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RE-SKINNING: PERFORMANCE-BASED DESIGN AND FABRICATION OF BUILDING FACADE COMPONENTS:

Design Computing, Analytics and Prototyping

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ABSTRACT

This article discusses a research/teaching collaboration between Perkins+Will and the University of Cincinnati and a unique design studio that was initiated as part of this collaboration. The studio investigated the relationships between performance-driven design, computational design techniques, integration of analysis tools with the design process and digital fabrication for a building facade retrofit. The studio project was an existing cold storage facility, which is being converted into a commercial office building. The objective of this collaboration was to integrate building performance simulations and modeling to drive design decisions, to use parametric design tools for exploration of building skin design and to investigate fabrication/prototyping methods for testing constructability and material choices. We discuss the design process as well as the results of this collaboration. We also conclude with final remarks regarding the best practices for collaborative research efforts between design practice and academic research institutions.

KEYWORDS: simulations, computation, parametric design, fabrication, building skin

1.0 INTRODUCTION

1.1 Background and Motivation

Developments in computational design and simulation applications are providing methods to improve current design practices, since the uncertainties about various design elements can be simulated and studied from the design inception. Building performance simulations aid in investigating design options and the overall building performance and are an integral part of the design process for energy efficient and high-performance buildings[1,2].

At the same time, computer-aided manufacturing (CAM) and digital fabrication are increasingly being used for design prototyping, because they are useful for testing constructability, material properties, form and geometric properties. By combining computational design tools with rapid prototyping techniques in the design process, designers and architects have real-time capabilities to generate multiple design options, iterate design approaches and end with scaled artifacts to study, review and critique the design solutions[3].

What exactly is parametric design? Parametric design relies on control of 3D modeled components through modification of certain parameters of a building model. These modifications are driven by mathematical formulas, data values, numbers or specific computer algorithms rather than manual changes of the model properties. Parametric design also requires use of specialized computer modeling software tools. A key advantage of a parametric design process is efficiency, allowing designers to be able to quickly adapt the characteristics of a model based on certain rules without having to recreate a separate model for each iteration or study. In a parametric design process, the rules governing the parametric controls and association of model elements may represent structural loads, environmental data (such as solar radiation, solar angles, wind velocity) or simply a change in dimensions.

These processes and tools are relatively new to the A/E/C design community. The benefits of parametric design tools in practice have been acclaimed, while also acknowledged as increasing in complexity and time required for certain design tasks[4]. There are case studies where parametric design methods have been used to determine building geometry and curvature of the cladding design for stadium buildings[5]. Other examples include parametric generation of tall building forms[6]. Computational tools such as Maya, Rhino and Grasshopper, CATIA, Solid Works, Inventor and Bentley's Generative Components are all examples of platforms that allow parametric control of model geometry based on rules and constraints. There are also examples of algorithms and computer code that can be used for parametric control of model geometry[7]. Also, custom plug-ins for existing design applications, which allow import of analytical data into BIM applications for parametric control of Revit families have been created and tested at Perkins+Will[8].

1.2 Project Objectives

In this professional and academic collaboration, topics such as parametric design, building performance analysis, simulations and fabrication were introduced with the objective to design and fabricate building facade components. A course named "Re-skinning: Performance Driven Design & Parametric Correlation" was developed at the University of Cincinnati School of Architecture and Interior Design during the fall of 2011. This course heavily relied on involvement of practitioners during the course. Co-taught by Ming Tang, Dr. Ajla Aksamija, Todd Snapp and Mike Hodge, the course covered parametric modeling techniques associated with performance-based design and digital fabrication.

The students were introduced to a real adaptive re-use project, where a 10-story, 400,000 SF (37,000 SM) cold storage facility constructed during the 1910's is being converted into a commercial office building. The independently structured exterior facade of this building will be removed and replaced. Therefore, the purpose of the collaboration was to design a new building skin for this project using digital design methods and performance analysis and to construct physical prototypes using digital fabrication methods.

These three primary objectives were investigated during the collaboration:

* Integration of performance analysis to drive design decisions
* Use of parametric tools to explore building skin design
* Fabrication and prototyping methods to test constructability, material choices and form.

The central feature of this collaboration was to examine new, emerging digital technologies and their applications for facade designs. The benefits for the design practice are that emerging design approaches, technologies and computational design methods were explored in relation to a real project. We addressed several questions during this process:

* Which tools are appropriate for the performance-based design approach? How do they relate to different design stages?
* What is the relationship between digital models and fabrication? What are the appropriate approaches for using design models to fabricate actual components?
* What are the best tools and practices for the translation of a digital design model to the physical prototype?

