

# PERFORMANCE-BASED GENERATIVE DESIGN

## An investigation of the parametric nature of architecture

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### 1. INTRODUCTION

Today, architectural design process is influenced by emerging generative/parametric design tools and advanced manufacturing technologies. Powerful computational tools can be used to produce variations in design while maintaining the dependencies and relations between iterations. Generative technologies, such as *genetic evolution (GE)* and *performance driven form seeking*, are used by architects to analyze and optimize early design solutions through parameter control.

#### 1.1 Genetic evolution

Evolution and genetic processes that apply biologically-inspired design thinking to architecture have begun to receive more attention due to the intriguing nature of these processes. Designers are using genetic evolution principles as to generate diversity within architectural forms.

Evolutionary design places emphasis on the generation of novelty and originality where the focus is placed on the production of optimal solutions and the processes used to find these solutions from the pool of possible candidates<sup>1</sup>. Besserud and Cotton discuss how the state of genetic evolution is “not necessarily interested in finding only the single most optimal design

solution...but interested in being able to visualize and evaluate a range of many well-performing design solutions.” (Besserud and Cotton, 2008). Emerging aspects in the practice of architecture involve utilizing genetic algorithms in the design process. Also, performance-driven design methods are used to generate rules, such as seeking ideal building forms that respond to environmental constraints. This performance-driven generative design process requires research on its integration to the fitness function, the genome, and the evolution engine.

#### 1.2 Performance driven form seeking

Supported by the modeling and simulations, Performance Based Design (PBD) uses evidence and data as the essential design driver, rather than architect’s intuition. It is a process to create a system of parameters which can be verified, validated and evaluated with facts. Oxman described it as design informed by internal evaluation.<sup>2</sup> (Oxman, 2009)

Here, the performance simulation is no longer just a phase to evaluate the form, but rather the engine of form generation.

The differences between performance-driven and traditional design methods are (Aksamija and Mallasi, 2010):

- *Traditional method*: has certain deficiencies because: (1) it includes simplified assumptions based on rules-of-thumb that can be inaccurate (for example, forcing an aesthetic feature); and (2) may not be accurate in relation with performance measurements of design solution.
- *Building performance-based design method*: has power in predicting a design solution because it: (1) uses performance measures with actual quantifiable data and not rules-of-thumb; (2) aims to develop a model of a complex physical system; (3) uses the model to analyze and predict behavior of the system; and (4) produces a more realistic evaluation of the design.

Today, powerful parametric tools provide both geometric modeling and analysis functions within a procedurally controlled network. The performance data such as heat gain, stress, and solar radiation can be easily quantified and defined to interact with other parameters. It seems that the evolution based computation should effectively generate and evaluate design iterations based on their performance, and seek the ideal solutions. However, there is one major constraint which makes this approach difficult to achieve, at least in the building scale.

## 2. CHALLENGES OF APPLYING PERFORMANCE DRIVEN GE TO ARCHITECTURAL DESIGN

Comparatively speaking, GE is far more successful in biology than architecture, since the process is limited by one major constraint. That constraint lies in the design process missing a shared body plan, which can be defined by common ancestors found in natural life forms passing their shared plan to its offspring – a parent / child relationship. In other words, by changing the proportions of the components in a shared body, nature can generate various types of creatures that all have a relationship tracing back to its original blue print. De Landa believes that "a kind of 'abstract vertebrate' which, if folded and curled in particular sequences during embryogenesis,

yields an elephant, twisted and stretched in another sequence yields a giraffe, and in yet other sequences of intensive operations yields snakes, eagles, sharks and humans." He also adds "...if evolved architectural structures are to enjoy the same degree of combinatorial productivity as biological ones they must also begin with an adequate diagram, an abstract building corresponding to the abstract vertebrate". (De Landa, 2001).

Realizing the difficulty of constructing a parametric shared body plan for an entire building, the authors deconstructed a building into relatively simple components which can operate within a generative computation system<sup>3</sup>. For instance, the parametric tools developed at Perkins+Will concentrate on paneling systems and their morphology. This investigation looks at the part and then applies the system to the whole.

