Research & Design in Shifting from Analog to Digital

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In this paper we track the evolution of computational design from its analog origins to its contemporary digital regime. Our long term goal is to qualify and quantify the implications of digital computation on design thinking and its influence on the architectural practice. Meanwhile, we present the results of our past few years of collaborative research in design and computation that illustrate the nature of the intellectual engagement required for appreciating the potential of digital design thinking and making. In a temporal frame, these results are expressed as a constellation of punctuated innovations emerging sporadically during the painstaking process of tackling architectural problems using digital means. In the long run, they hopefullyamount to an approach to fleshing out a paradigm shift from analog to digital and building a knowledge foundation of architectural methods.

INTRODUCTION

We employ this paper as a vehicle for consolidating our research work. This allows us to focus our efforts and communicate our findings with the community of computational design. Our research is situated within a commercial architectural practice, which directs a fair amount of our attention towards the development of building-performance-oriented solutions. Thus, our efforts are focused on establishing bridges between the traditionally-analog building-industry ecosystem (including architects, engineers and fabricators etc) and on investigating digital design as an instrument for thinking and practicing architecture.

The basis of modern computation is founded on the notions of discrete information description and processing. Computational methods spring from these ideas and build on different levels of abstraction from signal processing (low-level) to digital media (high-level). In the realm of design, computation has established a strong presence around the topics of form and geometry. We appreciate that this adoption has benefited the design community enormously by expanding its expressive repertoire. It has also fostered an environment suitable for experimentation and research, by challenging traditional constructs of what architecture is and/or encompasses. It is our assumption that the current state of computation as a high-level interface with unconventional form has ceased to be beneficial to the community. Digital design is no longer a novelty, as we have successfully managed to create a demand for it, for both internal and external consumption. Moreover, we identify form-oriented computation as now being almost an impediment to further progress, unless it begins addressing its pragmatic consequences. We claim these may be systematically approached by the same means: computation. We do not perceive the architectural community as ill-mannered, denying to enter into potentially lower levels of abstraction. On the contrary we believe, to a certain degree, that it was lured into the domain of digital computation but left isolated in a digital sandbox with no means of proactively dealing with the emergent issues.

In this respect, we strongly believe that digital design is not merely the product of employing digital media. On the contrary, it is a process of an intellectual engagement with the concepts laying underneath digital computation. Our approach to performing the analog to digital paradigm shift is founded on the concept of bridging. Our bridges establish relationships between what is already inscribed in the architectural sub-conscious as being plausible and extend out to the potential for innovation offered by the digital.

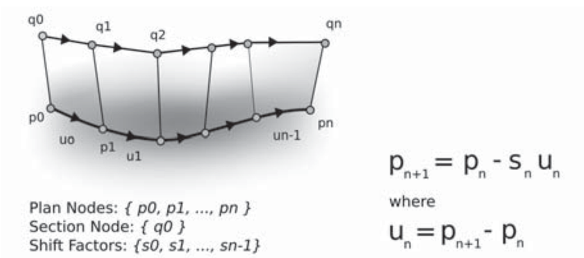


FIGURE 1 Diagram of the first principles.

METHODOLOGY

Specifically, we present a range of solutions that we devised for creatively tackling traditional architectural design problems. Our method involves revisiting analog solution-precedents, only this time, employing digital media as both a way of thinking through the problem definition and of responding with novel solutions. The process of re-reading the contextual assumptions and embarking from them was not merely based on style but also on necessity: the necessity of establishing a stable point of reference for comparatively evaluating and communicating our processes and products. Eventually, we are able to effectively address the architectural problems that spawn the research but also open up a new potential by exploiting the emergent behaviors of

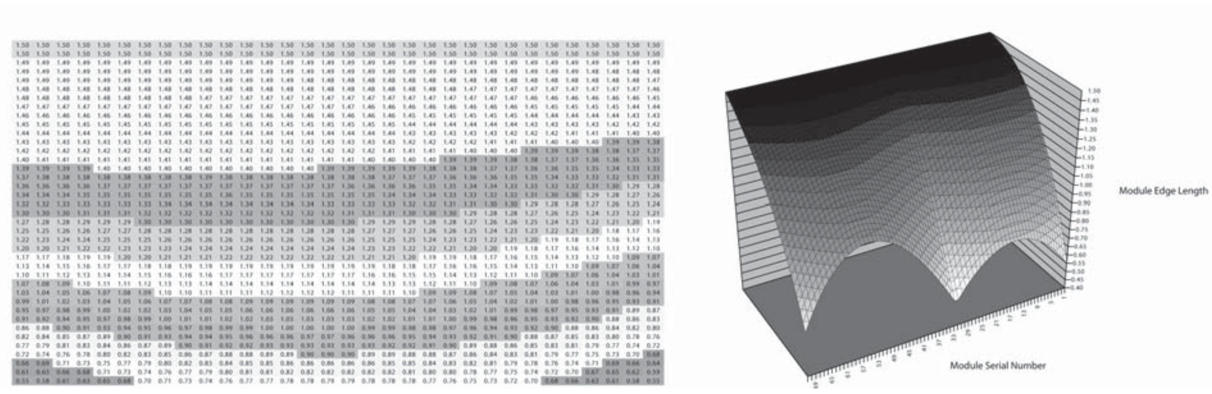


FIGURE 2 The explicit parametric map of the solution.

