Fast Geometry Optimizations for Architectural Workflows

A Case Study on the Computational Geometry of High-Rises

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1

1 The façade articulation of the examined case study - Al Sa'ad Plaza Towers in Lusail, Qatar.

ABSTRACT

Streamlined geometry optimization processes are crucial for maintaining the integrity and feasibility of geometrically complex forms. These geometries, in addition to the aesthetic goals of the designers, must also adhere to the reality of fabrication, material properties, and statutory constraints. Traditional purely cost-reducing optimizations, or methods borrowed from other domains, such as computer graphics, can deviate from the original design intent and have reduced efficiency when used in architecture. It is therefore essential to strike a balance between optimization and the desired aesthetics for architectural solutions. Integrating these strategies late in the design process, as post-rationalizations, often leads to time-consuming and expensive revisions, that once again compromise the viability of the designs. This can be prevented by seamlessly integrating said optimizations into the design cycles, ensuring the constant delivery of project iterations, hence being fast, efficient, and reliable, coupling performance with design intention. This paper presents an integrated process for fast computational geometry optimizations within architectural workflows, enhancing design fidelity and minimizing dependencies on time-consuming and isolated post-rationalization efforts. By choosing a challenging, doubly curved façade high-rise as a case study, we aim to demonstrate how simplifying multi-objective problems can expedite optimization processes that are specific to architectural design. We advocate that the adoption of pre-initialized geometrical configurations, fast iterative searches, force-driven optimizations, and analytical geometry approximations, can, when paired with modular parametric models and interoperable data, streamline the design process, and allow for quick, yet informed decision making.

INTRODUCTION

While delivery timelines for large-scale architectural projects become shorter, the level of geometric complexity of the architectural form, increases. This complexity presents significant challenges across every phase of a project, from the initial concept to construction documentation and fabrication. The recent adoption of computational design came to address these form-finding problems. In the field of Architecture, Engineering, and Construction (AEC), geometry optimizations do not only satisfy the designer's aesthetic vision, but also comply with fabrication limitations, material characteristics, and legislation constraints. Therefore, unlike in the realm of Computer Graphics (CS), where said optimizations predominantly aim at reducing computational complexity and compute cost, optimizations used in architecture must be carefully planned and implemented. Errors or inaccuracies in optimizing the architectural form can have severe repercussions. Once a design is constructed, there is minimal or no scope for adjustments, and attempting corrections can lead to extreme cost implications. Typically, geometry rationalization is regarded as a secondary step in the design process, and often contradicts initial design intentions due to the lack of immediate feedback. Additional to these challenges, optimization in design is intrinsically multi-objective, and often involves reconciling competing goals. This means that any stochastic or brute force solutions employed tend to be slow, running asynchronously, or necessitate special setups with manual user interaction for the acceptance of results, as in the case of Genetic Algorithms (GAs). When said optimizations are adopted in the design cycles, they frequently rely on specialists or heavy computational resources, causing delays and inefficiencies to the fast-paced design environment. Timing - when to incorporate optimization workflows into the design process - is critical as late engagement can disrupt the projects timeline and delay feedback. This ultimately results in a waste of resources on proposals that are not viable, only to later undergo Value Engineering (VE) post-rationalization during construction, at the expense of the original architectural vision.

In this paper, we argue that the adoption of rapid and precise computational geometry optimization processes, coupled with robust data exchange infrastructure, into existing parametric models, can streamline the architectural design process. Our hypothesis suggests that implementing this approach can enhance control over the design outcome, reduce error, and facilitate systematic exploration of the design space. We argue that injecting fast analytical optimizations throughout the form-finding process, as well as identifying and replacing any slow parts, can later reduce rationalization exercises, maintaining the integrity of design decisions. This approach allows for the efficient evaluation of alternatives, balancing performance, constructibility, cost, and material considerations.

