The Bishopsgate Tower Case Study
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This paper summarizes the ongoing research on the Bishopsgate Tower in the City of London designed by Kohn Pedersen Fox Associates. We present a pre-rational geometry computational solution targeting a constraint-aware exploration of the architectural design-space, while interactively optimizing building performance in terms of constructability and cost-efficiency. We document a novel approach in building metrics optimization supported by parametric technologies and embedded analytical algorithms. The process is indicative of how computational methods will develop in the future and help designers find solutions for increasingly complex spaces.
1. Introduction

Increased use of parametric CAD systems within the architectural profession in the last decade is encouraging a resurgent interest in geometry as a system. Many recent architectural concepts, particularly but not exclusively in the area of ‘free form’ have been based on new sculptural freedoms made possible by CAD tools such as doubly curved surface modelers. One trend within the profession has been to treat such forms as essentially inviolate or constraint-oblivious. CAD (and parametrics) has been used primarily to post-rationalize the forms to make them constructible.

The authors of this paper maintain that a pre-rational approach to geometry is preferable for achieving higher performance results in the domain of large scale building design. In the world of commercial office development two factors are paramount: cost and return on capital. Often these considerations, in addition to technical issues, dictate relatively simple geometric solutions. The breakthrough in this development is achieving complex designs through simple fundamental geometries. These geometries can express architectural ideas while keeping their construction simple. Computer aided design systems enable architects to explore design concepts and integrate aesthetic and programmatic constraints. The pre-rational approach to computational design sets stable grounds for a constraint-sensitive design space exploration by forming a dependency relationship between form and its constructional implications. Moreover, we will illustrate how this mode allows modern analytical design methods to better integrate within the overall design process and inform its evolution.

This ongoing research is part of the community’s efforts to introduce and integrate cutting-edge digital methodologies into the design practice. We illustrate the potential of these technologies through the documentation of our solution.

2. Methodology

The Bishopsgate Tower was designed with the facilities provided by parametric modeling software, namely Bentley’s Generative Components. The Bishopsgate-System was implemented in the C# programming language as an in-process server to the parametric platform. The interactive system is composed of a series of object-oriented assemblies specialized on specific aspects of the design problem space.

The drivers for the selection of this development configuration were dictated by the need for high-performance, interactivity and flexibility for accommodating the scale and complexity of the project. We identify three domains, running parallel with the phases of schematic to detail design, in which parametric technologies assisted in the development of the project:

1. The formal expression and exploration of the schematic design.
2. The building information extraction and evaluation.
3. The optimization of building performance criteria.
In summary, we present the geometric logic of the parametric model with focus on the pre-rational design approach, supported by forward unidirectional associative geometry mechanisms. The need of measuring the building’s performance explicitly, keeping track of its history and guiding its development is covered in the information management section in which we briefly discuss an integrated XML-based publication system and a collection of VB scripts for information validation. We conclude the documentation with an in depth presentation of a novel algorithmic process for the building’s facade optimization, inspired by behavior-based algorithmic processes found in the field of artificial intelligence. We will return to those sections after a brief description of the architectural context and goals for this project.

3. Architectural description

The Bishopsgate Tower, located on Bishopsgate and Crosby Square will become one of the most significant new buildings in the City of London with a design that will strengthen the overall character and identity of the emerging cluster of tall buildings in this location. Figure 1 The proposal will make a substantial contribution to the public realm, opening up the ground level area to pedestrians and linking a number of important urban spaces along Bishopsgate and St. Mary Axe.

3.1. Contextual considerations

The overall design is highly location-specific resulting from the combined pressures of a very large office building (approximately 1,000,000 sq. ft.) situated in the heart of the City of London. The design is responsive towards planning considerations related to its impact on both the overall townscape of London and the immediate urban fabric. In addition, it addresses several environmental considerations related to energy efficiency and natural ventilation.