The authors, in a performance based design course offered at the University of Cincinnati, simplified the process and instructed students to concentrate on surface panelization with a certain number of parameters. Here, computation and simulations were used to adapt abstract architectural forms, geometries, and components through the control of quantified parameters. The results were viewed as optimized solutions based around certain performance parameters.

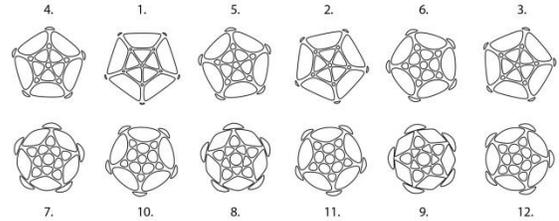
## 3. TEACHING METHODOLOGIES

In utilizing CAD/CAM and simulation tools, the authors merged design computation, digital form seeking, and fabrication through an interdisciplinary collaboration. Building on the ideas associated with generative design processes, we taught two architecture graduate courses at the University of Cincinnati, one titled *Performance driven design and Prototyping*, and the other titled *Non-linear design and parametric thinking*. Both courses focused on computational methods for generating designs through in-depth studies of generative systems. The course concentrated on the parametric design sequence associated with three approaches:

- First, students were asked to investigate procedural modeling for a *shared body* plan. This investigation provided the foundation for the morphological computing.

- Second, their investigation was on *performance-based form seeking*, which became the rationale to define the rules and patterns.
- At last, *digital fabrication* served as the physical realization defined by material, manufacturing technique, and assembling methods. In these three parts, starting with the early design stage, the consideration of “fitness survival” impacted the entire design process.

such as floor area and room dimensions. The goal is to set a few requirements for the plan configuration and rules and let Galapagos generate options for designers to choose from (Figure 1-bottom).



### 3.1 The parametric nature of “shared body plan”

In order to define a spatial “shared body plan”, students composed object families by grouping parameters. Modifying parameters within the design framework allowed for a greater level of morphology to generate variations across individual family instances without losing a defined typology. A correlation was established among these individuals, which allows them to have the same “gene” and be able to “blend” to breed into next generations. A network of operations was used to define the morphing process and assign the weight and correlation to each driver parameter. For instance, a series of snowflake geometries can be generated by manipulating the rules across iterations (Figure 1-top). Realistically, this could be used to create shading patterns on buildings, or develop optimized window screens that respond to environmental issues such as wind and solar gain.

A pre-existing GE solver plug-in, Galapagos, was used as a means to evaluate solutions. Galapagos runs in Grasshopper through the Rhino interface<sup>4</sup>. Evolutionary computing works by giving each variable, or gene, an assigned fitness value. The solver then iterates through different mutations of genes with the optimized solutions surviving. Every iteration thus plays an important role in the way the genes combine. We also introduced several Grasshopper scripts, developed by Dima Chiriakov, which allows manipulation of complex multi-objective problems with each assigned weighted score in Galapagos<sup>5</sup>. For example, in the building layout experiment, a large number of architectural solutions based on a simplified layout were generated in response to multiple weighted fitness criteria

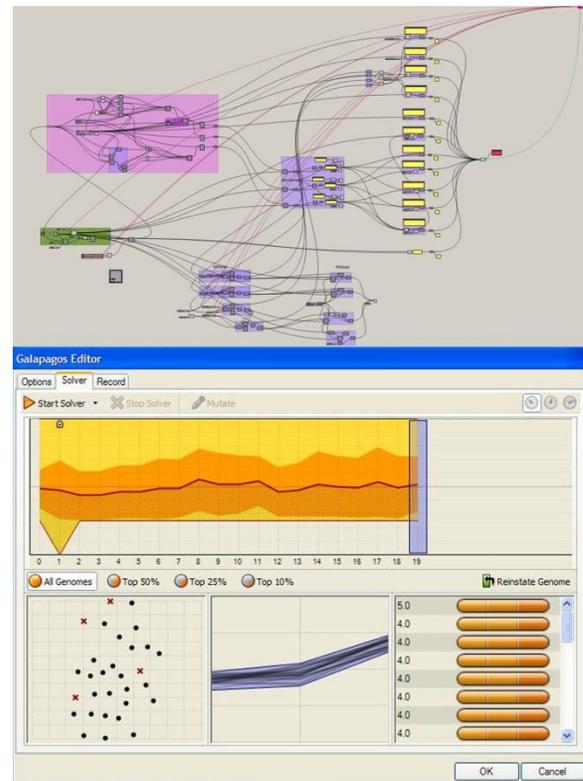


Figure 1. (top) Inspired by the shape and process of a snowflake falling and melting. This screen mimics the form of this evolving circular form. The student simply did an animation snapshot to produce 12 instances of the “snowflake”. By student George Faber.

