represent a choreography of design intent—where spatial form, structural behavior, and tectonic expression are shaped by the interaction between machine, material, and process.

Robotic forming treats material behavior as a generative force. By manipulating elasticity, bending capacity, or hygroscopic response, designers can induce curvature or deformation without subtractive waste. Through custom end-effector tooling, robotic steam bending and self-shaping composites enable complex geometries to emerge from calibrated physical feedback. Bending-active timber structures and hygroscopic laminae exemplify this approach, where geometry is not drawn but grown from force-responsiveness.

Robotic assembly shifts focus to the placement and joining of discrete elements with sub-millimeter accuracy. Workflows here enable mass-customized joints, intelligent aggregation, and multi-component logic, as seen in the BUGA Pavilion, livMatS Shell, and Sequential Roof. Robotic arms operate not merely as automated tools but as instruments of craft: embedding material know-how into machine choreography.

Hybrid workflows seek to integrate the strengths of additive and subtractive methods. Examples include the use of 3D-printed mineral foams refined through CNC milling to create lightweight, stay-in-place formwork[19], and timber cassette fabrication combining adhesive deposition with robotic precision routing. These processes mitigate the waste of pure subtraction and the anisotropy of pure addition, enabling performance-tuned, multi-material assemblies.

Taken together, these robotic modalities mark a shift toward process-informed tectonics—where form is neither imposed nor optimized in isolation, but emerges from the interplay of fabrication logic, material capacity, and design intention. Yet despite their sophistication, such workflows remain largely confined to lab-scale or pavilion contexts. Their systemic translation into architectural delivery continues to face barriers of regulation, certification, scalability, and institutional readiness—a set of challenges examined in the following section.

## 4 Validating Design Intent: From Systemic Barriers to Performance Testbeds

The translation of computational design intent into architectural delivery does not end with material realization. It must ultimately pass through layers of validation—technical, institutional, and operational—that determine whether a system can be certified, insured, and sustained over time[21].

Within the Computational Delivery Framework (CDF), this final phase interrogates how digitally authored systems confront the realities of architectural practice: codes, costs, labor, durability, and public trust.

This section is structured in two parts. Section 4.1 identifies the systemic barriers—economic, regulatory, cultural—that obstruct the scaling of digital fabrication from prototype to building. Section 4.2 responds by analyzing building envelopes—especially façades and roofs—as uniquely demanding testbeds, where simulation becomes operation and design intelligence must prove its performance in measurable, certifiable terms.

Together, these two layers form the "validation loop" of digital architecture—where generative freedom is reconciled with institutional accountability, and where innovation is judged not only by what it can imagine, but by what it can endure.

### 4.1 Systemic Barriers to Architectural Delivery

Despite growing sophistication in digital fabrication, the systemic translation of computational design into architectural delivery remains obstructed—not by technical immaturity alone, but by the institutional, economic, and cultural infrastructures in which architecture is realized[22]. Within the Computational Delivery Framework (CDF), this section maps the bottlenecks that emerge when encoded and choreographed design intent attempts to cross into the domain of warrantable, large-scale building production.

Economic and logistical barriers persist as primary obstacles. High capital costs, fragmented supply chains for non-standard components, and the difficulty of deploying robotics on active construction sites undermine scalability and cost competitiveness. These constraints prevent digital fabrication from achieving the robustness and replicability expected of conventional construction systems.

Technical fragilities further limit scalability. While simulations and digital twins promise predictive control, they often fail to capture material non-linearity, performance drift, or assembly tolerances at full scale. Structural reliability, long-term durability, and multi-material integration remain under-validated, weakening trust in performance claims.

Institutional inertia compounds these issues. In the absence of established building codes, certification pathways, and long-term data, novel systems struggle to secure insurance, liability coverage, or permitting[4]. Without mechanisms of institutional validation, even

high-performing prototypes remain confined to one-off approvals and cannot mature into warrantable structures.

Labor and cultural gaps intensify these frictions. The growing divide between computational designers and construction trades creates resistance to integration. Limited reskilling programs, deskilling anxieties, and professional inertia slow the adoption of digitally-driven workflows, even when technical capacity is present[22].

Together, these interlocking barriers reveal that the primary challenge in scaling digital architecture is not design ingenuity, but the absence of a socio-technical delivery infrastructure. Digital fabrication must be understood not only as a material process, but as a regulated, insured, and inhabited institution—one shaped as much by codes, labor, and policy as by tools and algorithms[4].

### 4.2 Envelope Systems as Testbeds of Accountability

Building envelopes—particularly façades and roofs—offer a uniquely rigorous testbed for translating digital design into accountable building performance. As highly visible, regulation-bound, and climate-exposed systems, they sit at the convergence of design intention, fabrication complexity, and institutional constraint. Within the Computational Delivery Framework (CDF), envelopes constitute the most consequential scale for validating design intent under long-term technical, regulatory, and operational demands.