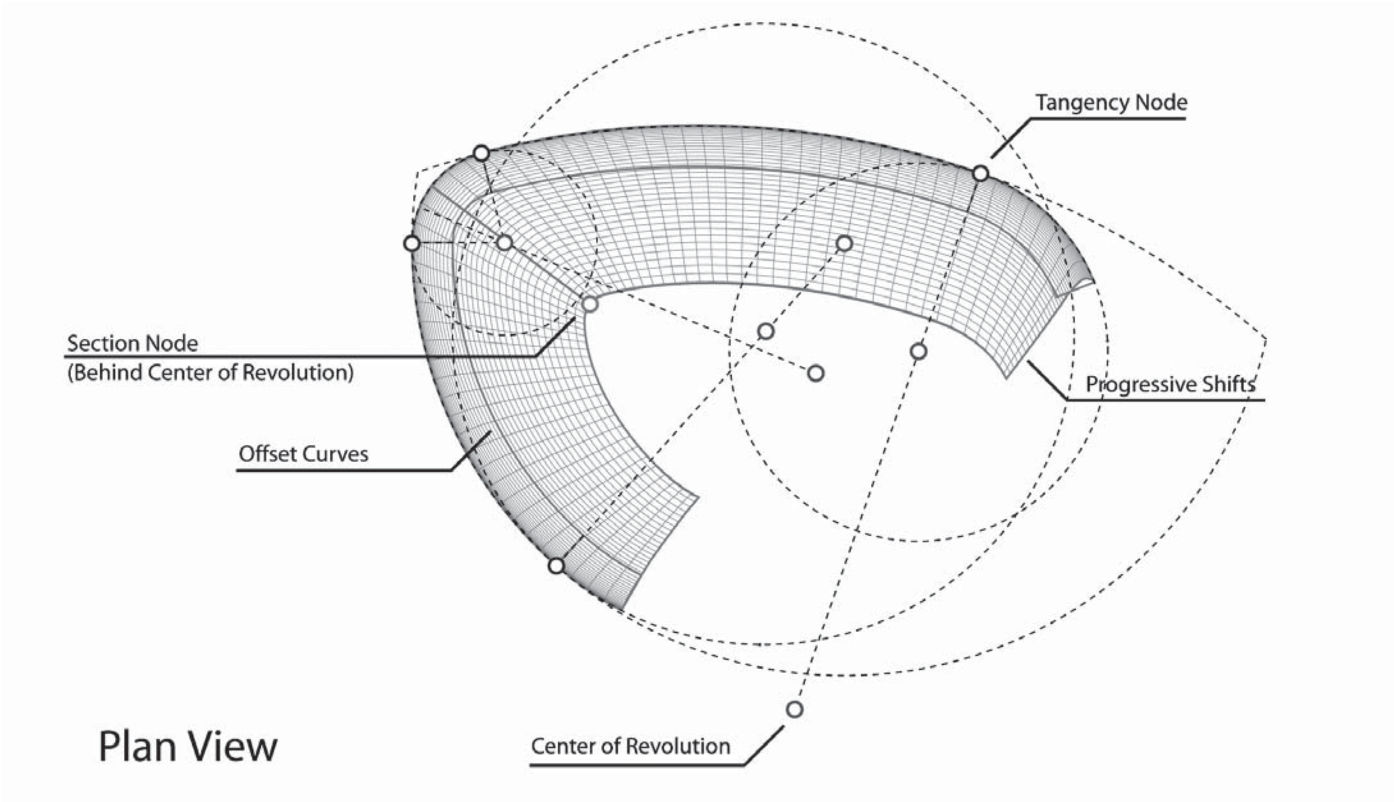


FIGURE 3 A building design of a curved envelope that bends beyond the revolution center.

our systems. By these means, we are showing how it is possible to achieve a smooth transition of mind-set between what is already known, what is imaginable and what is potentially achievable. Moreover, we are given the chance to highlight the intellectual differences between the two modes of thinking. Finally, we are able to better communicate our results to the wide and diverse audience involved in architectural design.