Figure 1 (bottom). Genetic Evolution based building layout produced by a Grasshopper definition with Galapagos. The success meter is based on true (1 score) or false (0 score) against 12 rules, and to satisfy all these requirements. Multiple generations were used to optimize the solution up to a maximum fitness value of 12. By Dima Chirakov.

### 3.2 Performance driven design and evaluation

The authors used two methods to transfer data between performance simulation programs and modeling software. In the first approach, we used MS Excel to build the bridge. A Revit plug-in, developed at Perkins+Will using Revit API, was introduced to students. The performance data collected from environmental and energy simulation programs can be streamed into Excel and then Revit family in order to parametrically control its morphology. The solar radiation, heating gain, and other non-geometrical data control the panel components and form an adaptive building skin which responds to the environmental data (Aksamija et al., 2011).

The second method is using image-based geometric morphing to transfer the data. By capturing the quantifiable data into image patterns, such as solar radiation map, designers can use the graphic information to drive the deformation and morphing across the family components. This method was initially developed to use GIS mapping to construct the large scale urban form (Tang, 2006)<sup>6</sup>. We refined the method to link a 2D bitmap to each component's morphing weight. The building performance data, such as acoustic and solar radiation analysis results, were integrated into the 3D façade design (Figure 2-top). "The encoding of parameters as a bitmap, either generated by mathematic equation or performance analysis, let the students easily visualize the inter-connection between the data input and the corresponding variations across the 3D façade. (Tang and Anderson, 2010).

### 3.3 Generative approaches during the fabrication and prototyping

Both courses discussed the necessity of expanding the performance-driven form seeking process into the fabrication and craftsmanship. This integrated approach investigates how the large quantity of iterations can be filtered and selected based on the feasibility of fabrication and materialization processes. Often, the essential values of architectural prototyping, such as the property of the material, size constraints of fabrication machines and the assembling techniques, are evolving into a selection process. The process is based on both quantifiable criteria, such as cost, as well as non-quantifiable criteria, such

as aesthetic qualities. After the selection process, each project was fabricated and assembled through laser cutting, CNC milling, rapid prototyping, mode casting, folding, and conventional origami and weaving processes. These techniques and methods were utilized as a means of studying the designs at varying scales (Figure 2-bottom). The tangible artifacts represented the constructability review that each group went through. The precaution to the manufacturing process and material issues, such as tolerance, strength and elasticity, were used to manually modify design iterations to adapt to these constraints.

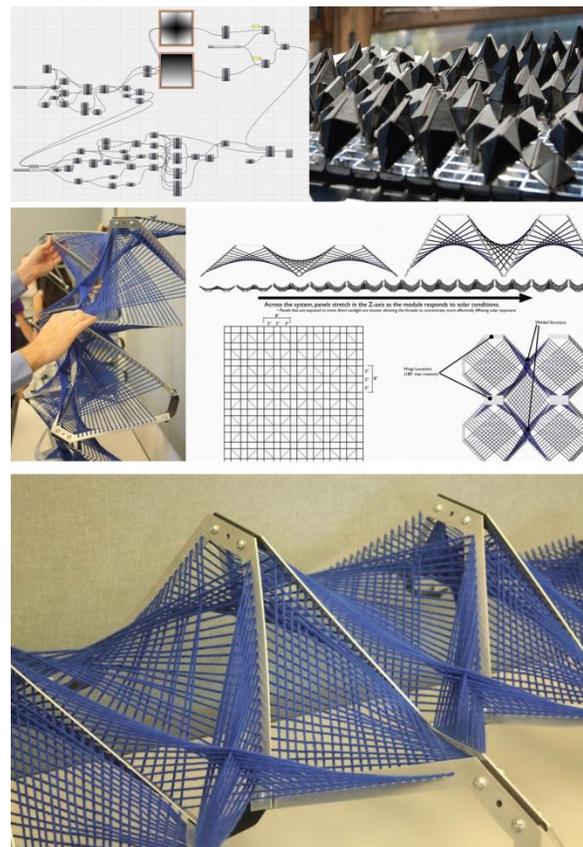


Figure 2-top. The final and possibly most important function of this study is the reaction to "heat" interpreted in the form of an image file. The result is a kinetic composition with potential response to a number of conditions, such as sun exposure, programmatic light issues, and ventilation necessity. By student Kevin Donovan.