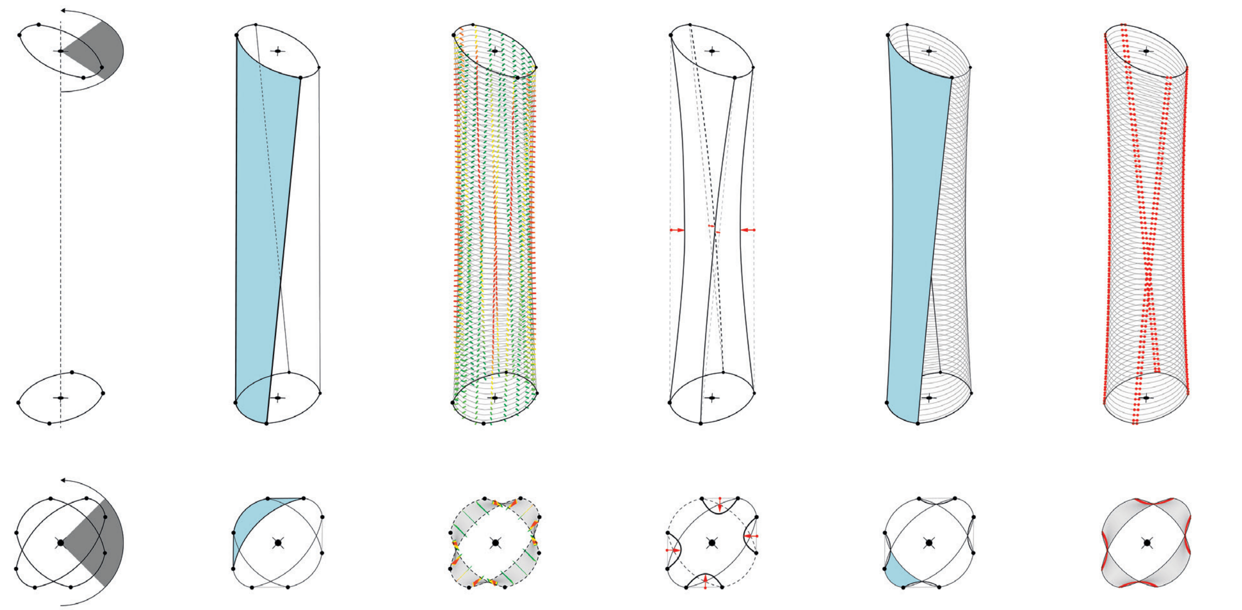
To support our hypothesis, we will delve into a case study on the Al Sa'ad Plaza Towers, focusing on the development of its doubly curved façade. We document a step-by-step breakdown of the methodology for testing existing optimization techniques and substituting them with faster and simpler alternatives. While going through a series of techniques implemented, we argue that utilizing a lightweight yet robust method for transferring design data is essential for the success of our process. This exchange of design data also allows for Unit Testing (UT) the generated geometrical design, while ensuring compliance with the aforementioned constraints, achieved by utilizing Hermes, our proprietary interoperability tool. We assess our system against established geometry optimization literature within the scope of the AEC, to gauge performance, user interaction, and visual fidelity. Insights and challenges from implementing this approach are discussed, offering a perspective on the value of such optimizations, and elaborating on future research.

RELATED WORK

Existing literature covers the optimization of complex geometric forms extensively but tends to overlook the importance of speed and the timing of integration, which are essential for uninterrupted design delivery. While parametric modeling has become widely accepted for design exploration, seamlessly incorporating optimization strategies is challenging.

Geometry Optimization Methods for Building Envelopes

Optimizing architectural designs early on is crucial, as recognized by Andrade (Andrade et al. 2017), while State-of-the-Art (SOTA) literature generalizes optimizations and reduces the problem to the mathematical clarity of the initial Architectural Surface (AS) (Eigensatz et al. 2010a) or simplifies the discretization to mesh parallels (Pottmann et al. 2007). However, they often miss out on other design objectives such as operational energy efficiency - a key consideration in our case study. Additionally, while quadrilateral panels, are typically preferred over triangular approaches for efficiency and visual clarity (Glymph et al. 2002), design requirements may necessitate more elaborate shapes like the skewed parallelogram panes in our scenario. Merely reducing the diversity of panel types (Fu et al. 2010) does not always guarantee cost savings, nor an accurate representation of the AS, with Computer Numerically Controlled (CNC) manufacturing technologies offering cost-effective alternatives of less standardization, especially for planar glass. Resolving doubly curved



2

façades is a complex yet popular engineering challenge. Our case study engages in fabrication-aware design, trying to minimize the system's overall energy similar to other strategies (Tellier et al. 2019) (Eigensatz et al. 2010b) on efficient surface fitting.

Design Optimization in Architectural Design

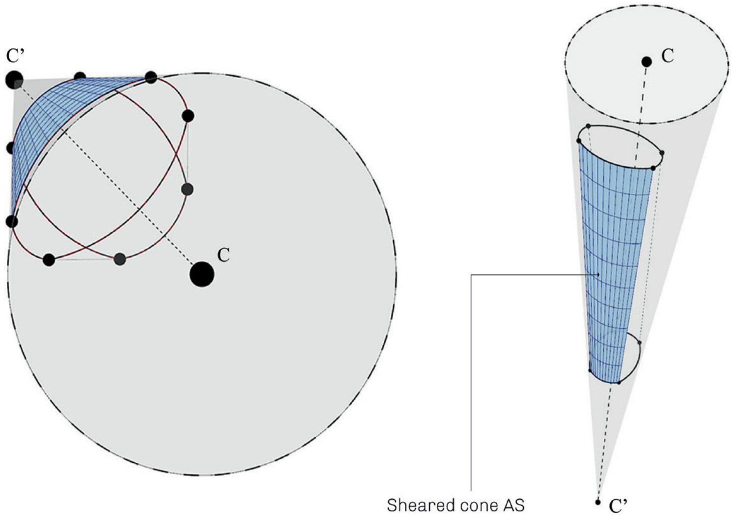
The benefits of design space exploration for the AEC are inherently connected to the adoption of a robust parametric model framework. Combining parametric modeling with optimization methods like Genetic Algorithms (GAs) or Particle Swarm Optimization (PSO) (Kennedy and Eberhart. 1995), which excel at complex, multi-dimensional issues, is widespread practice. Often, architectural design space exploration exercises, are constrained to the optimization of one specific objective, for example the structural engineering of proposed design solutions (Holzer et al. 2002) where a series of analysis results are used to evaluate the architectural form. In other scenarios, GAs are employed to solve contradicting optimization objectives. Aside from structural considerations, these can include other performance driven metrics such as solar insulation (Turrin et al. 2011) in attempting to fine-tune the architectural form. However, these approaches are limited due to the stochastic nature of the initialization process and the high computational costs required to reach viable solutions. Deep Learning (DL) techniques are being employed to expedite the exploration and produce innovative solutions that are learned from data rather than derived from parametric models (Bucher et al. 2023), although training these models remains time-consuming. In our methodology we will aim to free our parametric models from said techniques by adopting more efficient solutions, enhancing the speed of design cycles, ensuring ongoing delivery and reliability of design data via a continuous feedback mechanism (Kosicki et al. 2023).