It would have been unsustainable for the extents of this paper to provide full documentations for each of our projects. A few are already published (Dritsas, Charitou and Hesselgren 2006) and given enough time for documentation, a few more will come out in the near future (Dritsas and Rafailaki 2007). Instead, we decided to present a series of methodological mappings: re-occurring problem typologies paired by solution strategies. These mappings are typically the product of distilling design patterns out of similar or adjacent problem spaces. We will layout those mappings along a progressive story-line that presents our understanding of digital design and computation.

APPRECIATING THE DIFFERENCES AND ACKNOWLEDGING THE CHALLENGES

Case Study: Analog vs. Digital Pre-Rational Geometric Design for Free-Form Glazed Envelopes

We will start with presenting a computational geometric system developed for producing planar quadrilateral spatial configurations suitable for free-form glazed building envelopes. The problem of meshing free-form envelopes is quite intriguing because it brings up a few fundamental issues regarding digital design

The problem definition is: given a free-form surface (building envelope), generate a mesh (cladding layout) such that all faces (panel modules) are planar quads. Both constraints are architectural: Quadrilateral faces are preferable over triangulations for aesthetic and functional reasons. Planarity is primarily an economic constraint driven by the price ratio of planar glass over cold/hot-bent or even cast glass. Secondary constraints are employed in order to further simplify managerial and fabrication aspects of the design. For instance, there may be a need for congruency constraints among

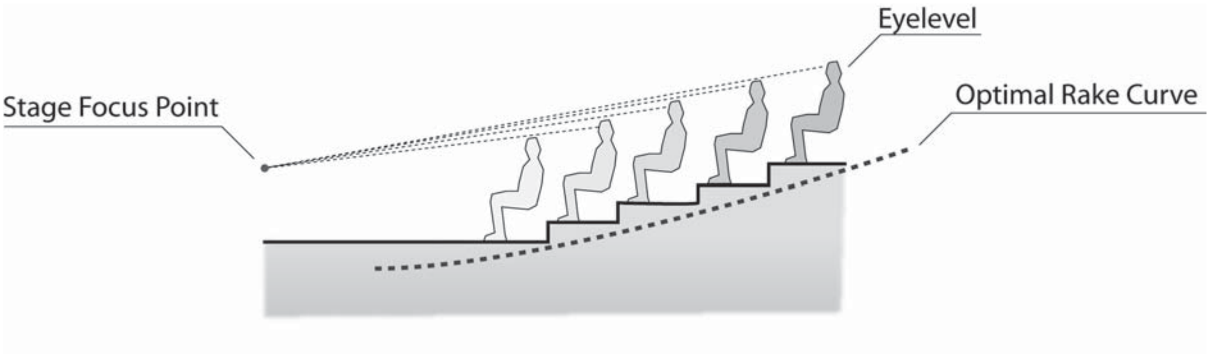


FIGURE 4 The diagram of sight lines.

the glazing faces for the sake of maximizing regularity and in turn simplifying the processes of fabrication and assembly.

The advent of digital technologies, namely CAD software, enabled designers to access true free-form envelopes based on surface and mesh geometries. Moreover, the development and spread of digital manufacturing allowed these forms to become technically and economically feasible. In the past fifteen years or so the demand for free-form built form has initiated a chain reaction, as more and more designs came into reality, they intrigued and trained the public's aesthetic sensibility and in turn increased their demand. Notional paradigms of this process that we ought to acknowledge are Frank Gehry's Museum in Bilbao, Spain and Normal Foster's SwissRE in London, UK.

Traditionally, glazed curved envelopes have been addressed through geometries known for providing pre-constrained solutions to the problem of the planar quads. This approach is commonly attributed as pre-rational for its: (a) deterministic results, (b) linear behavior, and (c) geometric construction. Early interpretations of pre-rational geometric design are based on analytical solutions, yielding quadratic surfaces and of revolution, as a means of proactively constraining the problem's complexity into manageable subspaces (Glymph et al. 2003).

While these requirements are completely reasonable for most designs, they seem somewhat unjustified in the context of the current and future developments of design and fabrication technologies. We no longer have to perform calculations manually; computers perform them much more effectively both in virtual (CAD) and physical (CNC) space. We can access the same problem spaces by iterative computation. This shift has already started to take effect in the sciences. For instance, the finite elements or computational fluid dynamics methods are good examples of this logic. A recent paper by Liu et al. illustrates how a computational method may be successfully applied in a specific problem scenario (Liu et al. 2006).

