

# INTEGRATED ENVIRONMENTAL DESIGN AND ROBOTIC FABRICATION WORKFLOW FOR CERAMIC SHADING SYSTEMS

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**ABSTRACT:** The current design practice for high performance, custom facade systems disconnects the initial façade design from the fabrication phase. The early design phases typically involve a series of iterative tests during which the environmental performance of different design variants is verified through simulations or physical measurements. After completing the environmental design, construction and fabrication constraints are incorporated. Time, budget constraints, and workflow incompatibilities are common obstacles that prevent design teams from verifying, through environmental analysis, that the final design still ‘works’. This paper presents an integrated environmental design and digital fabrication workflow for a custom ceramic shading system. Using the CAD environment Rhinoceros as a shared platform the process allows the design team to rapidly migrate between the environmental and the fabrication models. The recently developed DIVA plug-in for Rhinoceros allows for a seamless performance assessment of the facade in terms of daylight. Glare and annual energy use are addressed through connections to Radiance, Daysim and EnergyPlus simulations. A custom Grasshopper component and additional Rhino scripts were developed to link the environmentally optimized CAD file via Rapid code to a novel ceramic production process based on a 6-axis industrial robot. The resulting environmental design-to-manufacturing process was tested during the generation of a prototypical high performance ceramic shading system.

**Keywords:** Ceramic, Workflow, Performance, Facade, Robotic Fabrication, Simulation

## 1. INTRODUCTION

Building Envelopes are among the most complex architectural components, combining aesthetic, structural, environmental, and construction concerns, to just name a few. The envelope design process traditionally involves architects, engineers, specialty consultants, and fabricators, each working within their own digital design environment. Information exchange via generic file exchange formats severely limits collaboration. Addressing this problem the authors developed a newly integrated design to robotic fabrication workflow that bypasses several proprietary software platforms, each of which requires specialized training and significant annual investments. Based on a low-cost, commonly used CAD environment (Rhinoceros 4.0), design and fabrication models refer to the same data set. Parametric tools facilitate the environmental design

process and tie directly into industry-standard performance evaluation platforms. Optimized shading lamellas can be produced using a novel ceramic fabrication process that supports the production of varied ceramic shading louvers via a configurable mold and the associated ceramic

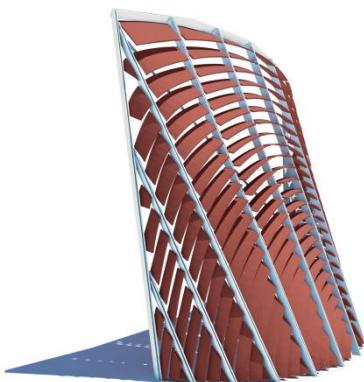


Fig. 1 Rendering of high performance shading system

deposition system. To demonstrate the feasibility of the newly integrated workflow a prototypical robotic work cell was set up and tooled to produce a highly varied, environmentally optimized shading system.

## 2. ENVIRONMENTAL PERFORMANCE: FORM OPTIMIZATION STRATEGIES

The newly developed design workflow allows for validated simulations to be integrated into all phases of the design process. The workflow addresses two trends in contemporary architectural design practice. First, disparate software is used for the schematic design and simulation of daylighting, glare, and energy use. Designers seeking to incorporate simulation results into early stage conceptual design are not only required to master several software interfaces, but manage a complex workflow that requires several steps of exchanging 3d model information between programs. A second important trend is the increasing use of parametric design, here referred to as the definition of form driven by relationships between variables, encompassing methods described as relational modeling, variational design, constraint based design, procedural modeling, and algorithmic design. While these methods are not new, and to some extent exist in any computer-aided design (CAD) environment, new interfaces have increased the accessibility of such methods to a broader range of designers. To address these two trends, a plug-in for Rhinoceros called DIVA-for-Rhino was previously developed [1]. Rhino was chosen because of its widespread use in North American architecture schools, its increasing use in practice, and the availability of plug-ins like the graphical algorithm editor Grasshopper. DIVA stands for design, iterate, validate, and adapt. It is an interface for Rhino that brings together a series of performance evaluations including radiation maps (Radiance/GenCumulativeSky), visualizations (Radiance), climate-based metrics (Radiance/DaySim), glare analysis, and LEED IEQ Credit 8.1 Compliances (Radiance) [2].

