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Physics Simulation and Form Seeking in Architecture Design Education

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Abstract: This paper presents a method for integrating rule-based architectural form seeking with the aid of digital techniques using rules of physics and evolution. Computational methods of dynamic simulation are used to optimize volatile solutions, through the simulation-based design process, also known as "generative design". The paper further describes the experiential learning outcomes gained through the application of simulation as a method for solving specific design challenges. The authors focus on how a structural-based solution can evolve during the early design stage. The research projects presented anticipate the changing variables in the design process and embed these variables in a "misbehaved" and "zoomable" model. Structural simulation and genetic evolution optimization tools are used to represent tectonic and building envelope variables within the parametric equation. This simulation-based process explores parametric techniques that allow for and encourage non-linear workflows. In this process, architects do not directly manipulate a solution. Instead, various algorithms and computational tools are used to build a system of rules. The simulation-based design approach allows for parametric control of iterations and seeks the optimized final form and function.

Keywords: Simulation, generative design, computation, parametric design

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1 SIMULATION-BASED DESIGN

Simulation-based optimization has intrigued architects through a controlled process where prior experience is augmented by the addition of data to drive design decision-making. This design process integrates interdisciplinary analysis and evaluative processes in an automated system that assists in designing better-performing buildings. In the practice of architecture, this process is based on various generative design methods such as topology optimization. Some of the emerging aspects of the architectural practice involve utilizing genetic algorithms in the design process, as well as digital simulations and performance-driven design to generate complex building forms that respond to predefined rules. The use of computation within the design process sustains a rule-based method for making design decisions. By not being limited by a strict linear workflow, where manually altering previous decisions is time-consuming and requires a regression of the design stage, architects are now able to establish novel non-linear workflows where multiple design aspects can be encoded as predefined rules. The authors name this transformable architecture as "zoomable form" driven by physics rules and simulations. Adaptive architecture form allows for an adaptive method to create a constant stream of the observable field of options for a design solution.

2 METHODOLOGY

Through several courses taught at the University of Cincinnati, the authors explore how simulation-based computation is changing a static architectural form into an adaptive system that can respond to its structural performance. Here, form is no longer only defined through Cartesian coordinates; rather it depends on a multitude of supports and applied forces. Designers today no longer need to view design as manipulating a static object, but rather creating "transmutable" systems that are driven by various physics rules. Two

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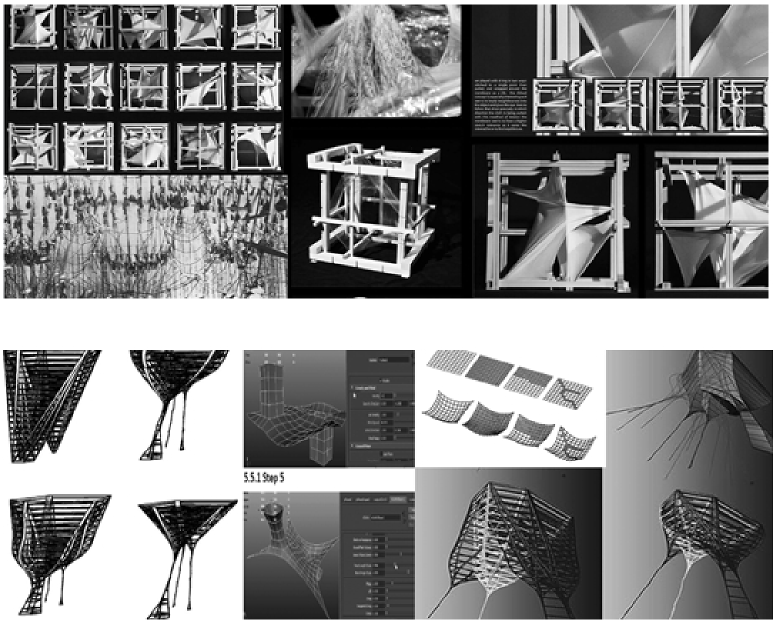