The collaboration offered us a route to investigate innovative design methods, observe the design and development, document results and applications and share the outcomes and insights into the changing nature of design affected by the emerging computational design methods. This article reviews the design process, collaboration and the results and provides recommendations for best practices for collaborative research efforts between design practice and academic research institutions.

2.0 PROJECT OVERVIEW AND COLLABORATION

2.1 Fulton Redevelopment

Fulton Redevelopment project is located in Chicago, Illinois, and is currently used as a cold storage facility. It was designed and built in the 1910's and consists of

400,000 SF (37,000 SM) of space. This 10-story building is located in the traditional food distribution part of Chicago. Over the last ten years, the surrounding area around the site has undergone drastic changes and redevelopment. For example, new multi-family residential construction, commercial developments as well as adaptation of the existing building stock into residential or commercial buildings have turned this area into a mixed-use neighborhood.

The building's immediate site was rezoned from industrial to commercial use. This building is one of the tallest buildings in the immediate area and has an excellent connection to the existing transportation infrastructure for public and vehicular transportation, as seen in Figure 1. A new elevated train stop is located in close proximity to the site.

The building's primary structural system consists of reinforced concrete slab and columns with drop panels. The existing independently structured exterior walls consist of brick masonry and original cork insulation, whose primary function was to isolate the interior cold storage facility from the exterior environment. The vertical piers and cross beams are thermally isolated from the main structure with cork infill. Since the building's current function is being converted into a commercial space, the primary existing structure will be retained, while the exterior facade will be removed and replaced with a new building skin. The objective is to open up the interior space, provide sufficient daylight and design a high-performing building envelope that minimizes energy consumption.

Figure 1: Fulton Redevelopment project and site.

2.2 Collaboration Process

This collaboration was based on a close working relationship between a design practice and an academic institution. The focus of the project was to redesign the building facade for Fulton Redevelopment using building performance analysis software to guide design decisions as well as emerging computational tools for parametric design and fabrication. The practitioners provided all of the background information about the project and presented and instructed students on the best methods for integration of building performance analysis tools into the design process. Remote video conferencing, podcasts and online collaboration tools were used effectively to monitor the progress of the course and to provide guidance for further development of design solutions and fabrication of prototypes (Figure 2). Also, meetings were scheduled to review and critique design development.

Figure 2: Collaboration.