The distant views from the Thames dictated that a distinctive profile was required, while the closer townscape views demanded that the form should be more visually fragmented. The effects of a rectilinear volume extending directly upwards from the site’s footprint would have been massive; instead a form that diminishes vertically was more suitable. The form is meant to...
appear very slim and elegant when viewed from its narrowest southwest face, and very imposing when viewed about its wider faces. The basic form springs from a curvilinear canopy extending over the surrounding public space, evolves vertically while slowly reducing in size, and resolves itself into a helical shaped roof. Figure 2

The refinement of the form evolved around factors related to both the existing built space and its future developments. The inclination of the facades was derived largely by the need to minimize the building’s impact on certain ‘Strategic Views’. For instance, the views along the Queen’s ceremonial route on Fleet Street, show that the proposed building does not impinge upon the view of St. Paul’s Cathedral. This removed a major point of objection from the Heritage bodies, who had actually halted a previous project for a tall building on the site by a different architectural practice. In addition, the adjacent proposed building by Richard Rogers Partnership (122 Leadenhall Street) features a distinctive sloping plane on its south facade which called for visual control and tuning of the void space between the two buildings. The springing point and the visual axes of the roof’s helix were defined in relationship with the existing ‘Tower 42’ and the consented ‘Heron Tower’.

3.2. Environmental considerations

Sustainable systems are integral to the architectural design. The aerodynamic shape improves the performance of the naturally ventilating facade with its ‘Snake-Skin’ design. The outer layer of glass protects the sun-shading which reduces heat gain, and allows for operable windows at high levels. The environment study was performed by Hilson Moran Partners. Figure 3 The glass facade allows penetration of ample natural light,
thereby reducing the amount of artificial light required. A mixed-mode ventilation strategy optimizes all considerations of energy consumption and internal comfort. A computerized ‘Building Management System’ constantly reviews and optimizes the building’s energy performance. Use of biomass and photovoltaic low and zero carbon technologies are used to further reduce the carbon emissions.

4. Computation description

4.1. Formal expression and exploration of the schematic design

Design subdivision

The main issue with any large-scale building is that its construction and hence subdivision of the object is a primary driver in its design. The decomposition is driven by a variety of goals, visual, constructional or architectural. The visual goals are related to whether the subdivision emphasizes or de-emphasizes the form. At one end lie iso-curves and section cuts (‘egg-slicer’ mechanisms), u and v parameter curves, distorted regular lattice grids all providing visual clues to curvature. At the other end lies subdivision divorced from the underlying form, providing visual ‘shock effects’. These typically relate to some other underlying mechanism, including random and pseudo random patterning. The constructional goals include an understanding of the suggested construction process, from prefabricated components to continuous on-site manufacturing. The size and assembly of components and their jointing methodology becomes an extremely important design driver. The architectural goals include the notion of interfaces, between internal systems (such as partitions), as spatial delimiters between inside and outside but also as spatial delimiters in greater context (such as townscape). The material expressions are also extremely important, whether ‘transparent’ (in fact ‘crystalline’), translucent, solid or colored. Within the context of a skin, a large building has to tackle all of these issues, many of which are addressed at different levels of
resolution. It is for instance often sensible to design the control mechanism of an overall form as the parent of subdivisional strategies.

Built form

The overall form will tend to also control the fundamental structure of the building. Within the context of traditional approach to tall buildings the envelope also defines the primary structural tube (stiffened by connection to a vertical core containing lifts, stairs and services). The primary design focus for the Bishopsgate is to produce geometry which can be relatively easily manufactured and communicated.

The fundamental decision was therefore taken in Summer 2004 to build the geometry for the tower entirely from lines and arcs. The subsequent design development has substantiated this approach, and a structural system was designed for the geometry of the tallest office building being planned for the City of London, the Bishopsgate Tower. It has, among other things, yielded straight columns, and beams which are either straight or simply bent to a radius.

Geometry constraints

The geometry approach is based on a number of simple constraints. The design process however makes it vital that geometry approaches are flexible. This need for flexibility means that the focus in the design process moves from designing the object to designing the system which designs the object. The Bishopsgate Tower is therefore built on a sequence of parametric dependency models designed at each stage of the development of the scheme, always responding to the demands of the process. These models were built using Bentley Generative Components while the software was still in Alpha release stage. Within each model a number of parameters were evaluated until a new model was built when a new sequence of form-finding was started.