Figure 1. Gaudi Catenary study and physics-based form seeking (University of Cincinnati)

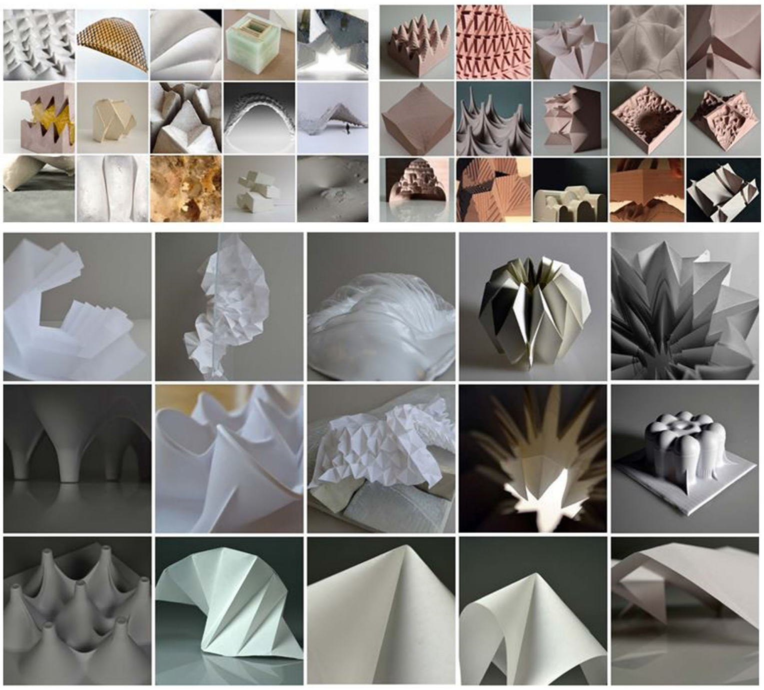

Figure 2. Empiric simulations: casting/hybrid analogs, vacuum forming/paper folding, and CNC routing (University of Cincinnati)

cases were introduced to illustrate the laws of physics and their relation to architecture. The first case study used Antoni Gaudi's catenary simulation method to determine how to optimize membrane and tensile structures. The second case study was the path optimization method based on Frei Otto's wool-thread machine. Both analog models were digitally reconstructed by a computer simulator based on the proximity and collision of points, lines, and surfaces. The essential objective of both case studies was to decode the analog process and migrate it to the digital simulator. Variables such as material properties and dynamic forces generate through this process both the three-dimensional massing and time-based media to visualize the form seeking process. (Figure 1)

Students first studied these analogue models to investigate the structural and formal characteristics of fabric with the intent of adapting its form to various constraints and different forces. The second step is the creation of a digital simulation and the comparison of the results with the analogue model. The structural performance and material properties are calculated in the physics engine of Autodesk Maya. Students set up the different physics rules, material properties, and collision objects to investigate how the textile structure can negotiate amongst these conditions.

2.1 Zoomable World/Misbehaved Tectonics

In the undergraduate second year studio, we began our working methodology through a heavily iterative process that had each student choose one tectonic system as a precedent for the case study. As textbook, we implemented the categorization set forth by Farshid Moussavi in her book titled "The Function of Form". The students had to understand the system they started with and physically and digitally model the assembly to document the laws and constraints of each structural system. Following this introduction, the following six weeks focused on rebuilding and digitally remodelling each system while engaging six different media with their implicit ways of making. They included: textile architecture, casting/hybrid analogs, 3d printing, vacuum forming, paper folding, and CNC routing (Figure 2). Students were asked to speculate on how various ways of constructing mutate the chosen precedent. The exercise was sequential in nature, meaning that at the beginning of each process students departed from where they left off regarding the development of the precedent and its associated representation. Each student was asked to build and rebuild models of the precedents and study the systems through drawings and diagrams. In turn, through this empiric simulation, students documented various material-specific parameters and developed rules-based methodologies to describe each tectonic mutation.