Digital production processes that were used during the course allowed for distinct design and fabrication phases (Figure 3). Initially, information about the site and its characteristics were compiled and assembled from GIS application as well as existing building conditions from the original construction documents and BIM model. Different software programs were used to develop design concepts, such as Revit, Maya, Rhino and 3D Max. During the design phase, simulation and performance analysis tools were introduced, such as Ecotect, Vasari and custom spreadsheets. Results of the analysis process, such as solar radiation along the different facade orientations, were used to drive design decisions and design optimal facade solutions. Parametric modeling tools, such as Grasshopper, Maya MEL scripts and customized plug-in for Revit, were used to size and position building skin components and determine appropriate forms and geometry based on analysis results. The design phase required the use of simulations and parametric modeling techniques for the design of forms and components based on performance data. The digital fabrication phase introduced different techniques, such as laser cutting, CNC milling and 3D printing, which allowed design solutions to be physically studied and examined. The end results were physical prototypes of building skin components.
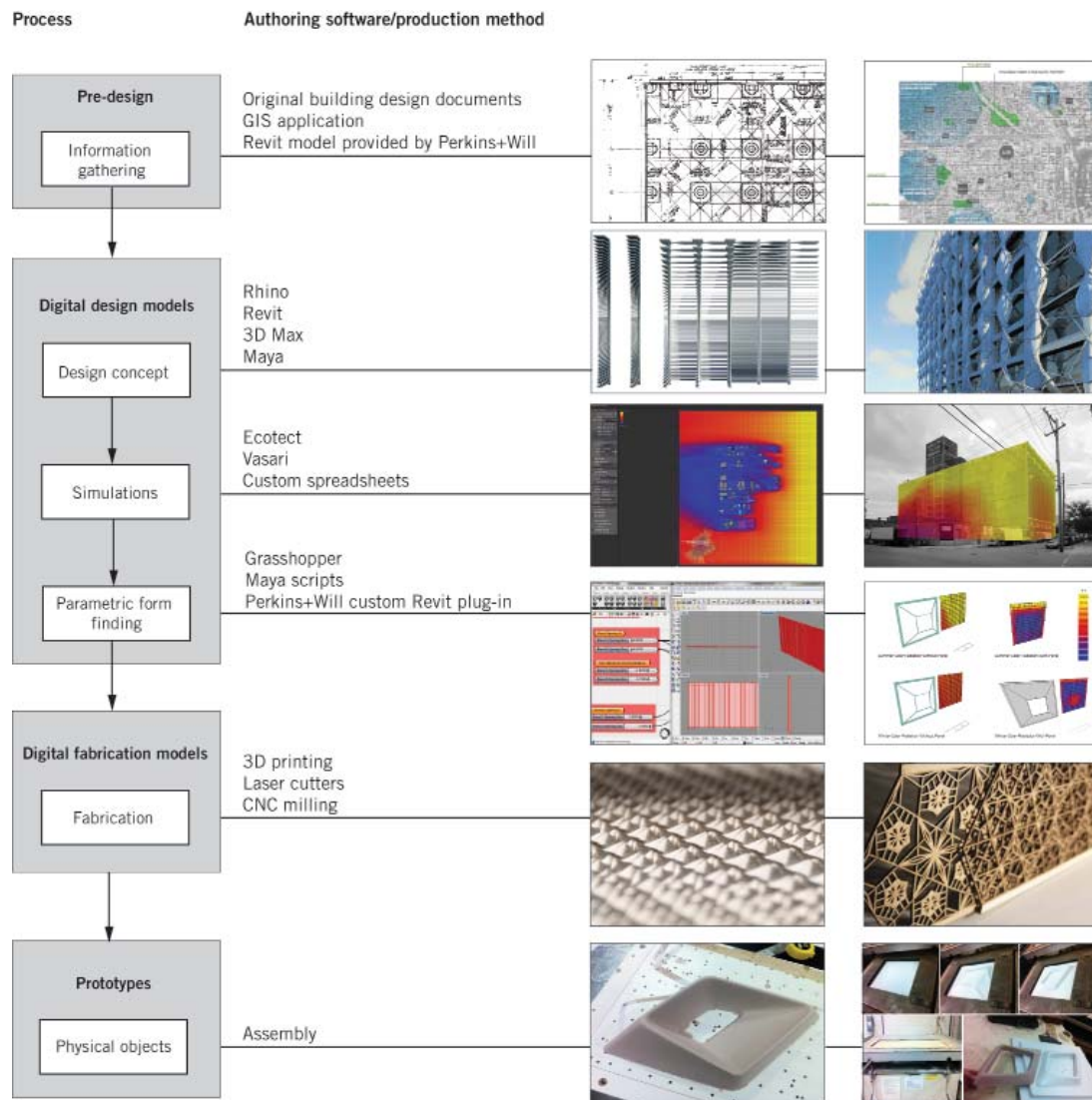

Figure 3: Building skin digital design and fabrication process.

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3.0 PERFORMATIVE DESIGN AND DIGITAL FABRICATION

Emerging digital processes are beginning to impact the profession of architecture in a manner similar to what has occurred in other creative/design disciplines providing new methods to evolve the practice of architectural design.

Traditionally, building performance is considered as an evaluative process. As such, the traditional design typically uses analysis and simulation tools at set destination points in a linear design process. However, performance driven design processes provide computational means to evaluate solutions at any stage and preferably, from the onset of early design to maximize the potential of an integrated design/performance feedback loop. The non-linear parametric model associations, connected to the input from analysis and simulation software, can provide a design feedback loop between geometry and performance/environmental data. In this relationship, parametric geometry associated with analytical data can represent building massing, envelope/wall system shading components or bay spacing in a column grid tied to an external envelope/skin module. In a performance driven design approach, the performance results can become the input for parametric control of geometric model elements, as seen in Figure 4.
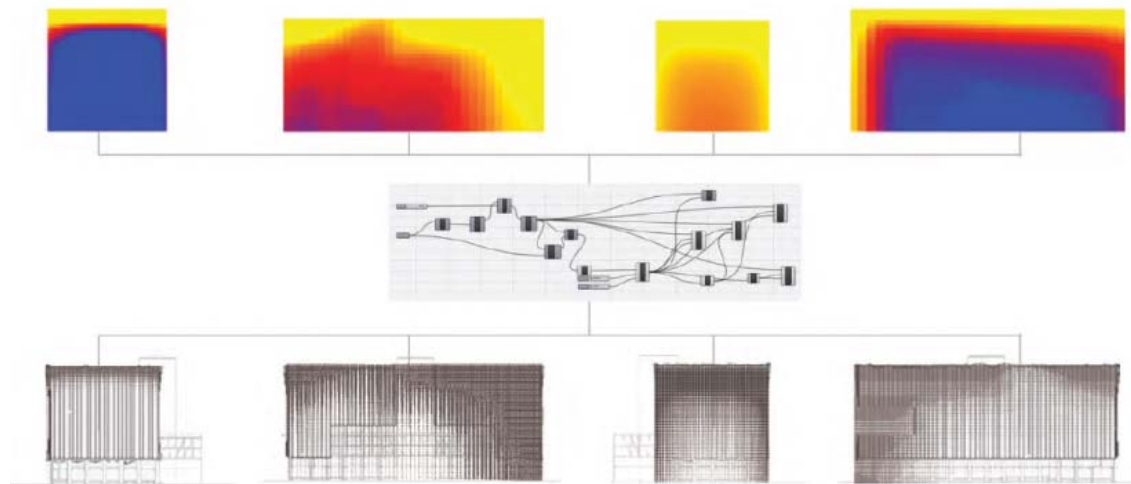