In addition to the simulations enabled by DIVA, a Grasshopper component was developed to add a description of each variant's shading geometry to an input data file (IDF) for thermal analysis using the EnergyPlus

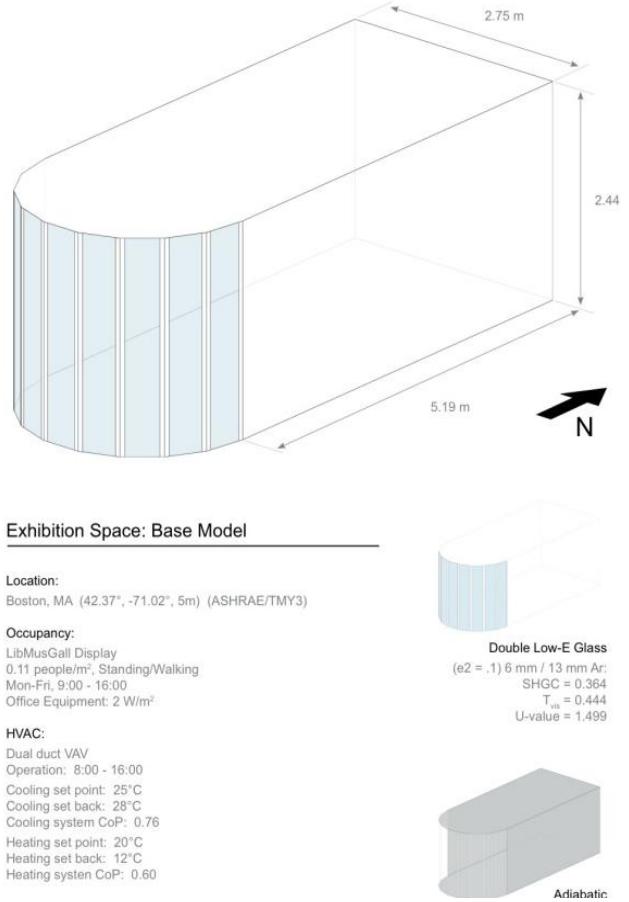


Fig. 2 Thermal model variables

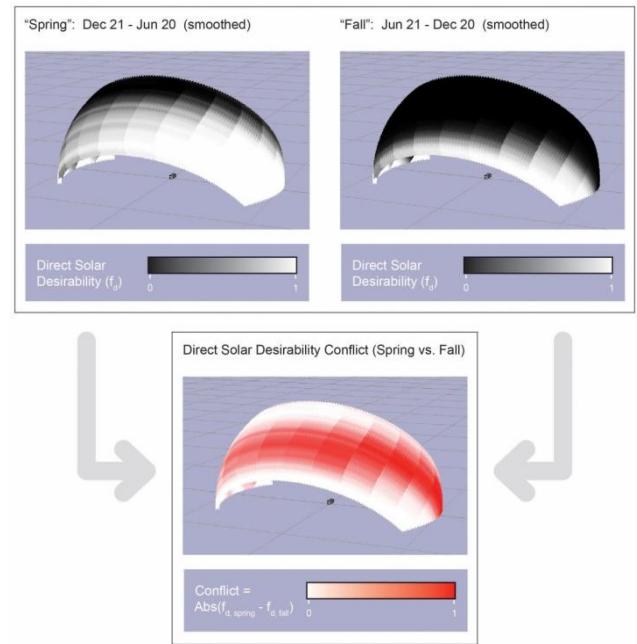


Fig. 3 Different shading demands combined into a single "custom" sky patch

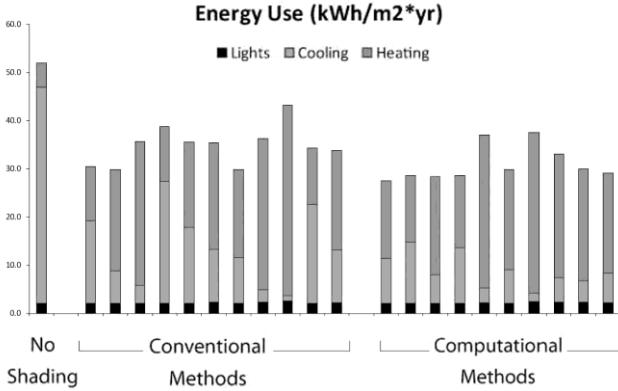


Fig. 4 Annual lighting, cooling, and heating energy for the shading variants tested

engine [3]. The key variables of the thermal model are described in Figure 2. It is a single zone model, with all surfaces set to adiabatic except the glass façade, representative of a single room in a larger building. Each shading variant was added to the exterior of this model for the thermal, daylight, and glare simulations.