Design history of form finding

The original form-finding search (early 2004) was done essentially manually when a wide variety of options from very simple geometries (cylinders, prisms etc) were evaluated. Figure 4 From this original work it became clear that a roughly triangular floor plate provided the only reasonable solution on the given site capable of accommodating the approximately 1,000,000 sq ft necessary to make a viable project at this high value site. The basic problem of a roughly triangular floor plate is that its townscape impact viewed edge on is essentially benign — it is a slim design. However when a triangular floor plate is viewed face on the visual impact is large.
The design team approached this problem by creating a wrapped surface which divided the face into two visual components. These two visual components were then tamed in townscape terms by creating a helix cutting the wrapped surface. The helical cut starts at the height set by the adjacent Tower 42 and St Mary Axe (at approximately 180 m). The cut then traverses the surface up to the pinnacle of the building (at around 288 m). This architectural gesture acts as the distant view cue for immediate identification. One advantage of the form is that its inherent asymmetry allows clear orientation in relation to the city. The overall form is thus designed to achieve maximum slimness for the considerable bulk of the building.

This slimness is also accentuated by the fundamental idea of tapering the building. The taper to an extent is an architectural response to the Richard Rogers proposed tower to the immediate south of the tower. In addition, the taper on the south face of the tower opens up a gap between 122 Leadenhall Street and the Bishopsgate Tower, valuable in townscape and wind flow terms, and allowing a glimpse of the St Mary Axe by Foster and Partners.

The geometric problem originally posed was one of finding a coherent geometric schema which would allow a tapering building where each face was sloping differently but which was yet built from simple geometry capable of simple construction. One of the authors proposed a simple schema consisting of flat tapering planes joined by sheared cones. This schema was applied to the whole building and became the foundation of the geometric system of the overall shape. Such a system has many degrees of freedom and the implementation had to make choices as to how the dependency mechanism should be structured. The first move was to create a polygon defining the springing points of the tapered planes. Each corner has a chamfered tangential arc. The first question that arose was how to control the arc radius? There was no intrinsic advantage in controlling the arc radius explicitly by a radius particularly since the radii at each corner would vary as a function of the sheared cone. The choice was made to a linear set-out where the arc radii were controlled.
indirectly by giving a length to each flat face which established the tangent position. Figure 5

The issue then was one of direction and origin of setting-out. The obvious origin point was at the intersection of the wrap with itself. That point itself is located arbitrarily in space in relation to the complex site boundary. The first model set out the building anti-clockwise. This method inevitably resulted in the wrap intersection point not aligning with a putative division system. At this point of the design it was assumed that the facade module would taper in alignment with the building. Hence each linear facade segment was made of a multiple of a standard bay (which was varied between 1500 and 1800 grids and a number of variations between). It was obvious that this geometric schema would need somewhere to ‘take up the slack’.

The decision (September 2004) was therefore taken to reverse the setting-out, starting from the wrap intersection point (which would therefore coincide with a notional mullion and more importantly Column 1 of the structural system). This created a variable dimension at the wrap intersection, an architecturally satisfying solution. The centers of the sheared cones all lie on a single vector. This vector (and the intersection with each floor plane defining the actual arc) can be computed by constructing the vector on the plane and its intersection with the NEXT plane. Hence only a single vector on a plane drives the taper of the cone. That means that in a linear setting-out system the only additional variables which need to be supplied is the inclination and taper of each plane. These two parameters indirectly control the radii of the sheared cones. While the design assumption was that the mullion system would taper in sympathy with the tapered planes it was important that the taper was the same on each plane. Solutions were constructed where the taper was exactly 1 mm per planning bay per floor on all tapered planes. Naturally at each stage of the design floor areas were reported back from the parametric model. As with all commercial developments lettable space is at a premium and small variations can make substantial differences.
Structural system
The structural column setting-out is generated from the design skin, but have combinatorial issues of their own. The arcs at corners had chords lengths added rounded to the nearest possible module. Combined with an offset from the design surface these provided location points for the columns. In addition to a regular spacing the decision was taken to position the columns symmetrical with respect to the principal arc corners. Even within this constrained set there were many possible combinations, most of which were evaluated. In addition there were constraints imposed by foundation conditions and access roads. These resulted in a number of columns being born off by V frames. The final number of columns were 21 (solutions ranging from 19 to 23 columns were investigated). Figure 6 The huge benefit of the original design geometry is that every column is straight. However no column is vertical, their inclination is governed by the design surface.