Our implementation follows a similar approach. We prioritized usability and simplicity of implementation for our paneling method, since, apart from its developers, we are also its users. Constraint systems, either proactively address the problem requirements or post-rationally enforce them on a given a free-form envelope. We appreciated that a post-rational method would need to accept the possibility of a departure from an original form through fitting and perturbation mechanisms, as

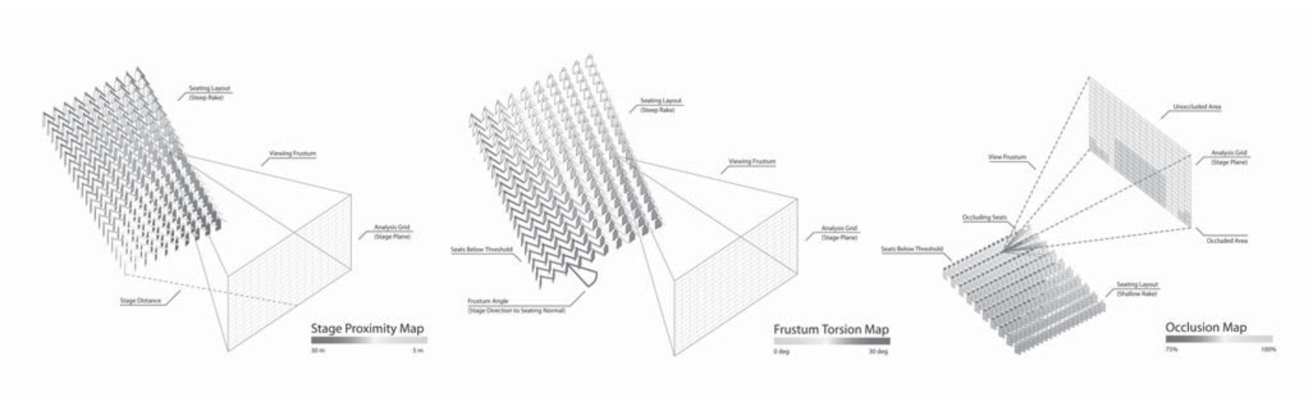


FIGURE 5 Physical Distance, Frustum Torsion & Spatial Occlusion diagrams.

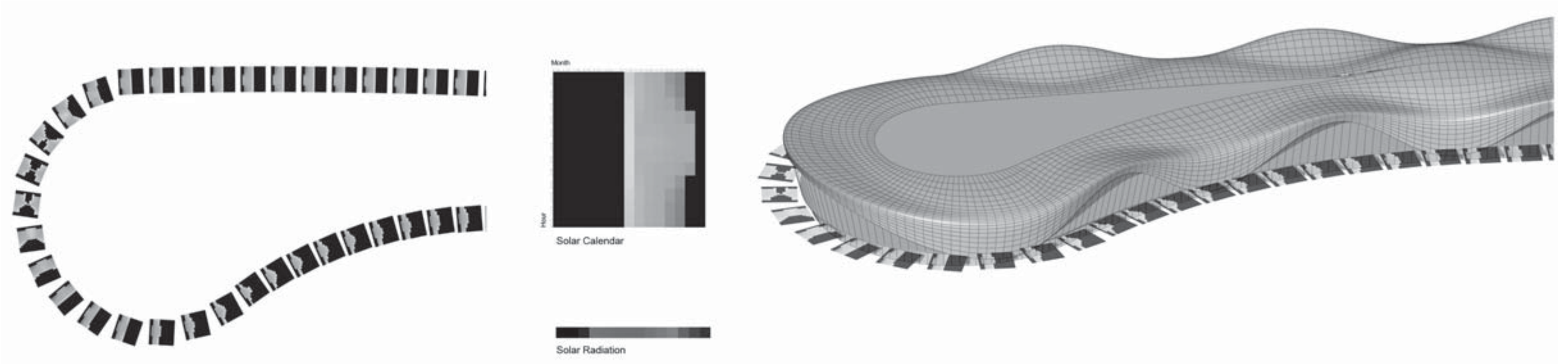


FIGURE 6 A situated analytical representation of the light exposure over a full calendar year time per façade unit.

not all forms can be meshed with planar quads. On the other hand, a pre-rational method would incrementally build on a system already known for being consistent with the problem's domain.

We selected the latter. Our system builds on the first principles known for satisfying the problem requirements: triangle strips with shifting peaks across shared edges. Planarity is assured by the triangular bases and quads are produced by clipping those triangles; series of those strips assemble planar-quad meshes. Each element of the mesh is defined by a linear shifting factor (Figure 1). Details of the algorithm will be discussed in a future paper.

The pre-rational method assures validity and stability without the difficulties of perturbation, which are commonly expressed through questions such as: How much are we off from the original form? If I push or pull the envelope this way, where and how is it going to deflect? On the other hand, due to its bottom-up mode, our method requires the build up of elaborate abstraction mechanisms and user-interaction interfaces for dealing with the enormous amounts of information. A linear factor per panel is more than enough to make the process counter-intuitive for even an envelope of a few panels (Figure 2)! Embedding numerical solvers eventually resolves some issues but black-boxes the system. In this respect, we feel that a circle is closed and a pattern emerges.