New structural hybrids have emerged through misuse and appropriation inherent to each of the six fabrication processes (Figure 3). Students were introduced to design methods that incorporated experimentation and thinking through making. Over the course of six weeks, students formulated their own distinct provisional working methodologies. Also, at the end of the process, each student arrived at a personal catalog of tectonic possibilities with their associated material fabrication (Figure 4). The tectonic systems considered were: grids and frames (one-way frames, two-way frames, diagrids, grid-slab frames, double-layer grids), vaults (barrel vaults, cross vaults, complex rib vaults, fan vaults, curved rib vaults, cellular vaults), domes (surface domes, ribbed domes, stacked arch domes, Yazdi-Bandi domes, Kar-Bandi domes, Kaseh-Sazi domes, Muqarnas domes), folded plates (folded plates, folded plates and trusses), shells (conical shells, umbrella column shells, hyper curved shells), and tensile membranes (parallel cable tensile membranes, radial cable tensile membranes) (Moussavi 2009).

The resulting work was exhibited in a local gallery owned by 3CDC, a major real estate developer in the area. The 6" x 6" grid of artefacts was exhibited as a commentary on the current state and future possibilities of tectonic manifestations and on the implications that technology can have on larger urban scapes. The highly iterative process questions the use of the "computer as a tool" and proposes a re-crafting of architecture as a starting point for the post-digital practice.

The second part of the semester exposed students to various provisional working methodologies that continued the discourse generated by the obsessive initial

Figure 3. Hyper-Curved Shell I by Hannah Westendorf; Hyper-Curved Shell II by Jessica Dancer; Diagrid by Matt Miller (University of Cincinnati)

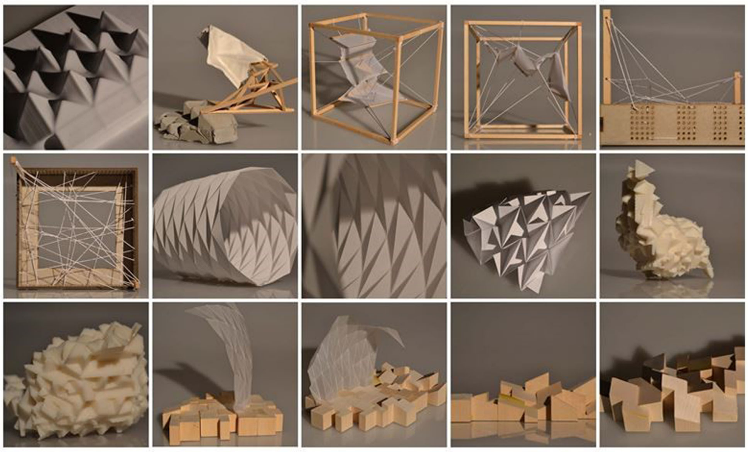

Figure 4. Permutation, Folded Plates by Paul Neidhardt (University of Cincinnati)

indexing. Methodologies included site sensitive design, precedent driven design, and operational (verb based/spatial grammar) design. Unlike the traditional Bauhaus education, this pedagogical approach exposed beginner students to the multiple variables and complexities of the sometimes irrational, highly intuitive, but mostly constrained design process. Instead of offering students with a set of fictitious rules, they were exposed to various and perhaps contradicting perspectives that elaborated on concepts such as mat-building, field conditions and form selects function strategies.

2.2 Zoom Out: From Mat to Field

In 1914, Sant' Elia was already rendering in his "Futurist Manifesto" various arrangements of planes, public spaces, stairwells and inhabitable pockets of space while proclaiming that "roofs and underground spaces must be used" and advocating for plastic dynamism (Da Costa Meyer 1995). In 1974 Alison Smithson was introducing in her article entitled "How to Recognize and Read Mat-Building", the taxonomy of mat-urbanism (Smithson 1974). Mat-building is an open-ended system that is inherently generative. Its elements repeat at different scales, based on a dynamic and perpetual interplay of negative and positive spaces. "The cluster of parts, both interior and exterior, allow for addition and subtraction over time. They combine to produce a built environment that is always evolving, a work in progress, remaining in the process" (MacDonald 2009).