Figure 4: Translation of performance analysis data, such as solar radiation, to form generation via parametric design tools.

As an example, the core of performance-driven design process can be environmental performance data based on simulation results used directly as an input to the parametric building model. The data can be transferred to the model via a spreadsheet or software application plug-in to drive element/component optimization in the model.

Computer-aided Manufacturing (CAM) tools have also yielded a significant leap for designers providing new digital fabrication means of exploring material limits and form. By combining parametric design tools with rapid prototyping techniques into design process, designers and architects have opportunities to generate multiple design options, iterate conceptual approaches and end with scaled artifacts to study, review and critique the design solutions.

These strategies were introduced to students as a series of projects through scaled models, simulated construction and material experimentation. Digital representation (immaterial process) and fabrication (material process) are considered hybrid activities. Digitally generated design solutions were used for digital fabrication, such as 3D printing, CNC milling or laser cutting methods. Several different strategies were used that investigate building representation (immaterial process) and fabrication (material) process, summarized into two distinct paths:
- *Physical representation:* end product as scaled model for physically realizing immaterial form
- *Physical prototyping:* material and form-driven design process.

Part of the challenge, when using digital fabrication in the design process, is the ability to realize the conceptual idea within size limitations and allowances of the current fabrication tools. For example, one of the chal-lenges is how to break down complex forms, which are generated from performance-driven design process, as simplified components that can be manufactured by fabrication and assembling. This can be solved by the slicing and tessellation method, where a complex form is divided into a large quantity of two dimensional contours or patterns, which are fabricated individually and assembled to construct the original form.

The workflow from performance data, such as solar radiation, to the pattern of building skin, to the fabrication stage provided many interesting approaches for building skin designs, which are discussed in the next sections.

4.0 RESULTS

4.1 Adaptable Building Skin
This approach developed a design scenario for adaptable building skin components, which would be able to respond to daily or seasonal environmental changes (Figure 5). The design solution includes two facade systems: 1) standard curtain wall as the primary facade; and 2) secondary movable panels that respond to the changes in environmental conditions by opening and closing. The movable panels consist of channel glass with aerogel insulation and a track system attached to the building's primary facade. These secondary panels would provide improved thermal insulation for the building envelope when this is needed and would reduce building's energy consumption. For example, they would be able to close during nighttime hours when the building is unoccupied, therefore reducing the heat loss between the interior and exterior environment. Parametric design tools have been used to control the positioning of the movable panels along each facade.
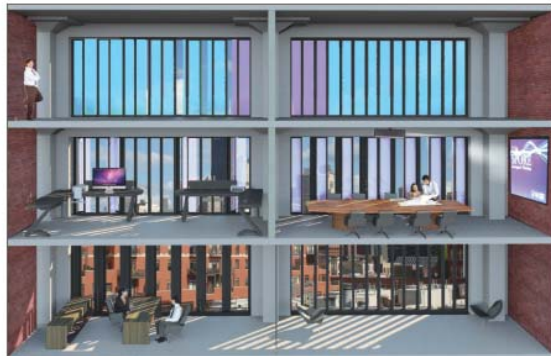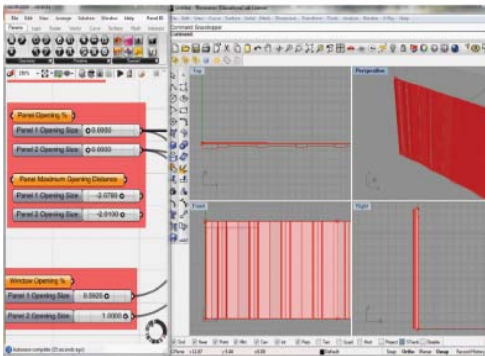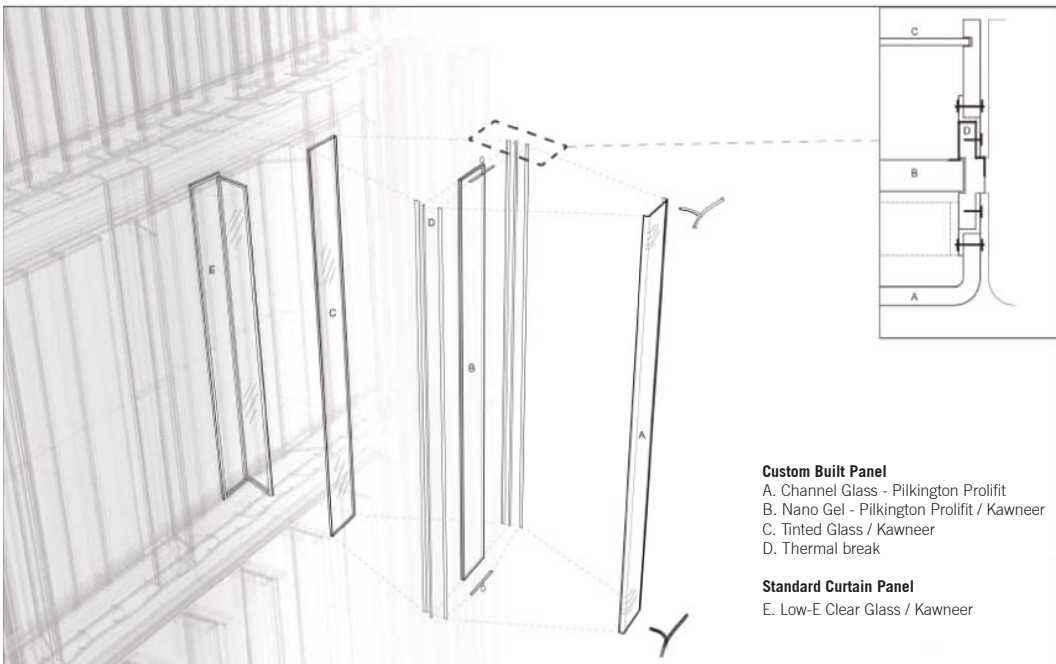
Custom Built Panel
A. Channel Glass - Pilkington Prolifit
B. Nano Gel - Pilkington Prolifit / Kawneer
C. Tinted Glass / Kawneer
D. Thermal break