Before discussing the rather more involved issues about digital design research, let us first focus on the results extracted from this case study. On the positive side, we may admit that we have opened up new possibilities for design expression. We were able to practically describe building envelopes that would have been otherwise inaccessible (Figure 3). The digital method has liberated us from the laborious task of calculation and allowed us to focus on the design. In effect, this allows us to metrically overlay architectural considerations by interpreting and implementing pragmatic constraints. As a whole we are given the opportunity for profound design investigations of form. While enumerating the advantages of digital design as it is helpful in motivating people to join the community, we believe that it is the challenges that demand equal attention because they define the boundaries for which further research is needed to expand.

Beyond implementation issues and strategic algorithmic design decisions, there is a common thread which may be examined in the context of inventing design tools. First, let us return to the traditional requirements of linearity and determinism, and realize that they are not merely technical. On the contrary, they hint about visual cognition, which is an important aspect of design intuition and visual thinking (Arnheim 1969). Linearity for instance, implies that a system's non-linear complexity may be decomposed, accessed and reconstituted through partial linear behaviors; these in turn foster intuitive interpretation and creative intervention. Determinism is as psychological issue in as much as it is a practical one. It provides the assurance that a solution space will be reached, will be stable, if not unique, and easily communicated and reconstructed by legacy operators.

This discussion becomes gradually more interesting as it allows us to delve deeper into the effects of adopting digital design methods. We are witnessing some emerging problems which are both technical and perceptual. The challenge of visual cognition and human-computer interaction illustrates one aspect of these problems. In the domain of practice different kinds of efforts are required for integrating digital methods in architecture in its current state. Finally, there is a bigger envelope that encompasses both architectural practice and education, which is linked to the formalization and dissemination of knowledge, the appreciation the intellectual investments, and the fostering the environment for generation. We would like to study these a bit closer.

For instance, in the case study of the glazed envelopes we need to appreciate the necessity for mathematical and engineering knowledge that is required for traversing the problem's solution domain in a systematic way. Moreover, the process of revisiting a traditional methodology, reinterpreting it, and expanding it with a new set of tools forces many previous assumptions to collapse. Those need also to be reconstructed from their fragments. The transition from analog to digital envelopes brings about the problem of complexity management. We need to investigate methods of making the process more accessible to all the parties involved. We need training in adopting this new way of using design tools. We need smart methods of handling the managerial nightmare of fabrication and assembly construction. These are all non-trivial problems that require more investment. They typically are expressed with simple definitions. For instance, a new problem that emerges from free-form envelopes in the one of geometric congruency: How can we group panels according to their dimensions such that they form a minimum number of groups within a tolerance? This would help in construction. How do we deal with computational resolution that goes beyond ours? This would allow us to fully exploit and appreciate the digital precision in design. The analog response towards these consequent problems is already preemptively given: We confine the design space. How can we address these novel collateral issues within the digital without retreating back to analog?

DESIGN OF ANALYTICAL EVALUATION SYSTEMS

Case Study: An Algorithm for Theatrical Seating Layout

There is an inherent friction between human and computer intelligence which becomes evident every time we stumble upon perceptual tolerances. Moreover, complexity management is deeply rooted within perception. In this respect, computational design needs to escape these boundary conditions by marching forward and providing means for mediated design cognition. Externally, these means provide indications that facilitate architectural judgment. Internally, they may be employed for computational traversals of diverse or optimal solutions. Our interpretation of this process is expressed through the design of analytical evaluation systems. This section focuses on the process of expressing design evaluation criteria (indices) as means of understanding aspects of architectural space. A case study of a theatrical seating-layout evolution algorithm will illustrate how a digital process can go beyond the analog approach of the sight-lines and propose new set of design metrics and evaluation criteria. By those means it is possible to track quantitative and qualitative characteristics of a design through digitally mediated perception mechanisms.

How shall we design a theatrical auditorium such that it ensures good visibility for the majority of its audience? (Let us forget listening for a moment). What is a good seating layout, and what is a better one? As in the previous study this design problem seems straight foreword but it hints at even more complexities. In this case there is a genuine lack of clarity for goals, rules and constraints. The traditional approach to this design exercise involves the use of the archaic construct of sight-lines (Figure 4). While we do not object to the loose empirical basis of these systems, we do notice an unnecessary analog fixation intheir application and a fertile ground for digital innovation. Sometimes these analytical systems capture quite elegantly a set of some interwoven constraints; for instance, the requirement for a clearance from occluding elements (both architectural elements and people) from within a viewer's frustum. Yet they most typically tend to enforce unjustified or rather heavy-handed generalizations that constrain design exploration. Today we are in a position to create intelligent evaluation systems by computation that may reach higher levels of precision and provide more indicative information of the actual spatial performance conditions.