In architectural and urban design, mat-building became visible for the first time with the actualization of Berlin Free University in 1963 by Candilis-Josic-Woods and the Municipal Orphanage in Amsterdam in 1960 by Aldo van Eyck, and in the US with the US Air Force Academy in 1954 by SOM. In the definition of mat-building, the Smithsons replaced the model of the city as a compilation of individual buildings with a woven aggregate formed of stems which lead to clusters. In doing so, they create a unifying mesoscale that blurs the boundaries between the architecture and the urban domain. In later projects, such as the La Villette Competition by Bernard Tschumi and the Yokohama Port Terminal by FOA, a further development of mat-building is conceived that expands on the principles set in the 1950's, when the language was limited by the manufacturing tools and processes of the day (with standardized and rectangular elements).

Exploring plastic dynamism as "a significant evolution of the rectilinear formal language of mat into a more open-ended universe of form-making", students were asked to document the site through a series of field drawings that address forces such as: topography, access, and flows (MacDonald 2009). Departing from the latest version of the misbehaved tectonic system students identified three drawing techniques for their investigation, such as point-grid technique, overlapping fuzzy domains to generate emergent subdomains, and intersecting fluids. The selection of the site, delineated within what Alison and Peter Smithson would call the "charged void" of a natural and urban habitat, was left at the students' preference. The focus of the studio was to perform novel and comprehensive interventions within rigorous assemblies of building cells and voids. The outcome is systematically engaged building and landscape, architecture and urbanism as "autopoietic", highly correlated and differentiated conditions (Maturana and Varela 1980).

2.3 Zoom In: Form Selects Function

While operating the previously defined field conditions, students were asked to make design conjectures that mitigated between cellular units with their aggregation patterns and larger, smoother components with their field conditions. The agenda was to produce mutations of the formerly defined misbehaved tectonic system, "understood as offerings, opportunities, potentials rather than solutions. In that regard, we functioned on the code of novelty as the prerequisite and only employed the criteria of utility and beauty as secondary, fitness testing and reassuring measures" (Schumacher 2011).

Our methodology involved the "form to program heuristics, translated as form selects function instead of function selects form" (Schumacher 2011). We oscillated between the ludic and the investigative, while engaging post-rationalization and programmatic adaptability techniques. "Function, was here therefore understood as 'capacity' or 'affordance' that opens itself up to an evolutionary formation of new purposes rather than fulfilling a fully predetermined purpose" (Schumacher 2011). Program was defined function of active and passive elements. Students were asked to weave these elements as necessary based on intrinsic [program related] and extrinsic [site related] forces. Programmatic constraints were mitigated through the misbehaved structural system. Water collection and solar energy harvesting, for example, were incorporated through folded plate roofs and tectonic frames and grids.

2.4 Tools

After exploring rule-based design in various case studies, the method was tested in relation to structural optimization. The objective of the project was to encourage students to experiment with structural data and design a responsive solution. Long spans and tensile membranes were studied as rule-based systems function of material properties, stresses, loads, deflection, and surface tension data. The authors used a hybrid software approach that includes Maya, solidThinking, Catia, Rhino, Karamba, TopOPT, and Millipede for Grasshopper. The results were composed of complex structural models that were customizable based