Structural bracing system
The bracing system allows for more than 1000 possible braces. The design intention is that they gradually drop off towards the top as they are less required. The manual schema produced some 300 members. These were later subjected to an optimization algorithm [2] developed by ARUP structural engineers and this was further reduced to some 250 members.

Helical top
The shape of the helical cut was the next principal design element. In order to control the shape of the cut a ‘normalized law curve frame’ was built. Rather than representing the true unwrapped surface on the diagram all near-vertical mullion lines and inflection points to arcs are represented as vertical lines. Equally the heights are represented as true z heights ignoring the effect of the tilted planes. The law curve is controlled by a set of points such that the planes are cut by a straight line and the sheared cones have a smooth transform. Figure 7
This schema gave rise to a large set of variations driven by Client and Regulatory body input, and was explored on top of varying base forms. Each form was evaluated from a large point of critical street level views; it was essential that the helical form could be appreciated from all important

views. One critical view is clearly from Mansion House where the tower is very visible above the old Stock Exchange and it is here that the wrap successfully breaks the composition into two bodies.

Snake-skin

The initial design concept of tapering modules was abandoned in late 2004 in favor of a linear setting-out on a regular 1.5m module. The topic of the snake skin will be discussed later in detail in the facade optimization section.

4.2. Building information extraction and evaluation

A custom-made building information management solution was developed for the Bishopsgate Tower to allow the regular evaluation of various design metrics. The computational solution introduced and utilized a variety of experimental methods of design metrics representation. Figure 8

Information filtering

The parametric model produces and exports calculations which were initially presented in a tabular spreadsheet format. The metrics include
primarily floor plan and facade area measurements, along with various quantity calculations and serializations of members. Two aspects of this system were further developed into new solutions: a metrics publication system through XML data streaming and an automated error detection system.

In the first instance, the need for intuitive and prompt evaluation of the facade optimization metrics led the development of an information publication system using web technologies. During the optimization process, the parametric model produces an enormous amount of information - anecdotally known as the 200 meters long spreadsheet. This ended up being practically impermeable due to its shear volume. The need for contextual filtering of information and the intuitive presentation of it, led to the incorporation of a 'data server' module in the same parametric system. The application produced programmatically XML data sheets formatted as web pages and published in the local intranet. The system allowed us to keep track of the volume of data and filter out information according to query selection criteria.

Information verification
In the second case, we observed that in some instances, numerical errors produced by geometric operations affected the generated design information. These numerical stability issues [2] generated a few irregular elements. For this purpose we developed a validation system to prevent visually undetectable discrepancies. Specifically, the parametric model integrated a module that outputted VB scripting files for the Rhinoceros platform. The scripting file contained a series of commands capable of reproducing the geometry accurately and a set of functions that performed the validation. For example, the script compared all facade panels against their set-out paths as well as with each other for the detection of registration errors.

4.3. Optimization & configuration
The development of a computational solution enabled us to push the design research one step further by integrating optimization in our parametric process. The configuration of the facade was performed by a specialized optimization algorithm. In particular, an iterative process was developed that targeted the minimization of the double skin facade’s cavity and the maximization of the gross internal area (over constant building volume).

Two basic alternatives were originally explored for the mullion arrangement. The initial idea was of a constant set of mullions per floor, running on top of notional envelope’s domain. The base geometry was capable of producing a pre-constrained planar panel configuration. Yet the desire for a regular and modularized facade scheme shifted the attention towards a fixed-size linear set-out solution. Figure 9
Physical Characteristics and Constraints

The facade is composed out of a single flexible module type. The module is composed of an internal upright frame, positioned on the slab-edge, and an external spatial frame which registered in space in relation to the internal. Both panels are rectangular and their sizes are constant all along the facade. The internal continuous skin forms the building’s enclosure while the external overlapped skin provides weather proofing and natural ventilation. Figure 10