Adaptive façades exemplify the shift from simulation to operation. The Adaptive Solar Façade (ASF) on the HiLo building converts environmental optimization into kinetic performance through photovoltaic tracking panels[14]. Metrics such as Daylight Autonomy (DA) and Energy Use Intensity (EUI) offer evidence of success, yet persistent gaps remain in actuation reliability, maintenance strategies, and certification pathways[14]. Similarly, the Media-TIC building in Barcelona integrates ETFE cushions with structural optimization, balancing daylight and insulation—while still facing regulatory lag and market hesitation[23]. Advancing Technology Readiness Levels (TRLs) demands rigorous multi-scalar testing, from FEM-based simulation to full-scale load validation and integration with digital twins for long-term monitoring[24].

Roof and shell systems extend this accountability framework. Projects like the livMatS Biomimetic Shell and the HiLo Roof show that computationally optimized, robotically fabricated systems can achieve both code compliance and energy efficiency[21]. Yet these achievements also expose bottlenecks: high fabrication costs, embodied energy intensity, and specialized labor demands all complicate real-world adoption and lifecycle viability[22].

Across these cases, the building envelope emerges not as a passive separator but as an active interface—responsive to environment, embedded with intelligence, and legible to regulatory oversight. These systems reframe architectural agency around stewardship: of performance, durability, and institutional credibility. In doing so, they demonstrate how computational methods can evolve from formal exploration into validated architectural practice.

## 5 Discussion and Conclusion: Toward a Validated Practice of Digital Architecture

This paper has traced the trajectory of computational architecture through three successive phases: encoding, materializing, and validating design intent. Through the lens of the Computational Delivery Framework (CDF)—introduced herein as the paper's central methodological contribution—we have shown how design intelligence is reshaped at each stage: first by performance objectives, then by fabrication constraints, and finally by institutional standards of credibility.

### 5.1 Emerging Tensions in Computational Practice

Three systemic tensions emerge across this continuum:

(1) Geometric freedom vs fabrication feasibility

While parametric design enables complex formal articulation, its translation into subtractive, additive, or robotic processes reveals persistent conflicts around tolerance, tool access, and material behavior. What is optimized digitally may be infeasible physically[8].

(2) Speculative prototypes vs warrantable delivery

Prototypical works have accelerated innovation, but remain institutionally isolated. Envelope systems—subject to weathering, regulation, and operational cycles—demand higher levels of accountability, from certification to insurability[21].

(3) Simulation optimism vs institutional accountability

Digital twins and simulation models promise performance foresight, but lack integration into regulatory regimes. Without accepted standards of validation, feedback remains fragmented and unenforceable, creating a gap between perceived and warrantable performance.

These tensions underscore the need to reframe computational architecture as a recursive, testable, and institutionally situated practice—not merely expressive, but insurable, certifiable, and maintainable over time.

### 5.2 Contextualizing the CDF within Current Research

Recent advances in computational design have established integrative digital-to-fabrication workflows that optimize structural and environmental performance[5]. Seminal works on segmented timber structures and bio-based composites[4, 25] demonstrate sophisticated synthesis between geometry, material behavior, and robotic fabrication, while adaptive envelope studies further refine performance through parametric optimization for energy and daylight efficiency[15]. These approaches, however, remain largely focused on internal technical validation within controlled fabrication settings[26].

Building upon this foundation, the proposed Computational Delivery Framework (CDF) extends beyond performance optimization to formalize a third, often overlooked phase—Validating Intent. This phase

integrates institutional accountability, certification, and insurability as quantifiable components of the digital workflow, addressing the administrative and legal bottlenecks that hinder the scalable implementation of advanced architectural systems[27]. In doing so, the CDF bridges technical innovation with the regulatory and procedural mechanisms necessary for accountable architectural realization.

Three contributions emerge from this study:

(1) A full-cycle delivery model that connects generative authorship with fabrication logic and validation mechanisms;

(2) A framing of envelope systems as strategic testbeds, where digital architecture must prove itself across TRL, performance, and regulatory criteria;

(3) A future-facing agenda for performance-accountable innovation.

In this context, "accountability" refers not only to measurable performance, but to a system's ability to be certified, insured, and maintained across its lifecycle. It represents a convergence of technical reliability and institutional legitimacy.

### 5.3 Outlook and Conclusion

Future research should extend this agenda by:

• Embedding insurability into generative workflows—aligning design exploration with institutional risk modeling;

• Operationalizing digital twins for regulatory negotiation—enabling adaptive compliance and evidence-based permitting;

• Scaling hybrid validation across simulation, prototyping, and post-occupancy data—creating a closed-loop system of architectural credibility[22].

The Computational Delivery Framework (CDF) proposed herein offers a structured pathway for navigating these tensions. Ultimately, the task is no longer just to generate form—but to ensure its survival across matter, institution, and time.

## Acknowledgement

This work is supported by Hunan Provincial Natural Science Foundation of China (2023JJ40146), Hunan Provincial Social Science Achievement Review Committee (XSP2023YSZ003), Macao Foundation (MF2402)

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