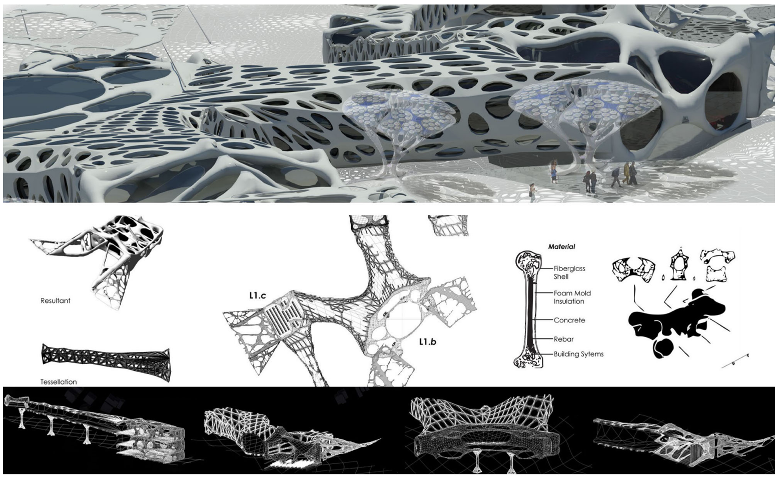

Figure 5. Various structure and load simulation components in solidThinking by Paul Thong (University of Cincinnati)

on rules that govern loads and supports, finite element (FE) optimization, as well as on genetic evolution (through an engine named Galapagos). This method proved to be an invaluable resource with an unlimited potential for structural form exploration. (Figure 5)

Students were required to develop a sequence of iterations that were captured to reflect the optimization process. Rules such as constraints, types of supports and materials were added to yield a matrix of structural form. As a result, students created a high degree of complexity and explored the dynamic possibilities of form building with relatively simple rules embedded in the parametric scripts. These codes contain building performance data from surface deformation to stress loads. The encoding of parameters to construct the abstract building topology lets students easily visualize the inter-connection between rules and corresponding variations. They, consequently, learn how to integrate laws with numeric variables into the design process and, as a result, determine how architectural form should adapt to above-mentioned the rules. Therefore, building forms can evolve and adapt in relation to different load conditions.

3 PROJECTS

3.1 Form Optimization through the genetic evolution engine

For a train station design project, a long span steel frame was created without any load other than the structure's own weight. The maximum stress is determined to be an area that was high from the support plane and relatively far from the structural piers. Then the structure is evaluated based on its stresses, creating a more efficient system. Once the input information is used to create an assembled model, this model is analysed for its performance. This is done using a component found in Karamba which is specifically designed to "calculate the deflections of a given model". The "model" outputs values to visualize the deflection data gathered. Karamba runs a genetic evolution engine named Galapagos to determine the most efficient z coordinates of the surface points. The fitness value appointed in Karamba is displacement. The script changes the current surface to match these "fit" coordinates. Galapagos finds the best solution to be the most "fit" in regards to displacement, when the deflection of

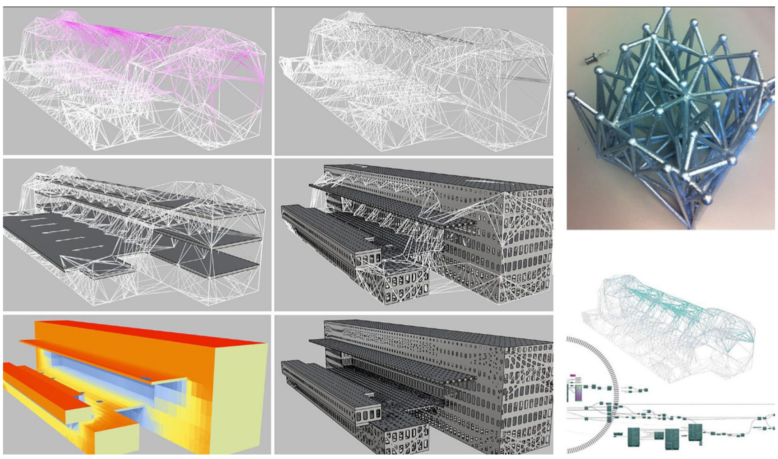

Figure 6. Structural optimization through a genetic evolution engine in Karamba: 3D print conceptual model by Mark Specker (University of Cincinnati)

the beam system is minimum under the point loads. (Figure 6)

The above images illustrate the structure concept of a train station. The size of the pipes is defined according to the stresses shown in the diagram. More stressed frames have a thicker cross section to provide for the support needed. The second process is to create panels along the surface that directly respond to the intersection of the frames and the exterior skin. Galapagos was an integral part of the process of creating the most optimal form of a structural grid. After all of the components are set into place, and the point loads are defined, Karamba seeks the most optimal solution automatically.