An initial study suggested the crucial characteristics of the facade system which were expressed as optimization constraints. The facade module induces a constant misalignment between the mullion-sets due to the perimeter reduction per floor. The cavity is part of the natural ventilation scheme and thus the air in-taking open-edges between the overlapping panels are subject to dimensional constraints. The physical dimensions and functional tolerances of the final members were also incorporated in the optimization’s collection of constraints. The challenge of the study was to define a self-optimized panel configuration system that avoids panel-to-panel collisions, achieves tightest packing and visual continuity.
In detail, the upper left corner of the snake-skin panel is constrained in space by a minimum distance from the spanning floor level and a functional void between the module’s panel pair. The snake-skin panel is also constrained by a maximal allowable notional volume around the building. Figure 11

**Geometric definition**

For setting a snake-skin panel it is necessary to identify the location of three points in space which define the registration plane. With one of them explicitly defined and a second implied, it was practically a matter of resolving the position of a single point. Three incremental solutions were developed and tested for the layout, each of which redefined the priority of the constraints.

**First version**

The first solution forced a regularity constraint between the spacing of the internal and external panel and simultaneously a constant dimensional constraint between the external panel and the maximal containing volume. The goal was to achieve exactly the same cavity dimension all around the facade and gain constructional simplicity. The number of modules per floor though is diminishing towards the top of the building due to its constant layout and its inward tapering. This rendered the scheme as practically unfeasible due to the change of curvature around the perimeter which caused panel-to-panel collisions. In addition, the constant spacing relationship by ignoring the subtle curvature characteristic of the notional envelope created visually unpleasant artifacts around the rounded corners of the building.

**Second version**

The second approach amended the constraint of constant spacing and focused on constancy of angle between the set-out path of the internal and
snake-skin panels. Thus it incorporated the curvature concerns into the solution space and allowed the external envelope to 'take the turns smoothly around the corners'. Furthermore, the flexibility of a non-fixed cavity opened a modest window of solutions to the collision prevention constraint. The optimization scheme achieved a 19.05% average cavity reduction or 1.23% of gross internal area gain. The obvious benefits of the process led to a third cycle of study.

Third version

While both of the first two schemes operated on an ‘educated guess’ style of optimization, the third one introduced an iterative heuristic search method. In this instance, the constraint of constant distance from the maximal envelope was amended along with the constant angular relationship between the pair of panels. Instead, the actual physical spacing between the snake-skin panels themselves was taken as the driving force of the method. The topology of the skin was examined and three possible collision cases were formalized into procedural evaluators. The locus of panel planes revealed a highly non-linear collision occurrence pattern which necessitated the introduction of a set of numerical solvers.

Algorithmic design

In detail, the position of an initial seed panel is defined in the end of the sequence of the set-out of the first floor. The following panels resolve their positions in space by iteratively searching for the tightest packing orientation while retaining a minimum distance between the previous panels (above, below and across the diagonal). These distances are directly related to the physical dimensions of the panels themselves and the ventilation constraints. Graphically, the role of the solver was in fitting the plane of each panel tangentially about a series of distance preserving bounding spheres, hooked on the vertices of the previously placed panels. Pseudo code 1.

begin OuterSolver
    solve Panel( null, null )
    for each Panel in FirstLevel
        solve Panel( previous_top, null )
    for each Level in OtherLevels
        solve Panel( below_top, null )
    for each Panel in Level
        characterize Panel
    switch Mode
        case Collinear: solve Panel( previous_top, below_top )
        case Convex: solve Panel( previous_bottom, below_top )
        case Concave: solve Panel( previous_bottom, below_top )

Pseudo code 1. The outer solver loop.
Design and computation

For the design of the interactive facade solver we devised a compelling methodology which worths explaining in detail as it hints for a new approach in expressing and tackling convoluted architecture-sensitive problems. In order to convey the complexity of the problem and the benefits of the method we will describe one of the multiple instances of the problem domain and present in detail a direct analytical problem solving approach.