The opportunity for the design of evaluation systems is one that requires responsibility in terms of appreciating and validating its results for what they really represent. Yet, it is also the site of the critical fusion point between the analytical mode of thinking involved in computation (science) and the synthetical mode of architecture (design). An analytical framework may be either appreciated against an absolute striation of a human condition (this specific amount of noise is tolerable by people) or it may be examined relatively against abstract constraints (the less environmental noise, the better). While we understand that in the first instance there is a need for a long term research on human factors, we claim the second approach back to architectural design. This relative relational framework will allow us to understand performance aspects during the exploratory phases of design and identify the neighborhoods of possible solutions. Later on we may fine tune the details individually against hard coded boundary conditions.

In our study for the theater-layout evaluation system, we soon realized the complexity of expressing metric information about performance. For instance, proximity to the stage may be seen as plausible constraint, but yet it soon becomes evident that seating in an acute angle from it is also undesirable. Moreover, the vertical angle (seating in upper galleries) is not equally weighted as horizontal angle (seating on the periphery). In addition, there are multiple terms of viewing occlusion that may be considered separately: blocking by other viewers or by building elements, for instance. This renders the idea of a single compact evaluation metric impossible or even naive.

While metrics such as proximity and angle may be accessed through geometry in a very similar fashion as the concept of the sight lines, spatial occlusion is a problem of a different nature. In fact it may be more effectively, if not only, addressed with discretized methods similar to computer graphics visualization algorithms and/or the finite elements method (Ham 1988; Adler 1999). We constructed a system that follows this paradigm: The plane of the stage is quantized and its elements are processed through a ray-tracing mechanism that implements viewing frustum culling as the means of blocking detection. In this fashion we expressed a dimension of viewing comfort for every seat in a theatrical layout as the ratio of the occluded over the maximal visible area (Figure 5). A technical paper regarding the implementation details will be published in the near future.

In a methodological context, the algorithm for theatrical seating layout evaluation becomes an exemplary instance of a general approach to addressing convoluted spatial configuration problems. It allows us to appreciate computation for enabling us to traverse the domain of a complexity which is beyond human cognition. In this respect it responds to the inquiry initiated in the previous section. Moreover, it sets the basis for a design approach to computation that goes beyond form and starts addressing human condition directly. In summary, it is our belief that mechanisms as such are beneficial for architectural analysis and design, and while they may call for empirical grounding and validation they also provide the basis for illuminating spatial qualities that are accessible even today only through architectural fiction. We need to acknowledge the intellectual contribution of the theories of Isovists and Space Syntax (Hillier 1996; Turner et al. 2001) and the studies for architectural visual cognition (Nagakura and Chatzitsakiris 2006) in the development of this research project.

SYNTHESIS OF DYNAMIC REPRESENTATIONS

Case Study: Algebras of Heterogeneous Considerations

Performance aspects of a design, generated by analytical methods, cannot be practically visualized and subsequently utilized without special modes of information representation. Accessing these metric data generally requires intense post-processing through various abstractions layers. Eventually, this endeavor produces graphical and numerical mappings which provide ordinal and/or cardinal clues; Potentially these are revealing of underlying systemic dependencies. The diverse and typically incompatible nature of these metrics brings about our next area of challenges in computational design. Namely, the necessity for a coherent information handling framework for allowing architects to operate on multiple design criteria by overlaying and stacking information in order to explore and assess the solution space in a meaningful manner and eventually steer towards favored solutions. We have experimented with various techniques of visual and numerical mapping for prioritizing and factoring data sets. These techniques are absolutely crucial in any time-based performance analysis such as environmental, occupancy, assembly sequences. Modes of specific data visualization are critical to the design process and often carefully designed themselves.

A case study was developed for the design of an airport terminal located in an area of desert climate. Different types of analysis were set up to evaluate an initial design and to inform further design development. The main environmental factor under these conditions is related to the solar radiation impact on the building envelope, consequently leading to heat gain and glare. These two factors are already very different types of phenomena springing from the same source. Known methodologies of simulation address either one or the other but fail in terms of delivering a correlated post-processing output. Thirdly there is the highly heterogeneous flight and operation schedule of the airport itself leading to specific occupancy patterns in time and space. Reading a design option's performance and steering towards better ones requires a comprehensive way of mapping these three aspects: Heat gain as a time depended spatial phenomena, glare as a time depended phenomena in the field of vision and occupancy as a time-space phenomena. The overlapping domains allow for synthesizing these readings and developing a method that could be described as algebraic.