FAST GEOMETRY OPTIMIZATION WORKFLOWS

Setup Overview

We will explore a series of form-finding and geometry optimization techniques used in the early design phases of the Al Sa'ad Plaza Towers, in Lusail - Figure 1. We select one of the four geometrically identical buildings from the cluster constructed in 2022. A 300-meter tower, that is characterized largely by doubly curved geometry, which smoothly transitions between two distinct 8-arc shapes along two axes of symmetry, and morphologically is classified as a "Merger" in Vollers' high-rise taxonomy (Vollers 2008) as seen in the breakdown of the geometrical operations that led to the final building envelope form in Figure 2. The initial geometry is a series of ruled surfaces between two 4-arc profiles rotated by 90°. Further constructibility constraints dictated describing the geometry with doubly curved surfaces and finally radial fillets were introduced at the surface edges for purely aesthetic reasons. We note two main processes in the documentation of our proposal:

- The form-finding for the overall AS
- Fine-tuning the cladding setting-out



3

2 Step-by-step diagrammatic overview of the primary geometrical operations forming the final AS.

3 Describing the initial AS by fitting sheared cones.

This way, we clarify the distinction between global optimizations that influence subsequent design decisions and more independent ones that deal with the topology of the panelization.

In summary, we are following the principles stated below to abstract the challenges involved, and systematically decompose larger problems into smaller, contained ones, which are computed separately. We attempt to achieve this by:

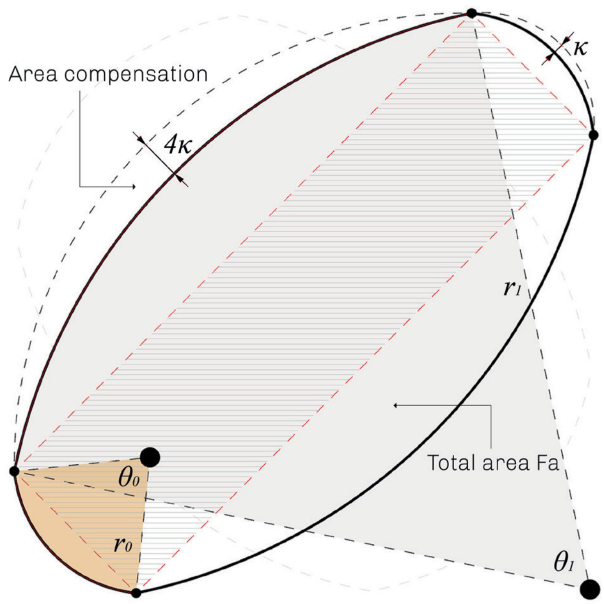
- Simplifying multi-objective optimization problems to lower-order polynomials.
- Employing fast iterative searches instead of stochastic approaches.
- Implementing pre-initialized configurations to speed up convergence.
- Applying a mix of force-driven and analytical optimizations for fast feedback.
- Introducing Unit Testing to identify failures and excess calculations.
- Accommodating data transfer among parametric models to enhance computation speed and support version control.

These methods were incorporated into the parametric models built using Grasshopper3d™ (GH) for Rhinoceros™. We developed most processes via custom C# components or with third-party libraries.

Form-finding the Building Envelope

Pre-initialized Architectural Surfaces: In our attempt to design construction-aware and cost-efficient geometries, we aim for simple AS well-suited for effective panelization strategies. As documented by Eigensatz (Eigensatz et al. 2010a), these include both doubly and single curved AS, such as cylindrical, translational, and rotational surfaces. As mentioned previously, we began the global form-finding with conic surfaces, created by sweeping a line segment across two arcs with different radii as shown in Figure 3. We opted for a floor-plate defined initially by four symmetrical arc segments, yielding sheared conic surfaces upon connecting the envelope's bottom profile to its rotated top boundary.

Simplifying higher-dimensional problems: The "morphed" AS scheme of the tower aligned both the architectural vision and structural performance requirements. The synergy between form and structure materialized through concrete cores and slanted steel columns, joined by outrigger frames for stiffness and strength (Ilgin et al. 2021), maintain both architectural and structural symmetry. The initial arrangement of columns along an idealized ellipse presented the first optimization challenge. Even though the AS generated is still translational, it failed to meet practical space-planning needs, due to the elliptical profile's constantly changing curvature. The solution involved cantilevering parts of the slab only up to a maximum of 1.5m to achieve AS without prohibitive costs. The sheared cone AS resulted in cantilevers more than 1.5m reaching even to 2.35m on occasions. This led to the geometric definition of the optimization, where the straight segments connecting the bottom and top profiles are replaced by arc segments having their mid-points penetrating the initial AS (see Figure 2, third diagram for reference). The new AS is now a double-curved geometry (see Figure 1, fourth diagram). For the algebraic definition, we aimed to preserve the building's total gross area for contractual commitments. After modifying the building's profile to compensate for the loss of area, the challenge was formalized within the minimization formula below, where Ta is the Target Area, Fa is the per floor area,



4

and n the number of floors.