Standard Curtain Panel
E. Low-E Clear Glass / Kawneer

Figure 5: Adaptable building skin. By John Fricano.

4.2 Double Skin with Kinetic Shading System

This approach developed a design scenario with glazed double skin building envelope, where an integrated shading system would be used to block solar heat gain and reduce energy consumption (Figure 6). The interlocking shading system would be positioned within the double skin cavity. It consists of horizontal louvers, which are able to rotate and change positions using a pivoting system. At least three levels of shading would be possible. Also, different facade orientations would be treated differently, varying the percentage of shading, number and positioning of louvers as well as the angle of rotation of some of the shading elements. Parametric design tools have been used to control the geometry of interlocking shading system, while digital fabrication and laser cutting have been used to develop low-fidelity physical models of the shading system.
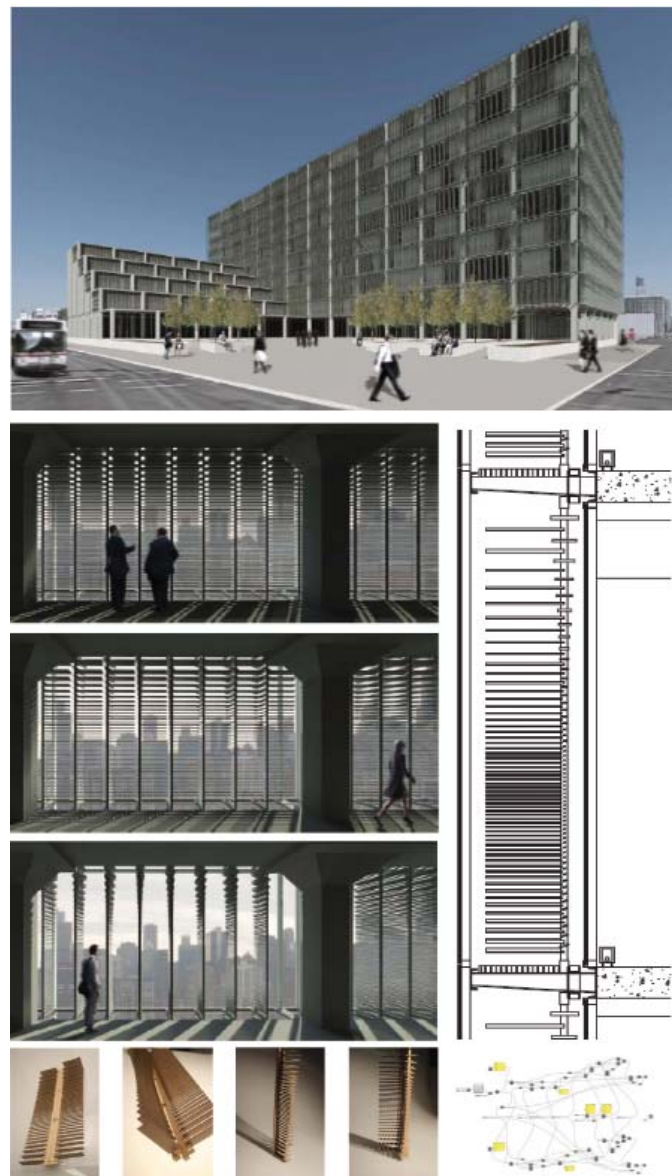