3.2 Material allocation

Students have investigated two simulation programs to optimize the material allocation within a defined structural form. The software solidThinking is an engineering tool that shows designers how forces act on a three-dimensional structural element. Therefore, it could be applied to produce more efficient structural elements only by having materials located where the stress is found within the object. This allows for lesser material to be used without altering the structural integrity. Consequently, solidThinking became a research platform for the implementation of experimental topology optimization procedures targeted towards structural design. Through an optimization process, the simulation engine analyzes a three-dimensional object, in conjunction with a series of forces and supports, to give a user the most efficient handling of material within the profile of the defined geometry. The highest stressed areas will require the most structure while the lowest stressed areas require the least amount of structure. Based on this knowledge, areas are pinpointed to remove material and cut down costs.

A similar tool named Millipede requires a structure to be divided into multiple voxels so each element is evaluated on its own. We take each element's center and create a voxel that is dependent on a color/stress. A piece that has high stress will need the most structure, so this void is smaller while a piece that has low stress has minimal structure with a larger void. This process ensures an efficient structure in response to the load. (Figure 7)

3.3 Stress map and adaptive panels

In this case, structural performance is placed as the ruling factor. Finding specific stresses in a system is key to knowing where to strengthen it. Inputs for the solver include supports, loads, and materials while the outputs are more complex but include a variety stresses and material manipulations. This simulation is superior to an analogue process because all of the calculations are automatic, and there is a potential to use the genetic evolution engine that selects the best iteration. Once the deflection and stress simulation results are coded into a colour map across the geometry, they can be applied to the original shape to seek a final, optimized structural and panelling system. This process is simply composed of evaluating which parts of the structure is

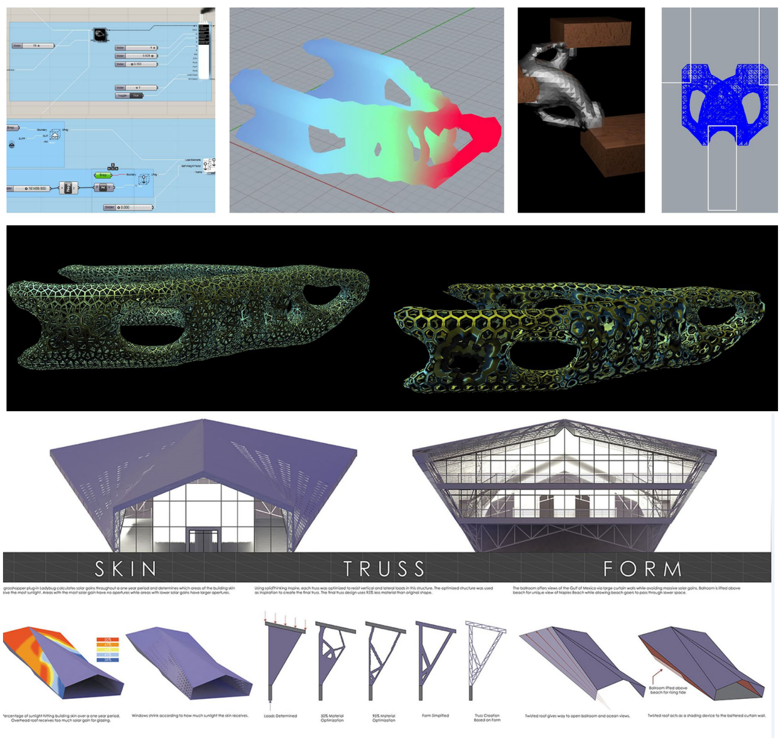

Figure 7. Finite elements analysis for material allocation based on load and deflection by Eamon Meulbroek, Zak Kolada (University of Cincinnati)