As previously mentioned, the solution to panel packing problem may be approached through the geometric problem of fitting a tangent plane from a stationery point in space through a pair of distance-preserving bounding spheres. Figure 12. An attempt to solve the problem by constructive geometry involves the following process: From the given vertex in space, there are two cones which are tangent to each of the bounding spheres. The tangent plane we are looking after needs to be tangent to both cones. The intersection of the plane defined by the circular imprint of one of the cones to its tangent sphere produces an elliptical (conic in general) cut on the opposite tangent cone. The definition of the solution-plane is given by the original vertex and one of the tangent lines between the circular imprint and the produced ellipse.

There may be at most four tangent lines between a circle and an ellipse. The solution of this problem geometrically (through parametric modeling) involves the extraction of all four tangent planes and the selection of the appropriate based on some local metric. The solution of the same problem algebraically yields either an explicit formulaic solver or the use of a
numerical scheme.

It may be evident that either way would result to a highly inflexible and non-scalable computational implementation. This is because there are cases where the plane has to be fitted though a more complex shape than a tangent sphere, as for instance an inflated edge or even a quad. Moreover, for each of the problem scenarios there needs to be a new numerical scheme / set of equations which are quite difficult to derive. Finally, this approach entails multiple exceptional case handling which increase the overall complexity of the system.

The sensible approach

The goal of the implementation was to achieve high performance without loss of intuition about the problem’s behavior. Moreover, the scheme needed to be flexible and extensible to future changes of the problem’s constraints and formal expression. This specification of desired effects define the concept of an intuitive computation: A process that can be easily communicated and enriched by a traditionally trained yet highly experienced architectural audience which is properly acquainted with the properties of a given problem.

Our method is closely related to the contextual information of the problem space, in the same fashion that a parametric model is the exact expression of the rules governing the formal product. This property allows us to keep track of the problem visually without the need for a layer of direct algebraic abstraction, or obfuscation in this context. Yet unlike geometric modeling where the process is typically suffocated by the tight relationship between the form/product and the rules/process, our method draws a clear line between them.

For embodying this concept we borrowed a metaphor from the field of artificial intelligence [1]: a sensible-behavioral system composed of a set of sensors, evaluators and actuators. A sensor acquires a measurement for the environment: typically some signed distance or an angle. An actuator performs an action: typically the application of a transformation. The evaluator directs decision making by comparing the data acquired through the iterative processing.

We imagined a person positioning and orienting a panel in space by pushing and pulling its edges. Each time he/she would measure a set of distances between the new position of the current and the neighboring panels. The selection of measurements would have been context-sensitive driven by the local conditions. Notionally after a number of iterations the panel would have taken an optimal position through a divide and conquer scheme, up to some perceptual tolerance. Pseudo code 2.

```
begin InnerSolver
    while ( Iteration < MaximumNumberOfIterations )
        transform PanelRegistrationPoints
        Instantiate PanelThroughRegistrationFrame
```

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probe SignedDistancesFromNeighboringPanelsEdges
if ( SpacingResidual < Tolerance ) then Exit Loop
select NewTransformationDirection

Pseudo code 2. The inner solver loop.

Evaluation
The method exhibits a few interesting characteristics: Initially, it is evident that all steps involved are quite simple. The actuation is a mere translation of a pair of points in space that define the registration plane. The instantiation is part of the parametric modeling process. The measurements are straightforward distance measurements. The evaluation is trivial and the selection requires only one precedent.

The parts are extremely loosely dependent with one another. The actuation is unrelated to the panels’ geometry (material and details). The evaluation is indirectly related to the panels’ form, but it is easily imaginable that it can be abstracted to a generic term of ‘closeness/proximity’ between operands. Finally, the selection is also unrelated to the actuation and geometric expression of the involved objects. This allowed us to easily switch panel representations (dimensions and form), redefine the priority of measurements/constraints and optimize the selection solver (switch from a divide and conquer bisection scheme to a gradient driven Raphson-Newton method).

The most intriguing effect was the transparency of the system. The constraint for an intuitive method was fulfilled successfully. This claim is supported by the fact that both the initial and boundary conditions of the optimization problem were directly expressed in the modeling part. Thus the convergence of the solver to the desired solution, rather than a solution, was intuitively established.