Figure 2-bottom. The system consists of a thread woven through a metal frame. As the module moves across the surface, the panel stretches in the Z-axis. This deformation causes the length of the arms to change while the number of weave holes is held constant per panel. By increasing the density of the

string (as the same number of threads are now covering a smaller area), more or less light is allowed to pass through, depending on the depth of the unit. This variation in porosity could be the result of programmatic concerns, a desire for views in/out, or for solar optimization. By student Ari Pescovitz.

**4. SELECTED STUDENT PROJECTS**

As described before, there are several expectations of pursuing generative design processes. One is using it as an optimizer to search a single ideal solution; another is using it as a creative generator for multiple iterations. Students were exposed to both methods.

**4.1 Project: Wing Design**

Generating a wing design is relatively complex due to the many parameters that affect its performance. Such parameters include: plan form and airfoil geometry shapes, angle of attack, draft, and lift factors. David Friedlander, aerospace engineering student at the University of Cincinnati, used Galapagos to aid in his wing design process. By developing several parameters and relationships as input nodes, it allows the user to be able to easily control, construct, and visualize the wing. A visual basic (VB) script was developed to aid in the design of subsonic fixed wings. With the GE engine of Galapagos in Grasshopper, the student was able to maximize the lift over drag for a three dimensional generated wing for the RAF19 airfoil lofted by eight sectional frames. After running the GE script, the results revealed a high aspect ratio wing with slight geometric twist at the wing tips. Here, the generative system acts as an optimizer and constructed hundreds of iterations across many generations pursuing the maximized performance (Figure 3).