Figure 6: Double skin and kinetic shading system. By Joshua Kuffner.

4.3 External Shading System

This approach developed a design scenario where a sliding shading system consisting of several layers of intricately designed patterns would be able to provide different shading percentage for the facade, seen in Figures 7 and 8. The primary building's facade would consist of a curtain wall with glazing and the secondary external shading system would be able to adjust patterned layers to allow control of shading gradients. Parametric design tools have been used to translate the images of incident solar radiation analysis results along each facade to a shading percentage gradient, which determined the amount of shading necessary for each orientation. Digital fabrication and laser cutters have been used to develop low-fidelity prototypes of the shading layers.
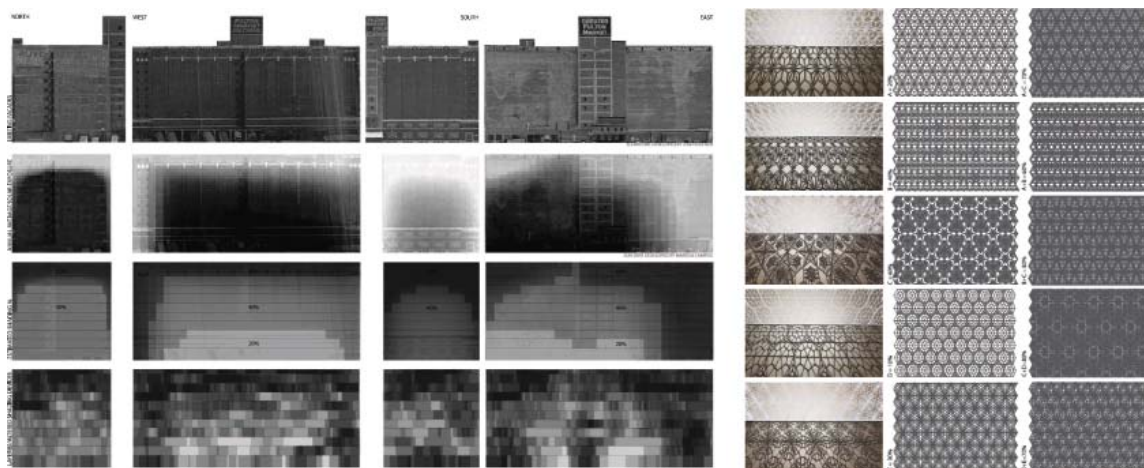

Figure 7: Solar radiation analysis and shading percentage gradient for each facade orientation. By Suncica Milosevic.

Figure 8: Exterior shading system and intricate pattern. By Suncica Milosevic.

4.4 Tectonic Building Form

This approach developed a design scenario where the geometry of three-dimensional shading elements was varied in response to solar radiation along the different facade orientations (Figure 9). Dimensions, depth and the percentage of glazing were varied to reduce solar heat gain for critical areas of the facade with highest solar exposures, while balancing access to daylight.