$$\Delta\alpha = Ta - \sum_{i=1}^{n}(Fa(i))$$

with

$$Fa = \left(\frac{\theta_0 \pi r_0}{180}\right) \text{-} 4r_0 \sin\left(\frac{\theta_0}{2}\right) + \left(\frac{\theta_1 \pi r_1}{180}\right) \text{-} 4r_1 \sin\left(\frac{\theta_1}{2}\right) + 4r_0 r_1 \sin(\theta_0)\sin(\theta_1)$$

where Θ_0, Θ_1 are the arc sector angles per level and r_0,r_1 the radii of the arcs. Facing an excess of variables as depicted in Figure 4, we could have ended up using a GA with $4*n$ number of genes, despite the high computation cost and risk of local optima. Instead, we tried to simplify the problem by:

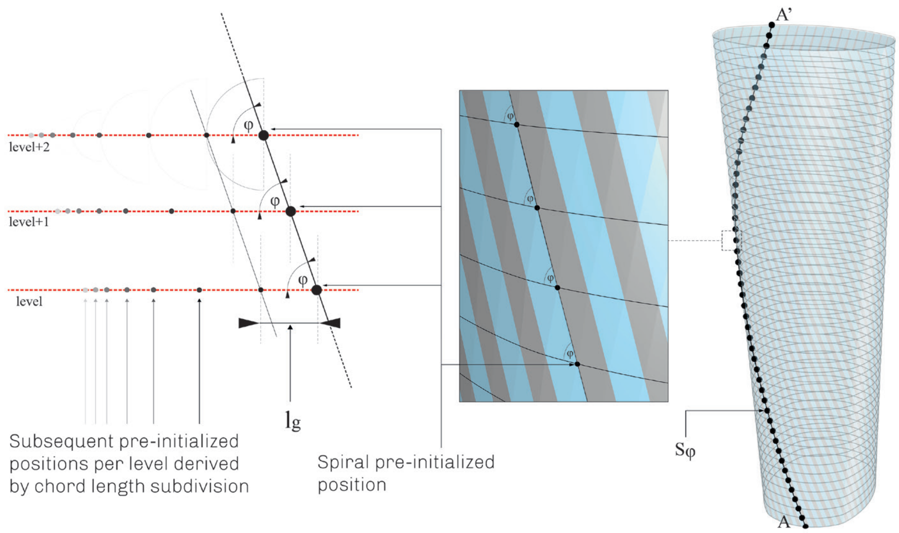
- Increasing only the existing r_0 and r_1 to compensate for area loss.
- Keeping Θ_0 and Θ_1 as constants, an initial condition from the previous step.
- Applying a parabolic distribution adjustment to the radii increments, emphasizing mid-level expansion in response to previous cantilever reduction. Note that top and bottom profile increases are zero.
- Associating the increase of r_0 and r_1 with a constant ratio $\beta=1/4$,see κ and 4κ in Figure 4.

This simplification allowed us to focus on optimizing a single variable κ , the maximum addition to the radii, in two steps. First, an exhaustive search identified the connecting arc segments that eliminate cantilever excess up to 1.5m. Then, we solve for κ applying the parabolic distribution of increases from 0 to κ on each one of the levels.

Employing Computational Geometry Properties: Four additional transitional arc patches were introduced to the creases of our AS, for smoother visual representation (Figure 2, last diagram). Picking an efficient Panelization Method (PM) for the new AS was crucial to meet cost and aesthetic goals. Optimizing the AS for cost involves minimizing the variance between the panels and the original AS surface (Eigensatz et al. 2010b), which can also include classifying panels. Typically, a reduced number of unique panels means lower costs, especially when these are fabricated with molds. However, the challenge with the current form is that each level of the tower has a different perimeter length. Employing quadrilateral panels with an equal count per floor would result in different widths and potential visual inconsistencies (Eigensatz et al. 2010a). To resolve this, we utilized a rapid optimization technique, leveraging the Affine Invariance property of B-spline curves (Wolters 2002) to uniformly scale floor boundaries, thus preserving the area while conforming to predetermined length constraints. However, the distinct visual impact of the optimized form with same perimeter lengths was diverging from the initial design intent. In the end we compromised by limiting the perimeter length discrepancies to a maximum of 2.8m along the tower's height and only 120mm between adjacent floors. This way we maintain the panels' visual continuity without sacrificing the architectural intent.

Façade Panelization Setting Out

Force-Driven vs Analytical Subdivisions: Effectively panelizing the AS required comprehending the properties of 8-Arc floor-plate boundary profiles. Discretizing free-form shapes into arc derivatives is common practice in related work, presenting challenges both in distribution of fitted panels and convergence speed, with a special focus on the optimization's initial state (Bo et al. 2011). Quick convergence relies on the initial subdivision of curved or circular arcs, a point well-documented by Douthe for grid-shells (Douthe et al. 2017) and similarly important in our case, particularly for the high-curvature zones, where even subdivisions yield uneven corresponding interior spaces. Addressing the site's harsh climate conditions, we aimed for upgraded shading benchmarks, cutting down on operational carbon and enhancing occupant comfort, hence fixing the Window-to-Wall Ratio (WWR) around 40/60 = 67%. Furthermore, space-planning considerations mandated identical glass panes in plan-view sizing. Therefore, the lower edge length of each quadrilateral panel remained the same tower-wide, with shading panels adapting ad-hoc to a new equal length per level, succeeding the previous optimization of perimeter lengths. Assuming the use of flat panels simplifies the problem by creating a polyline with equal numbers of glass and shading panels. With glass pane length l_g being a predetermined constant, we can calculate the shading pane length



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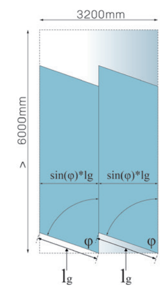

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4 The radii and angles of a typical level of the tower.