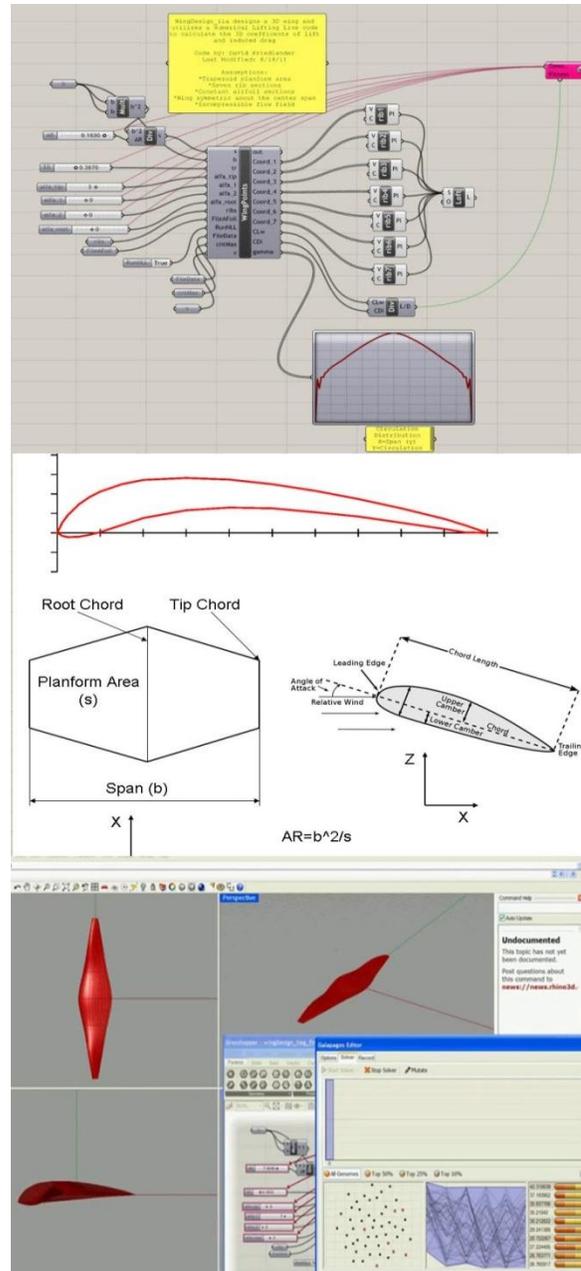


Figure 3. For this particular wing design, the student decided to use the RAF19 airfoil. Maximizing for lift over drag with 50 samples per iteration for 20 iterations, Galapagos came up with the following specs: Aspect Ratio=9.1629, Tip Ratio=0.3671, Angle of Attack=3deg at the tips, 0deg for remaining rib sections. By student David Friedlander.

**4.2 Project: Elastomeric Response**

Elastomeric Response is a student project which seeks design and discovery through digital and analog platforms. The system was designed through material testing and

materialized through digital modeling, tooling, and casting. Castable urethane elastomer was chosen because of its elastic properties, relative tensile strength, and translucent qualities. Here, the generative and iterations were achieved during the folding and sealing process. The form was derived using EPDM rubber roofing membrane by folding and stretching as the elastomer would have. Creating the prototype only in a digital environment became very difficult since it hard to simulate material property and deflection responding to various forces. A final study was produced that exploited the qualities in both the material and casting process (Figure 4).

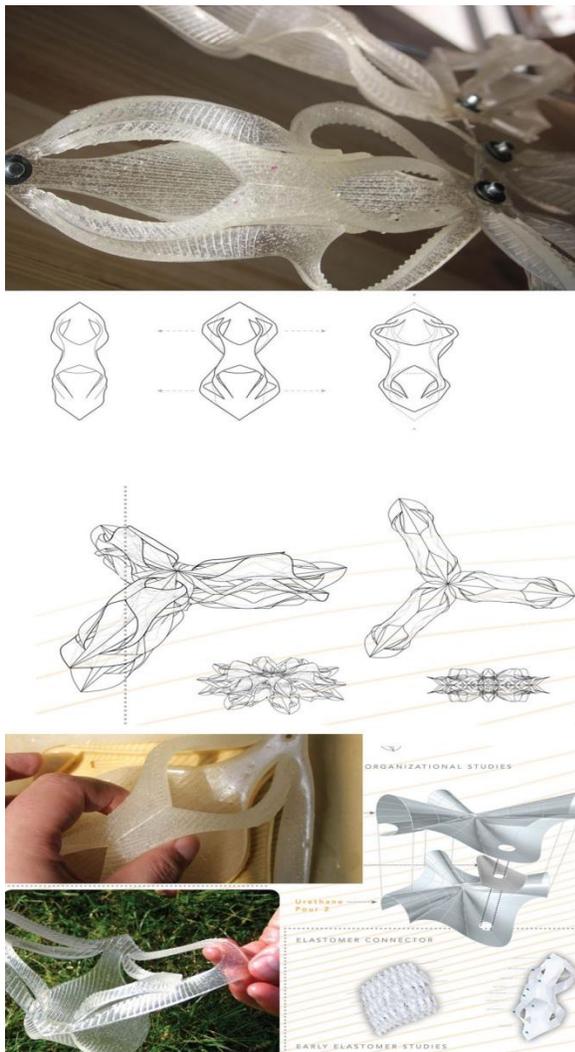


Figure 4. For casting, two elastomer compounds were combined (Hapflex 1021 and 1056) to yield a hardness of about 40A. Heat was then introduced to the elastomer cast to expedite the curing process. A flexible epoxy was used during the assembly process to bond edges and seams, allowing even the joints to

move as needed. Pushnut connections and custom cast connectors were used to connect the system of pieces together. By students Brian Ballok and Trever Jordan.

Due to the form's complexity and several undercuts, the students chose to cast the component's form as a flat surface, and then fold it to its final shape.

Students first created a "shared body plan" in Rhino, and then experimented with various CNC tool paths as a way of embedding a process into the surface for added details. A large number of iterations were generated and evaluated based on how the form could be stretched and folded three dimensionally. The evaluation process was executed by examining the physical mock up rather than GE computation. The final mold was CNC milled from high-density foam, sealed and coated with a release agent, then used to cast each module. This project showed the potential of crossing between digital and analog environments while designing the generative system.