The synthesis is performed by transposing, amplifying, and masking incoming information-sets, by means of embedded computation, and rendering it within the architectural model *in situ* (Figure 6). In this respect we have a composite live design diagram that encompasses a design intention, its performance repercussions, and its perceptual analysis/synthesis controllers. This representational framework which is sitting between analysis and design is quite open in terms of its inputs and outputs. It could apply to other forms of analysis metrics such as CFD, and energy consumption. Eventually it will yield a coherent map that could help steer the design based on a context of contradicting design vectors and dynamic conditions.

In the context of analog digital bridging this method of inclusive representation illustrates how computational methods are employed to render a visualization layer that allows for design consideration in a almost classical way: a designer's perception and experience. The significant difference in this instance is that the basis for judgment is not the architectural design or spatial condition itself but a map that synthesizes the criteria crucial to the design. This mediated diagram that sits along the design and exposes performance becomes an entry point for handling engineering and design considerations on a common ground and sets out an alternative model to a single criterion engineering optimization and architectural decision based purely on the design artifact. In this way it opens up the possibility for design knowledge to enter the digital realm and bring in human decision making. It will ultimately alter what is known as ever changing design expertise through a reciprocal relation with the digital.

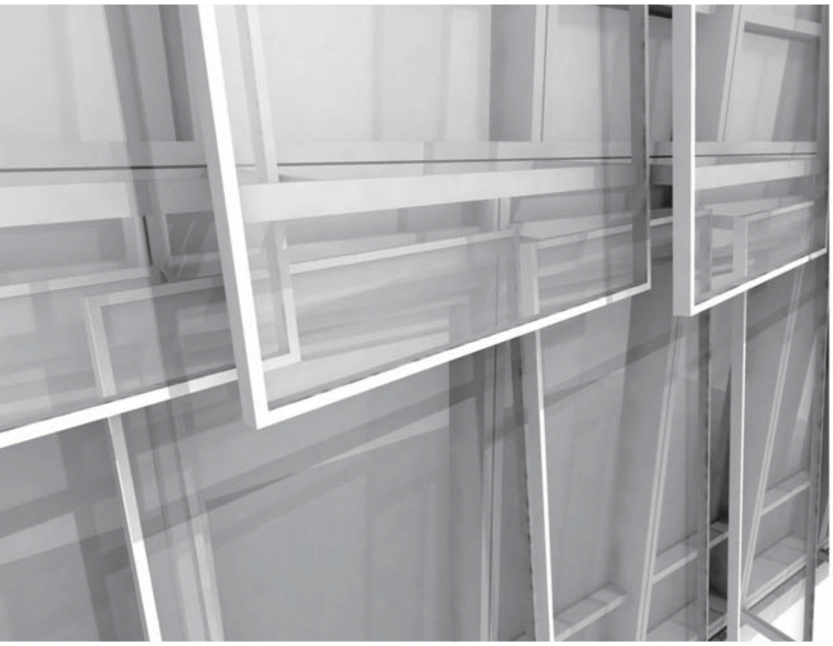
RECONSTRUCTING THE ORIGINS OF COMPUTATIONAL DESIGN

Case Study: A Building Envelope Design Optimization Method

Optimization as a scientific methodology is remote from architects' training and way of thinking. Typical aspects of engineering optimization involve the creation or adoption of theoretical models that capture subspaces of phenomenal behaviors, description of schemata defining explicit problem descriptions, expression of boundary conditions within which the problem space may be meaningful, selection and adaptation of directed problem space traversal mechanisms etc. Instead architects are trained in making educated guesses among options underlying multidimensional problem spaces and as remedy provide coherency by means of compacting meaning by design. While intuition is undeniably an important aspect of design, in the test bed of optimization it operates as a scalpel removing large polychora out of multidimensional problem spaces that may exhibit novelties inherent in their subtleties. Digital optimization methods are the contemporary means for querying a design solution in these domains. The power of these methods can be traced to their incredible speed, multiresolutional aspect, and also the possibility of revealing inaccessible domain properties or solutions. While these methods are heavily obfuscated by numerous technical issues, typically related to accuracy, tolerance, and numerical stability, they are becoming progressively more robust and accessible to the architectural audience. Our methodological problem space of interest is focused on integrating optimization methods within the already examined abstract evaluation systems and dynamic digital representations. Our requirement of establishing bridges with the architectural precedent is purely one of communication.