5 Compute the subsequent pre-initialized setting out positions from the spiral starting points.

6 Deriving the glass pane width from fabrication constraints for the panel distribution.

l_s and divide the boundary with chord lengths for n panels per level.

$$\Lambda=\frac{n}{2}(l_g)+\frac{n}{2}(l_s) \quad \text{which means that} \quad l_s=\frac{2\Lambda}{n}-l_g$$

where Λ is the floor perimeter length.

Establishing the global topology: Refining the setting-out topology required resolving the origin point for the chord length subdivision. The architectural vision and environmental considerations, such as optimal shading angles blocking direct sunlight, led to choosing skewed parallelograms as the PM for our study. This preference, in turn, implied a spiral configuration for the cladding layout on the continuous form of our design. Geodesic curves are an effective way of traversing doubly curved AS and are efficient in providing both the shortest paths and minimizing sideways (geodesic) curvature (Pottmann et al. 2010). However, these did not fit our roof design's aesthetic goals. Alternative strip discretization methods were considered, including using singularities (Knöppel et al. 2015) and yielding developable strips (Liu et al. 2006). Both ground and roof level profiles had unique requirements. Ground level for access alignment and the roof for solar radiation mitigation, influencing the start and end points of the spirals. Research on initializations of PMs with singularities by Mesnil (Mesnil et al. 2017) were explored for the roof. Finally, the optimization had to consider material wastage for the glass pane sizes due to the non-standard skewed shape. Taking all of these into account our optimization hypothesis is formulated as follows. Assume an AS that defines the form of our case study:

1. From pre-set point (*A*) on the bottom profile of the AS climb iteratively from across levels reaching one of the pre-initialized points at the top profile of the AS. The targeted point will be (*A'*), which we must find, as seen in Figure 5.

- At every step maintain a constant ascent angle φ .
- Angle φ must be in the range of 65° to 72°, for solar radiation benefits.

We solve the above by minimizing the deviation d'_A , which is the absolute distance of the end point A' of the last segment of the ascending spiral S_φ to the closest point from the pre-initialized points on the top profile. This function only takes a few seconds to minimize.

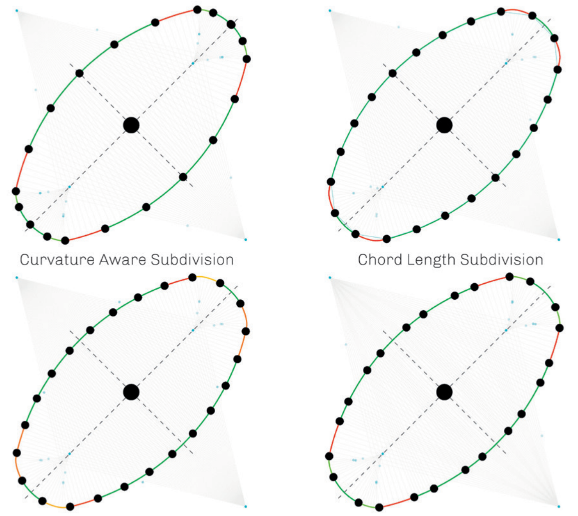
2. To determine the standard glass panel width for the tower, we attempt to fit two skewed parallelograms of skew angle $\theta=(\pi/2)-\varphi$ in a standard glass sheet of width 3.2m as seen in Figure 6. The resulting width is equal to $l_g=1.6/\sin(\varphi)$.
3. Replace l_g with this derived constant in the panel subdivision process for each tower level, starting at the intersection of S_φ with the level's boundary profile as per figure 6. The pre-determined locations for the panel setting-out points per level had a great influence on the rate of convergence for subsequent steps of the optimization process.

For this reason, we initially attempted simple uniform length subdivisions and curvature-aware subdivisions (Douthe et al. 2017) for deriving the setting out. Despite their relatively high success rate, these methods resulted in extensive computation times especially for downstream processes. In the end, we chose an iterative variable chord length subdivision approach as the fastest in terms of the total computation time amongst the ones examined.

Figure 7 illustrates this comparison between different subdivision methods. As expected, a quick analytical pre-computation step led to an initialized subdivision state requiring only a few hundred iterations for the force-driven optimization of step 4 below, to reach equilibrium for the entire tower, while also minimizing the failure probability of the system, as observed during the many iterations of its implementation. Furthermore, we discovered that initial discrepancies in panel sizes and panel curvature did not influence optimization convergence. On the contrary, accommodating most of the deviation in length on the last panel expedited the algorithm's computation cycles, as seen in Figure 8. A comparison of the various methods used can be seen in Figure 9. All computation was performed on a 6 Core Intel(R) Xeon(R) CPU 3.70GHz and 256GB of memory. As expected, these experiments are subject to the available compute power.

4. Employ a force-driven optimization of this initialized state where the objectives are a) equal glass width overall b) equal shading panel width per level c) maintaining torsional forces within the spiral segments. Using Kangaroo, a force-driven solver for GH, this optimization converged in less than 100 iterations (Figure 9), and can be seen graphically in Figure 10.
5. Acquire the final cladding setting-out for a given AS.