#### 4.3 Project: The Lily

The Lily is the result of parametric and non-linear design thinking which is applied to an initial goal. This objective began with the hopes of creating modular pieces that would interlock together without any extraneous connections, all while operating in such a way that the individual pieces would create many different shapes in their combined state, depending on the orientation and the number used. Several performance criteria were clearly defined at the beginning. These included tessellation qualities in order to conserve materials, flat-pack capability, so that the unassembled product could be shipped conservatively and cheaply, and finally, each individual piece to have a built-in means of connecting to the other so that no glue, tape or other adhesive was necessary.

Created entirely via sketching and numerous experimentations with scissors and paper, the parametric design process was not carried out through computer aided design programs. Like other generative approaches, the student did not have a clear image of what the final product to look like – the student merely had a set of rules that were strictly followed. However, rather than tracing the process through a Grasshopper script or similar means,

the results of the design development were visible in the discarded physical paper models (Figure 5).

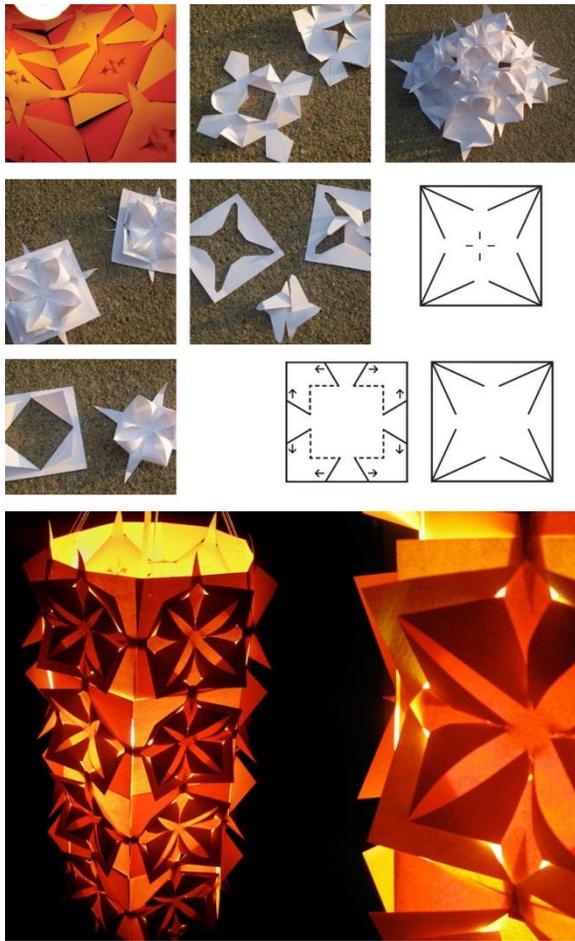


Figure 5. These parameters were directly linked to the final component operating as a performance-based design. Not only did it satisfy all the rules laid down, but it also had an appealing aesthetic quality. Furthermore, it is flexible, can take on a varied number of shapes, and can be coordinated so that the user can interchange components depending on the context of the surrounding environment. By student Sarah Mapel.

## 5. CONCLUSION

Rule based generative systems provide logic and reasoning to analog and digital design processes. Parametric thinking and the concentration of relationships between parameters have generated inspiring results. The essential part of this approach is how to parameterize the design process. By adding a large number of parameters, we have procedurally constructed very complex 3D

forms and were able to manipulate their final topologies interactively. Although the finished results were useful for understanding design process and outcomes, especially how the process can also be executed in the non-digital fashion, the means did not provide an in-depth understanding about generative design process for students and instructors. The evaluation of the result of a generative design process proved to be difficult. Using the developed framework as an optimizer to seek the ideal form provided us with a way to assign the fitness evaluation score. However, we do recognize that this process needs to be integrated rather than arbitrary in nature.