In our case study we examine a large scale cladding optimization of a particular building envelope. The double layer façade is composed of an internal skin that provides enclosure and an external skin that works towards the natural ventilation of the building. The external skin is comprised of a series of panels that overlap their neighbors in two directions (Figure 7). Moreover, the entire façade is registered against a curved composite design surface which forces the panel overlaps to be unique. Thus, the double skin cavity is variable in depth. We developed an algorithm for initially solving the envelope's panel registration. This algorithm numerically calculates the panels' positions and orientations in space and resolves clashes. An optimization extension was attached in the system for tightly packing panels and minimizing the skin's cavity area and thus maximizing the building's the gross internal area (subject to constant volume). Multiple lateral constraints are simultaneously computed such as: construction details expressed as physical dimensions and tolerances, assembly considerations encapsulated in clearances, environmental performance criteria captured by the gap dimensions for ventilation, aesthetic desires expressed as geometric continuity criteria, functional requirements translated to buffer zones for maintenance, cost efficiency measured by building area, etc.

The analytical results and implementation details behind the algorithmic approach have been discussed in a recent publication (Hesselgren, Charitou and Dritsas 2007). We would like to present here its external logic. In this section we are confronted with the problem resulting from a non-conventional building scheme conceived and designed by digital media. It is well-defined in both its means and goals, yet, its inherently complex nature as well as its vast size hermetically seal its domain traversal. Literally, it requires weeks of parametric modeling to describe such an organism, and even then the process of performing adjustments is still cumbersome. Computational optimization addressed not merely the aspects of the design calculations involved, but also allowed us



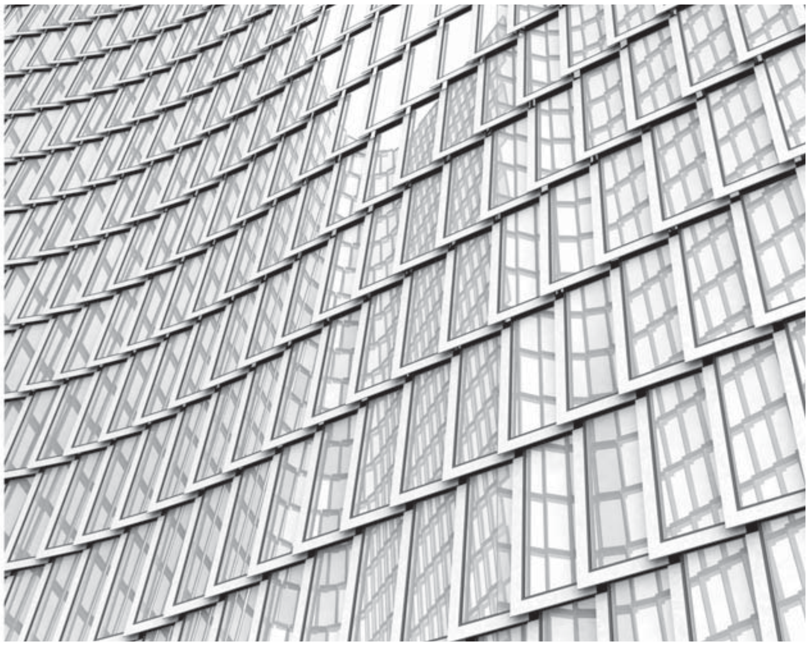


FIGURE 7 An aspect of the external cladding system.
FIGURE 8 (right) Overall geometric configuration of the snake skin facade.

to overlay and synthesize all of the above considerations in an integrated design system.

The optimization method was entirely conceived and constructed as a communication medium. We described the process as being executed by a person involved in the assembly of the façade. S/he would have to place the first pane arbitrarily. The next one would have to respect a clearance buffer from the previous, and so on. After the first level's cladding is completed, the next floor would be layed. This time the panels belonging to the floor below would also need to be cleared, etc. (Figure 8). Every aspect of the algorithm involved was directly mapped through an interface that any experienced architect or cladding engineer with no prior knowledge of computation could intuitively interact with and actively contribute to the design process. We believe that this approach provides a paradigm for integrating advanced digital methods in architectural design transparently and responsibly.

We also appreciate this method as a basis for a systematic framework of algorithmic digital design. Search methods offer a new paradigm: a design process with shared control between the computation and the design intent which evolves itself as a lattice of query criteria and filtering definitions. It is not impossible to imagine a condition where once a problem space is defined and a traversal mechanism is selected and attached, the rest of process becomes completely post-procedural, we are already "Googling" information in similar fashion. We envision this development as the basis for a new model for generative design: one which has an already rich context to operate upon, rules as query filters expressed through architectural inquiries and emergence as the result of a multiresolutional precision.

CONCLUSIONS

In conclusion we have progressively presented a series of solutions that on an application level of discourse respond to pragmatic architectural design inquiries of diverse nature. They illustrate a range of challenges innate within digital design thinking. We engaged them by means of revisiting traditional approaches, expanding them and accessing new design possibilities.

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