Embedding Fabrication Constraints: The acquired quadrilateral panels were non-planar, necessitating a classification by curvature for the cladding design, similar to the Lissajous Tower (Eigensatz et al. 2010a) where areas with extreme curvature values cannot be effectively described by planar skewed glass panes. However, the majority of panels even though doubly-curved exhibited very small deviation from planarity. To manage cost, we utilized a mix of planar, single-curved, and cold-bent panels. Cold-bending avoids kiln-forming as the glass adapts to molds, in this instance, the aluminum frame bearing the glass pane, yielding significant manufacturing savings (Fildhuth and Knippers 2010). Our optimization targeted a maximum 150mm deviation tolerance from planarity as shown in Figure 11. A rapid force-driven optimization attempts to minimize the deviations for most of the panels along the tower by iteratively rotating each panel along the median axis of its vertical orientation. We then replaced panels within this tolerance with cold-bent alternatives, achieving the threshold number by bending along the short diagonal of the panel. Panels could then pivot from their lower right node to enhance the spiral's continuity. Ultimately, 90% of the cladding was achieved with planar or cold-bent panels, while single-curved cylindrical panels addressed extreme curvature parts with more than 150mm deviation (Pottmann et al. 2008). Figure 12 displays



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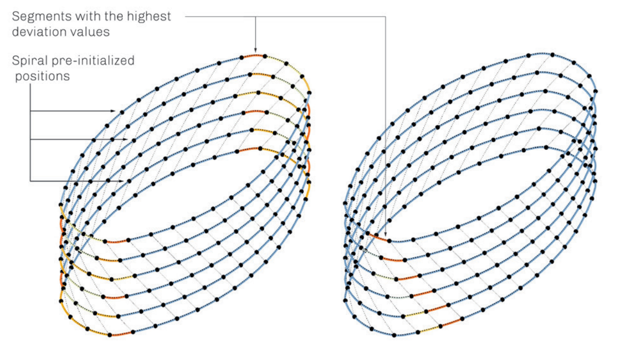


8

Subdivision Type	Pre-computing (ms)	Average Panel Deviation Length (mm)	Average Curvature Deviation (max	Convergence iterations	Compute Time (ms)
Uniform	0	12	8750	1000	40000
Uniform Shifted	0	18	9400	1300	45000
Curvature Aware	<10	600	10500	>1000	>50000
Curvature Inverse	<10	800	10600	>1000	>50000
Target Length	0	6	8700	800	35000
Uniform Chord Length	20	600	10470	400	25000
Iterative Variable Chord Length	20	260	9230	100	<5000

9

7 Different pre-initialized subdivision techniques for the cladding set-out.

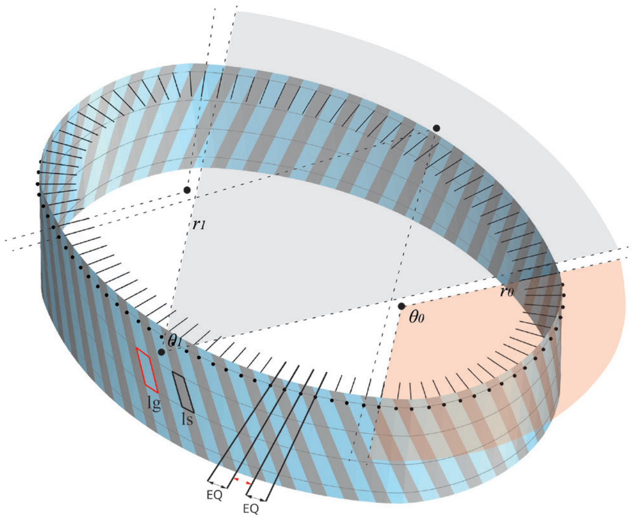
8 Largest deviations in a sequence of levels for uniform/chord subdivision.

9 Subdivision methods and convergence rates for force driven optimization.

the glass panes within the framing during installation.

Data Exchange and Unit Testing

While we argue for embedding optimizations, a common mistake is the coupling of said optimizations with content or geometry creation, which can slow down and even crash systems. A far more effective strategy is breaking down extensive tasks into manageable, isolated modules. Not only does it boost computational efficiency and simplify



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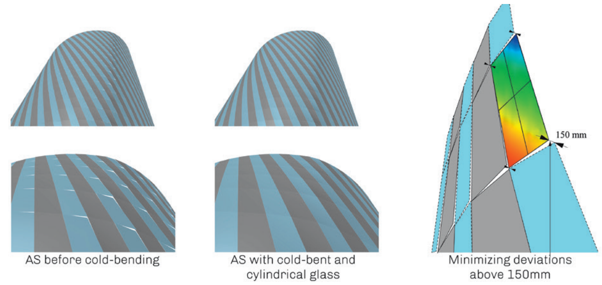

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10 The complete cladding setting-out optimization on a selection of levels.

11 The AS before and after the flat panel substitution.

12 The skewed parallelogram frames and the cold-bend glass.

maintenance, but it also allows independent upgrade deployments without compromising the entire workflow, with each part remaining unaware of the processes before and after it. Using this approach, we streamlined the workflow by utilizing our proprietary interoperability tool, Hermes, which enables seamless design data exchange among the project's various stakeholders, functioning as a series of micro-services. An additional critical component to the success of our system is the implementation of UT. These tests prevent unnecessary computations downstream and simplify the identification of common issues. They ensure the parametric models are aligned with essential metrics and adhere to constraints, whether statutory or performance driven. In our case study, the deployed UTs not only verified the dimensions of cladding elements but also enforced planning authority requirements such as fire safety distances, which are crucial for obtaining an AS that is compliant with downstream operations. In a simplified example, where new design-driving variables generate a tower form that does not meet fire egress distance standards, the system alerts the user of the issue, and all subsequent computations are immediately halted until the problem is addressed. We discovered that this intervention, when coupled with Dev/Prod (Development and Production) versions of parametric models, considerably reduced human errors and CAD inconsistencies.