A limitation of the system is related to its runtime efficiency in comparison to a glove-fit numerical solving mechanism. The purpose of the method though was not merely the solution of a problem but rather the development and design of an idea about its solution. In this context, it is clear that accessibility to the problem’s domain is more important than efficiency. Therefore, the proposed method targets the development of a platform for experimentation and exploration, which may be applied afterwards for direct solution finding.

Optimization results
The optimization method achieved a 33.34% of cavity reduction or a 2.62% of gross internal area gain. A future development of this method is planned to incorporate global optimization criteria such as cavity regularity constraints which may yield construction simplification. Graph 1

Graph 1. The optimization results.

Computational optimization methods for architectural and engineering
design have been presented in the near past \([4, 5]\). Geometric and numerical constraint solvers are increasingly embedded in many CAD software packages and the role of these digital methodologies has been delineated in recent publications \([6]\). The specific design and implementation suggests a methodology of how these technologies may be employed in the resolution of everyday architectural considerations which prove to be quite non-trivial problems.

The optimization of any multidimensional solution space entails numerous cognition-oriented issues which derive from the fact that both the initial conditions of a given problem and its solution domains are typically unintuitive to comprehend \([7]\). Thus, the need for developing intuitive methods of accessing these spaces becomes prominent. The implementation of the algorithm contained several interfacing features targeting the augmentation of the ‘educated guessing’ process. Instead of blindly shooting the problem with either brute-force computational methods or exotic numerical solving algorithms, the approach avoided taking the human observer out of the equation. In particular, the geometric elements under inquiry were equipped with ‘software sensors’ which triggered ‘attention events’ once violated. The parametric model in response to these events developed ‘geometric indicators’ around the ‘irritated areas’ and graphed out diagnostic statistics about the causes of the problem.

This concept of intuitive computational design operators \([8, 9]\) apart from its measurable benefits was also extremely successful in identifying characteristics of the process which were lurking invisibly within the streams of numbers. For instance, we were able to identify the patterns of the problem occurrence in relationship to the base geometry changes. We were able to observe and understand how the optimization behaved over loosely described formal criteria such as the skin’s apparent smoothness. In
conclusion, the role of this elaborate computational effort was to let us access the complex domain of the design, by expressing simple architectural inquiries, rather than just being a validation process.

5. Conclusions

The evaluation of the presented research will be discussed in relation to its two primary areas of consideration: one that comes from the context of an architectural practice in the development of tall building designs, with strong focus on performance criteria; and another, which springs from an academic endeavor in exploring the potential of digital design media and the modes of the interaction between the designer and the machine.

On one hand, the goals brought about in this research were driven by the need for explicit building performance evaluation and control. These performance criteria among others were economic, environmental and aesthetic. Through our implementation, we identified specific methods of expressing and integrating these diverse criteria through computation. We evaluate as the success of our approach, the gained ability to impose implicit and explicit constraints in both sub-domains but also the entirety of the design space. We understand these results as the evidence of an emerging digital economy and ecology in architectural design: A new mode of thinking empowered by higher cognitive resolution and broader accessibility in the complex domains of architectural design.

On the other hand, the challenge of delivering a computational solution itself brought about several opportunities to investigate the modes of digital design making. The necessities in this case were related with expressive and cognitive criteria: inventing methods for describing certain behaviors, making sense of their results and feeding back the knowledge into the system. The experiment conducted in this case was one of externalized perceptual mechanics: expressing methods of understanding in the form of computational constructs. The strategy behind those was to keep the human — computer interaction open-ended in an attempt to expand the exploration potential while converging to a solution space. The success of the approach was that many previously underlying patterns of the system where revealed and employed in the overall design. In this sense, we envision the future development of architectural design systems that exhibit tighter integration and more sophisticated modes of interaction between the designer and the machine.

In conclusion, we suggest that our research and development of digital design methodologies highlight aspects of the potential of a computation in architectural design which will be widely available in the near future. In fact, many of the domains investigated in this paper are open for further research and development. Our on going efforts are founded on the principles of tighter integration of technologies with the design process and the development intuitive and expressive solutions.
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