The score value needs to be defined for that purpose, which will allow different design iterations to be weighed against a common performance indicator. For instance, in the scenario of planning community-facilities, the effectiveness of the location is measured by a total sum of distances between the facility and the user. This simple maximum or minimum score comparison can be easily achieved and allow GE to optimize the solution. However, for a building performance related with many performance indicators, sometimes conflicting, such as day lighting value and heat transmission, the evaluation process became overwhelmingly complex for GE to respond. Also, integrating material properties values into a digital evaluation system is very difficult. That is the reason the prototyping with fabrication techniques and testing various post-digital actions is important part of the generative design process.

Overall, the research of parameterized generative design process through digital computation and fabrication is a valuable teaching and research method in architectural design field. This ongoing research is now focusing on how to reinforce the connections among the performance analysis, form seeking, and fabrication technologies under the umbrella of generative design.

## REFERENCES

- Ahlquist, S., and Fleischmann, M., 2008. "Material & Space: Synthesis Strategies based on Evolutionary Developmental Biology", *Silicon + Skin: Biological Processes and Computation, Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Minneapolis, MN, 16-19 October.

Aksamija, A., Guttman, M., Rangarajan, H., and Meador, T., 2011. "Parametric Control of BIM Elements for Sustainable Design in Revit: Linking Design and Analytical Software Applications through Customization", *Perkins+Will Research Journal*, Vol. 3, No. 1, pp. 32-45.

Aksamija, A., and Mallasi, Z., 2010. "Building Performance Predictions: How Simulations Can Improve Design Decisions", *Perkins+Will Research Journal*, Vol. 2, No. 2, pp. 7-32.

Bentley, P., 1999. "The Future of Evolutionary Design Research", *AVOCAAD Conference Proceedings*, Brussels, Belgium, 8-10 April, pp. 349-350.

Besserud, K., and Cotton, J., 2008. "Architectural Genomics", *Silicon + Skin: Biological Processes and Computation, Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Minneapolis, MN, 16-19 October, pp. 238-245.

De Landa, M., 2001. "Deleuze and the Use of the Genetic Algorithm in Architecture," *Design for a Digital World*, New York, NY: Wiley, pp. 117-120.

Oxman, R., 2009. "Performance-based Design: Current Practices and Research Issues", *International Journal of Architectural Computing*, Vol. 6, No. 1, pp. 1-17.

Simondetti, C., and Burry, M., 2000. "Mass-Customization in Design Using Evolutionary and Parametric Methods", *Eternity, Infinity and Virtuality in Architecture, Proceedings of the 22nd Annual Conference of the Association for Computer-Aided Design in Architecture*, Washington D.C., 19-22 October, pp. 239-244.

Tang, M., 2006. "City Generator: GIS Driven Genetic Evolution in Urban Simulation", *Proceedings of the 96th ACSA Conference*.

Tang, M., and Anderson, J., 2010. "Mathematically Driven Forms and Digital Tectonic: A Formula for Realizing the Digital", *Proceedings of ACADIA 2010 Conference*, New York, NY.

in which the formal manipulative skills and preferences of the human designer externally control the process to one in which the design is informed by internal evaluative and simulation processes." (Oxman, 2009)

<sup>3</sup> As Ahlquist and Fleischmann described, "space has to be defined to then be broken down into a series of calculable conditions that can enact pressures upon the organization of material and evolution of the form. It is ultimately critical to have a distinct view of what defines space, what are the characteristics of threshold, and how the constituent parts interact." (Ahlquist and Fleischmann, 2008)

<sup>4</sup> Galapagos, developed by David Rutton, provides non-programmers a graphic interface using GE to derive an optimized solution based on fitness functions.

<sup>5</sup> Simondetti described the form seeking process as "rule-based evolutionary algorithms to generate a common family of individual designs. These values are compounded to a 'score value'. These values are used as *fitness* value for the GA in the next generation." (Simondetti, 2000)

<sup>6</sup> The author developed a tool named "city engine", a new tool allowing designers to effectively implement GE techniques in the design-orientated environment without learning complex shape grammars.

## ENDNOTES

<sup>1</sup> Bentley believes, "instead of using evolution as an optimizer, evolution is now beginning to be seen as an aid to creativity—providing new forms, new structures and even new concepts for designers." (Bentley, 1999).

<sup>2</sup> Oxman describes this approach as "a determinant and method for the creation of architectural form. In such circumstances digital design diverges from a design paradigm