RESULTS AND DISCUSSION

Computational Performance and User Engagement

The proposed method yielded significant computational efficiency during routine use of the parametric models by our architectural design team. By eliminating costly GA optimizations, narrowing problem scopes, starting with initialized states, and implementing UTs, we achieved computation times under 5 seconds for the tower AS and roughly 15 seconds for the cladding optimizations. These times, based on a single-thread setup and reliant upon CPU power with the specifications mentioned above, allowed for near-instantaneous recalculation whenever any system variable changed. We achieved viable design solutions over 98% of the time, as verified by visual inspection of design iterations saved on our cloud database through Hermes. This streamlined optimization required no user intervention, enabling designers to operate the parametric models as a plug and play system, with the processes being a black box only accepting inputs and generating specific outputs. Usage data acquired from Hermes revealed high engagement, particularly at the start and mid-week, with a predictable dip on Fridays due to design documentation tasks. The total number of 16 unique users from an interdisciplinary team of about 90, from structural engineering, façade consultancy, and environmental engineering, demonstrated a very high adoption rate for a system, indicating a reduced requirement of computational design expertise.

Visual Fidelity Comparison

The framework's effectiveness is qualitatively demonstrated by rating the confidence in the constructed result's visual fidelity of the completed project to the original schematic design. With no need for post-rationalization or VE during construction, our system achieved building trust among

13

13 Comparison of schematic design rendering and an as-built photograph.

consultants, contractors, and the client, regarding cost efficiency as seen in Figure 13. The fast completion of the case study further highlighted the system's strengths, as design changes were happening hourly.

Reflections

Our approach has its limitations, notably the lengthy initial planning and coordination along with the need for some experience in parametric modeling from the design team. However, it benefits from a modular methodology that allows team members to work on separate tasks independently which offsets some of the shortcomings. While we've successfully managed to offload heavy computations, simplifying the optimization tasks has, admittedly, affected accuracy. Empirical observations to define ratios between variables of the optimization could also be refined, perhaps through statistical methods that learn these numbers, which comes with a lengthy training or data gathering process. Distributing tasks on more CPU cores, particularly for geometry creation, could boost our efficiency further. Finally, there is great potential for improvement and future research replacing some of these methods by others utilizing Reinforcement Learning (RL), especially when it comes to learning the relationships between data.

CONCLUSION

In retrospect, we are confident that our system played a pivotal role in the seamless execution of a highly complex construction project. While its superiority over other approaches is not guaranteed, its rapid and modular nature outweighed potential drawbacks, facilitating a smooth design process. This was further enhanced by our interoperability system, which ensured design data were recorded in version-controlled, auditable streams for on-demand retrieval. We hope for the widespread adoption of such systems within AEC. Beyond focusing on façades, we've successfully implemented comparable workflows across various crucial design aspects. Examples include space-planning, and the test-fitting of apartment units within parametric models controlling the overall form of the building. Finally, a key take-away from this study is that choosing optimizations is not only about precision or cost-effectiveness. Instead, optimization is a constant negotiation of goals, and specifically for the AEC, must harmoniously integrate aesthetic considerations to ensure project success.

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REFERENCES

Andrade, Diego, Mikako Harada, and Kenji Shimada. 2017. “Framework for Automatic Generation of Façades on Free-Form Surfaces.” *Frontiers of Architectural Research 6* (3): 273–89. doi:10.1016/j.foar.2017.04.003.

Bo, Pengbo, Helmut Pottmann, Martin Kilian, Wenping Wang, and Johannes Wallner. 2011. “Circular Arc Structures.” *ACM Transactions on Graphics 30* (4): 1–12. doi:10.1145/2010324.1964996.

Bucher, Martin Juan José, Michael Anton Kraus, Romana Rust, and Siyu Tang. 2023. “Performance-Based Generative Design for Parametric Modeling of Engineering Structures Using Deep Conditional Generative Models.” *Automation in Construction* 156 (December): 105128. doi:10.1016/j.autcon.2023.105128.

Douthe, Cyril, Romain Mesnil, Hugo Orts, and Olivier Baverel. 2017. “Isoradial Meshes: Covering Elastic Gridshells with Planar Facets.” *Automation in Construction* 83 (November): 222–36. doi:10.1016/j.autcon.2017.08.015.

Eigensatz, Michael, Mario Deuss, Alexander Schiftner, Martin Kilian, Niloy J. Mitra, Helmut Pottmann, and Mark Pauly. 2010a. “Case Studies in Cost-Optimized Paneling of Architectural Freeform Surfaces.” In *Advances in Architectural Geometry 2010*, edited by Cristiano Ceccato, Lars Hesselgren, Mark Pauly, Helmut Pottmann, and Johannes Wallner, 49–72. Vienna: Springer Vienna. doi:10.1007/978-3-7091-0309-8_4.