Parametric tools were used to size and position shading elements, which would be constructed from glass fiber reinforced polymer (GFRP) material. Digital fabrication process for this design solution used CNC milling to create molds for shading elements and low-fidelity prototypes were constructed from vacuum molding process with plastic material, as seen in Figure 10. Early study models were executed using 3D powder printing.
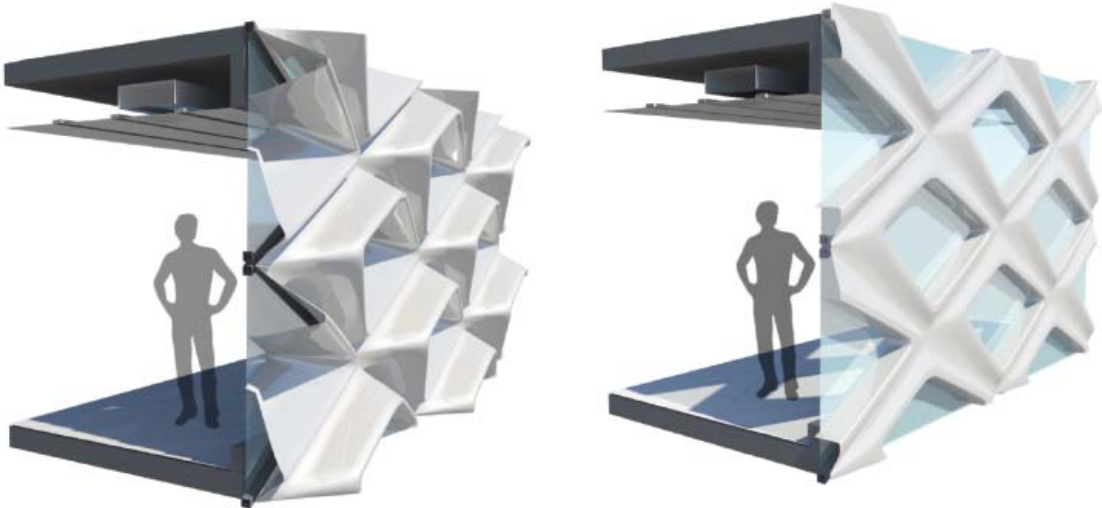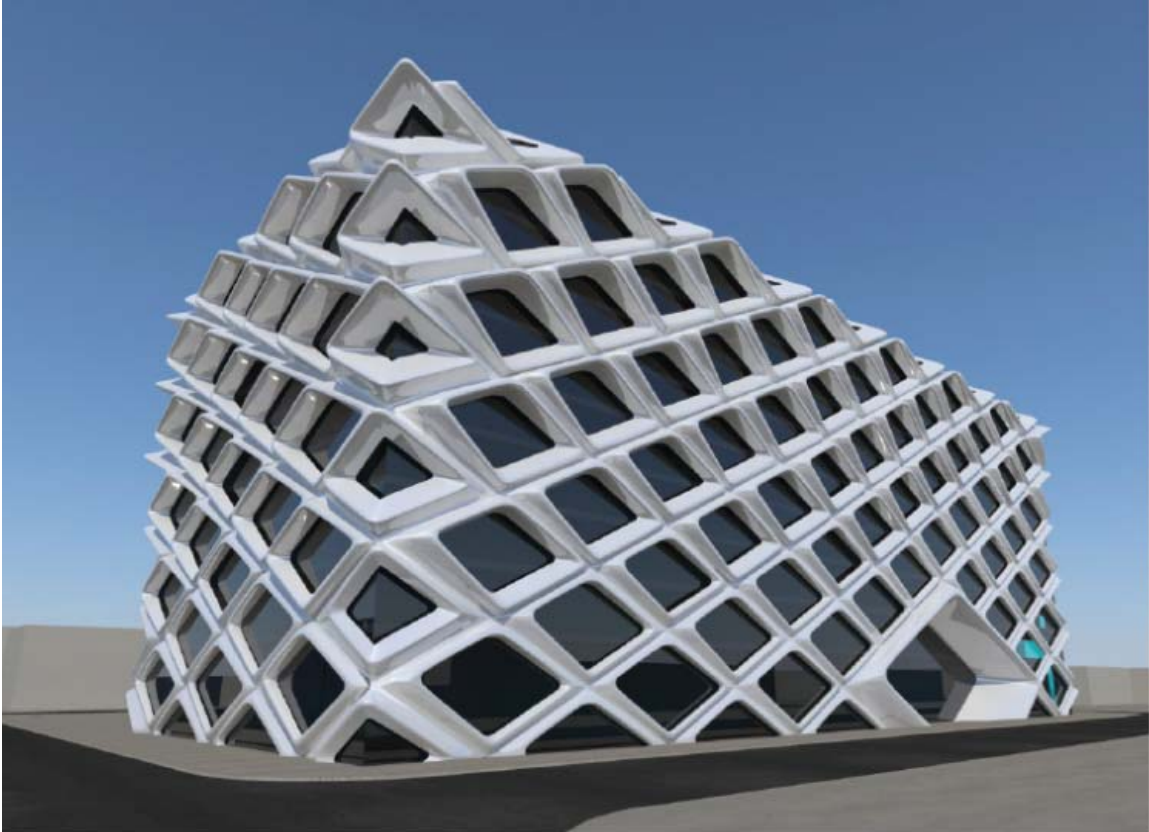
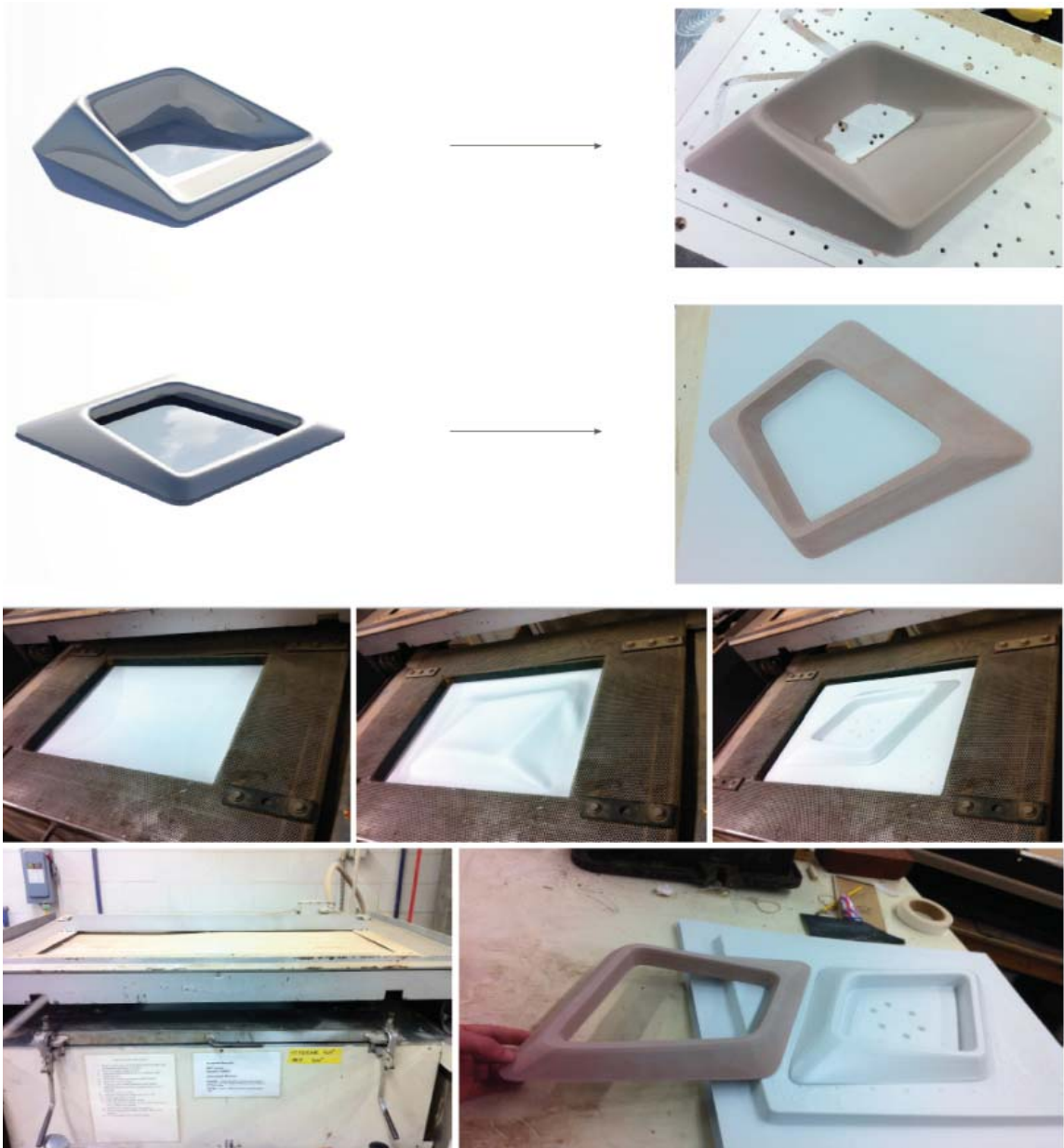25

Figure 9: Tectonic building form. By Andrew Newman.

Figure 10: Fabrication.

5.0 CONCLUSION

New developments in advanced computational tools and methods are offering unprecedented ways for design exploration and evaluations. Performance-based design that integrates simulations and environmental analysis in the design process has an advantage over traditional design methods, because it allows a certain design iteration to be evaluated against different solutions. Also, digital fabrication techniques allow for creation of physical prototypes, which can be used to evaluate constructability, material behavior and selection as well as aesthetic qualities.

This mutual effort between design practice and an academic institution can serve as a model for collaborative research activities, since it specifically addressed new ideas and methods for integrating practice, research and education on emerging technologies. The recommendations from this collaboration are:

- Both design practice and academic institutions benefit from engaging in collaborative research
- The benefit for practice is that emerging design approaches, technologies and computational design methods can be explored in relation to a real project
- The benefit for academic institutions is that this type of collaboration bridges the gap between the profession and research/educational institutions and provides an excellent platform for effective learning and connection to the practice.

Acknowledgments

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