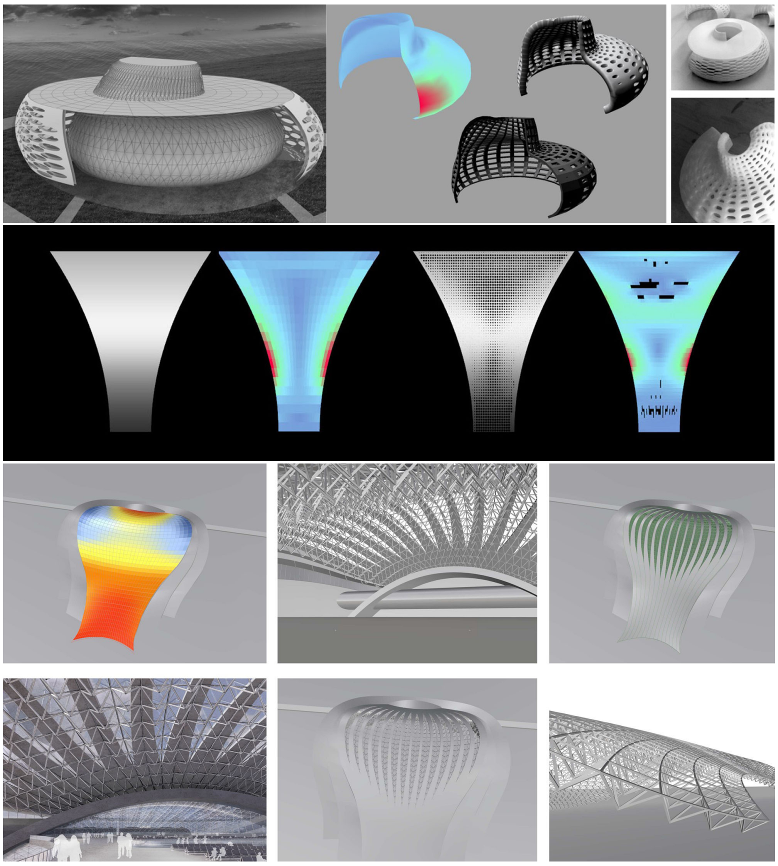

Figure 8. Stress loads control the panels and space frame topology by Denise Polk, Zak Kolada, Kristin Plummer (University of Cincinnati)

truly necessary and which can be eliminated. For instance, a perforated surface can be re-evaluated using the colour map to add more structure where needed until an ideal surface is found. This process creates a new perforated skin that has less stress than the solid sheet would have. (Figure 8)

3.4 Synthesis

Through the recoupling of the terms "zoomable world" and "misbehaved tectonics", concepts such as "misbehaved world" and "zoomable tectonics" are formed, which emphasize cross-programming strategies. These new terms employ the formula "form selects function" and hint at a unique, yet quasi-functional and resilient structural system. Following this process students are asked to synthesize the two parts of the semester and present through their projects a possible resolution to the zoomable world/misbehaved tectonics dichotomy. The outcome of this intensive thesis, antithesis, and synthesis process designed to exploit a tectonic system that meets the needs of a specific program elicited various compelling propositions (Figure 9-10). One of the students' resolutions titled "Muqarnas: Misbehaved" departed from the traditional muqarna dome's structural characteristics and constraints. As a result, a new system emerged to produce a contextually highly correlated, yet programmatically differentiated architectural taxonomy. An educational center for post-graduate professionals located in a forested park, the building is composed of a series of faceted columns of modulated scales that transfer loads through stacked plates. Muqarnas: Misbehaved, therefore, distinguishes itself from the other systems through its inherent structural "matted" condition (Hyde 2001).

The resulted field of inhabitable structural columns negotiates within its fabric the housing of inner [within the column] programmatic elements and outer [within the labyrinthine space around the columns] greater social interactions (Figure 11). The ideas explored encompass the migration of a structural precedent into a dramatically mutated taxonomy to maximize site specificity and programmatic flexibility while allowing for instances of mutual influence to occur. While the diagram has failed to revolutionize architecture as it proved nothing else than a Beaux Arts parti, "we are left with the difficult task to re-envision what makes form happen. Will the generation of tomorrow still make form or write algorithms" that generate a family of formal possibilities calibrated to a criteria set (Picon 2010)?