Eigensatz, Michael, Martin Kilian, Alexander Schiftner, Niloy J. Mitra, Helmut Pottmann, and Mark Pauly. 2010b. "Paneling Architectural Freeform Surfaces." In *ACM SIGGRAPH 2010 Papers*, 1–10. Los Angeles California: ACM. doi:10.1145/1833349.1778782.

Fildhuth, Thiemo, and Jan Knippers. 2012. "Considerations Using Curved, Heat or Cold Bent Glass for Assembling Full Glass Shells." In *Engineered Transparency*. Düsseldorf, Germany. https://doi.org/10.13140/2.1.1621.7604.

Fu, Chi-Wing, Chi-Fu Lai, Ying He, and Daniel Cohen-Or. 2010. "K-Set Tilable Surfaces." In *ACM SIGGRAPH 2010 Papers*, 1–6. Los Angeles California: ACM. doi:10.1145/1833349.1778781.

Glymph, James, Dennis Shelden, Cristiano Ceccato, Judith Mussel, and Hans Schober. 2002. "A Parametric Strategy for Freeform Glass Structures Using Quadrilateral Planar Facets." In *ACADIA 2002: Thresholds Between Physical and Virtual*, 303–21.
Pomona (California), USA. doi:10.52842/conf.acadia.2002.303.

Holzer, Dominik, Richard Hough, and Mark Burry. 2007. "Parametric Design and Structural Optimization for Early Design Exploration." *International Journal of Architectural Computing* 5 (4): 625–43. doi:10.1260/147807707783600780.

Ilgın, Hüseyin Emre, Bekir Özer Ay, and Mehmet Halis Gunel. 2021. "A Study on Main Architectural and Structural Design Considerations of Contemporary Supertall Buildings." *Architectural Science Review* 64 (3): 212–24. doi:10.1080/00038628.2020.175.

Kennedy, J., and R. Eberhart. 1995. "Particle Swarm Optimization." In *Proceedings of ICNN'95 - International Conference on Neural Networks*, 4:1942–48. Perth, WA, Australia: IEEE. doi:10.1109/ICNN.1995.488968.

Knöppel, Felix, Keenan Crane, Ulrich Pinkall, and Peter Schröder. 2015. "Stripe Patterns on Surfaces." *ACM Transactions on Graphics 34* (4): 1–11. doi:10.1145/2767000.

Kosicki, Marcin, Marios Tsiliakos, Khaled ElAshry, Oscar Borgstrom, Anders Rod, Sherif Tarabishy, Chau Nguyen, Adam Davis, and Martha Tsigkari. 2023. "Towards DesignOps Design Development, Delivery and Operations for the AECO Industry." In *Towards Radical Regeneration*, 61–70. Cham: Springer International Publishing. doi:10.1007/978-3-031-13249-0_6.

Liu, Yang, Helmut Pottmann, Johannes Wallner, Yong-Liang Yang, and Wenping Wang. 2006. "Geometric Modeling with Conical Meshes and Developable Surfaces." *ACM Transactions on Graphics* 25 (3): 681–89. doi:10.1145/1141911.1141941.

Mesnil, Romain, Cyril Douthe, Olivier Baverel, and Bruno Leger. 2017. "Marionette Meshes: Modelling Free-Form Architecture with Planar Facets." *International Journal of Space Structures* 32 (3–4): 184–98. doi:10.1177/0266351117738379.

Pottmann, Helmut, Qixing Huang, Bailin Deng, Alexander Schiftner, Martin Kilian, Leonidas Guibas, and Johannes Wallner. 2010. "Geodesic Patterns." *ACM Transactions on Graphics* 29 (4): 1–10. doi:10.1145/1778765.1778780.

Pottmann, Helmut, Yang Liu, Johannes Wallner, Alexander Bobenko, and Wenping Wang. 2007. "Geometry of Multi-Layer Freeform Structures for Architecture." In *ACM SIGGRAPH 2007 Papers*, 65. San Diego California: ACM. doi:10.1145/1275808.1276458.

Pottmann, Helmut, Alexander Schiftner, Pengbo Bo, Heinz Schmiedhofer, Wenping Wang, Niccolo Baldassini, and Johannes Wallner. 2008. "Freeform Surfaces from Single Curved Panels." In *ACM SIGGRAPH 2008 Papers*, 1–10. Los Angeles California: ACM. doi:10.1145/1399504.1360675.

Tellier, Xavier, Cyril Douthe, Laurent Hauswirth, and Olivier Baverel. 2019. "Surfaces with Planar Curvature Lines: Discretization, Generation and Application to the Rationalization of Curved Architectural Envelopes." *Automation in Construction* 106 (October): 102880. doi:10.1016/j.autcon.2019.102880.

Turrin, Michela, Peter Von Buelow, and Rudi Stouffs. 2011. "Design Explorations of Performance Driven Geometry in Architectural Design Using Parametric Modeling and Genetic Algorithms." *Advanced Engineering Informatics* 25 (4): 656–75. doi:10.1016/j.aei.2011.07.009.

Vollers, K. 2008. "Morphological Scheme of Second-Generation Non-Orthogonal High-Rises." Accessed June 5. https://www.semanticscholar.org/paper/A-Morphological-scheme-of-second-generation-Vollers.

Wolters, Hans J. 2002. "Rational Techniques." In *Handbook of Computer Aided Geometric Design*, 111–40. Elsevier. doi:10.1016/B978-044451104-1/50006-X.

IMAGE CREDITS

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