4 CONCLUSION

These several research projects examined approaches where physics laws were set and integrated into the parametric modeling pipeline to explore the potential

Figure 9. Composite hard membranes by Sam Kissing (University of Cincinnati)

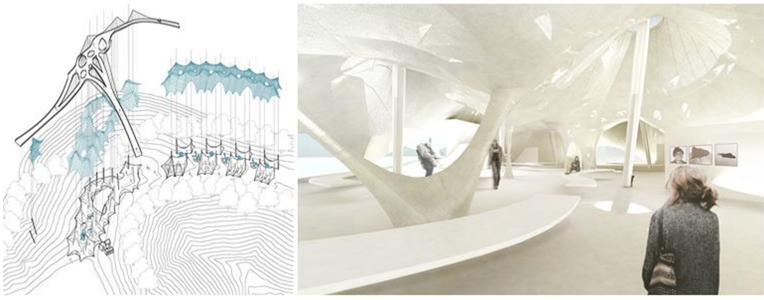

Figure 10. Membranes: misbehaved by Shinji Miyajima (University of Cincinnati)

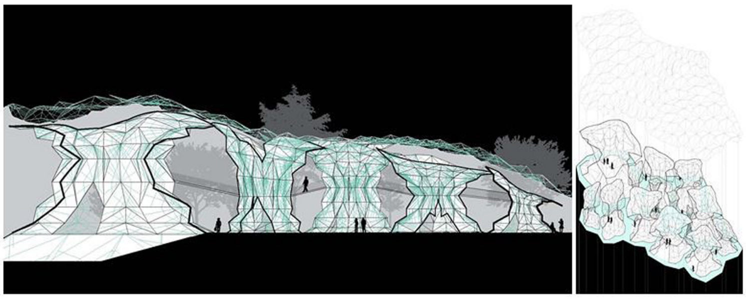

Figure 11. Muqarnas: misbehaved by Samantha Schuermann (University of Cincinnati)

to optimize parametrically a structural solution. The projects extended to the spatial interaction of the rules and their controlled objects. Form seeking was accomplished through the exploration of several simulation techniques, either physics driven or evolution driven. The authors believe that the results expanded the boundary of conventional form seeking through rule-based form seeking. Adjacent to the topic of rule-based morphogenetic, the topic of simulated topological creation has also influenced designers to think of form as a part within a tectonic system where the identity and position of each element is a multiplied across a field of constraints. Here, the formal order of components is decentralized from the predetermined form and exclusively ordered through its relation with all other elements of the system. So instead of thinking of form as the center, simulation-based design has taught students to specify the process of creation before defining the multiplicity of elements and local sources that will determine the formal elements' topology. As designers, we, consequently, need to be methodical about the system of inputs we feed into a parametric utility.

Given the contemporary tectonic incertitude, we are left to tackle the question of a working methodology as an active, at times explosive, but - most likely - in flux notion. Within the current world of multiplicity, the provisional method outlined above provides, through its media engagement, for "the much-needed fiction to begin reclaiming our own freedom" (Picon 2013). In the most reductive sense, the Zoomable World/Misbehaved Tectonic method redefined building typologies as non-linear, anarchic, and nomadic. This thinking creates links between pre-existing gaps while revealing resilient, subversive, yet rigorously targeted insertions in the built environment.

We can conclude that the simulation-based design process has created a concept of "zoomable" tectonics, instability and de-centralization from a static form. The paradigm in architecture has been conceived as an ideal form captured as a single entity. It wasn't until architecture theorists such as Reyner and Banham noted the possibilities of mutable relationships between building systems that we became critical of the architectural process and its outcome. Beginning with the analog form seeking experiments by Gaudi and Otto, we can see a much more interactive process influencing the evolution of structural form. Within simulation-based design, form is now understood as a process of component transformation, or modulation that behaves singularly to the specific rule it has to adapt to.

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