Two design generations were tested to compare the performance of conventional shading designs to a more formally accommodating constraint based approach. Following a baseline “no shading” variant, 12 iterations, generated manually for horizontal, vertical, and eggcrate louvers, were tested. These conventional designs were then tested against louvers which were constrained by shading dates or the shading desirability applied to the sun-path diagram as described by Olgay & Olgayay [4]. Figure 3 illustrates the approach to the traditional sun-path diagram. The desirability of solar gain, calculated from an hourly thermal simulation, is mapped to the region of the sky where the sun is located at that respective hour. The map further visualizes the conflict inherent to the fact that weather patterns are not symmetric around the summer solstice; solar gain may be desirable in the spring and undesirable in the fall for the same sun location.

Rather than rules-of-thumb for sizing vertical or horizontal projections, the use of the latter constraint based methods allowed the development of non-planar and non-cardinally oriented shading forms. The workflow validated the performance of unconventional constraint based forms. In addition, it developed a digital model of the design which

could adapt to a range of further material and construction constraints. This ultimately resulted in a complex louver design mapped over a conoid surface as a means of further developing the integrated workflow.

### 3. COMPLEXLY SHAPED CERAMIC LOUVERS

Ceramic materials, and specifically clay-based ceramics used in architectural construction offer the unique potential to realize complex form in architectural components when combined with suitable production methods. Given the potential formal complexity inherent in the ceramic material the research developed a novel fabrication process that integrates robotic systems into existing industrial ceramic processes. The integrated process allows the complexly shaped ceramic louvers to be produced. Current industrial production relies on hydraulic pressing and, to a lesser degree, on extrusion as the most commonly used production methods. These high volume production processes make individual part customization virtually impossible. Craft-based methods for customized ceramics are costly and produce highly variable quality. Shaped ceramic tiles similar to the shading louvers produced as part of the present work could normally be produced by extruding flat ceramic slabs and slumping them over single-use, individual molds - a potentially wasteful and time-consuming process. The newly developed, modular design to fabrication process for shaped ceramic tiles addresses specific production challenges of ceramics, but allows broader insights in the underlying principles of design automation in the context of architectural customization [5].

### 4. DESIGN DETAILING

Following initial performance optimization described above the louver geometry is further developed to accommodate specific construction parameters and material constraints. The environmental design process leaves off with a continuous louver surface model which, in a next step, is subdivided to accommodate the supporting structure and the associated louver length. The surface subdivision is automated through a Grasshopper definition designed to offset the user-defined supporting

structure and acknowledge the desired connection detail. The resulting individual louver surface geometry is used to define the central axis of the component and locate attachment mechanisms on the support.

The structural requirements of individual louvers can now be addressed within the thickness definition that also accommodates a reservation for anticipated shrinkage during drying and firing. The thickened louver is created by a surface offset that allows the trimmed end to remain normal to the louver in preparation for manufacturing.

## 5. SIMULATION FEEDBACK

At this stage the 3D design model includes all features needed to incorporate detailing and structural constraints. Since the model is produced within the software platform that also supports the environmental optimization, the final design can be easily used to re-run the simulation environment DIVA-for-Rhino. The simulation helps to understand how the performance of the shading system has been affected through the incorporation of construction constraints. The iterative feedback loop of simulation and design detailing is facilitated because the integration of detailing needs is automated. Once a satisfying solution has been derived the final geometry is frozen for use in the generation of the robotic code needed for the production process. In practice the latter step would be conducted by

the fabricator, while the former steps would reside within the design team including architect, façade consultant and environmental engineer.

## 6. INTEGRATED MANUFACTURING

To support the novel ceramic deposition process a modular variable mold was developed to overcome inefficiencies of traditional one-off mold techniques. The new low cost mold incorporates a series of adjustable 'pins' that can be translated in the z-direction to approximate complexly curved surfaces. Each pin is individually actuated by a custom end effector that is used in combination with a 6-axis ABB-4400 industrial robotic arm. After setting the pins their ends precisely replicate the digital surface of the thickened louver in the design model. Pins are locked into place and covered by an interpolative surface that accepts material deposition. To facilitate the robotic pin actuation a series of custom Grasshopper definitions and RhinoScripts were developed that derive positioning commands from the optimized geometry developed in the previous stages of the workflow. In this stage each digital component is extracted from the central digital construction model, rotated and positioned relative to the requirements of the manufacturing process. Additional material constraints can be considered and included as elements within the scripts. In the context of ceramic production, additional constraints

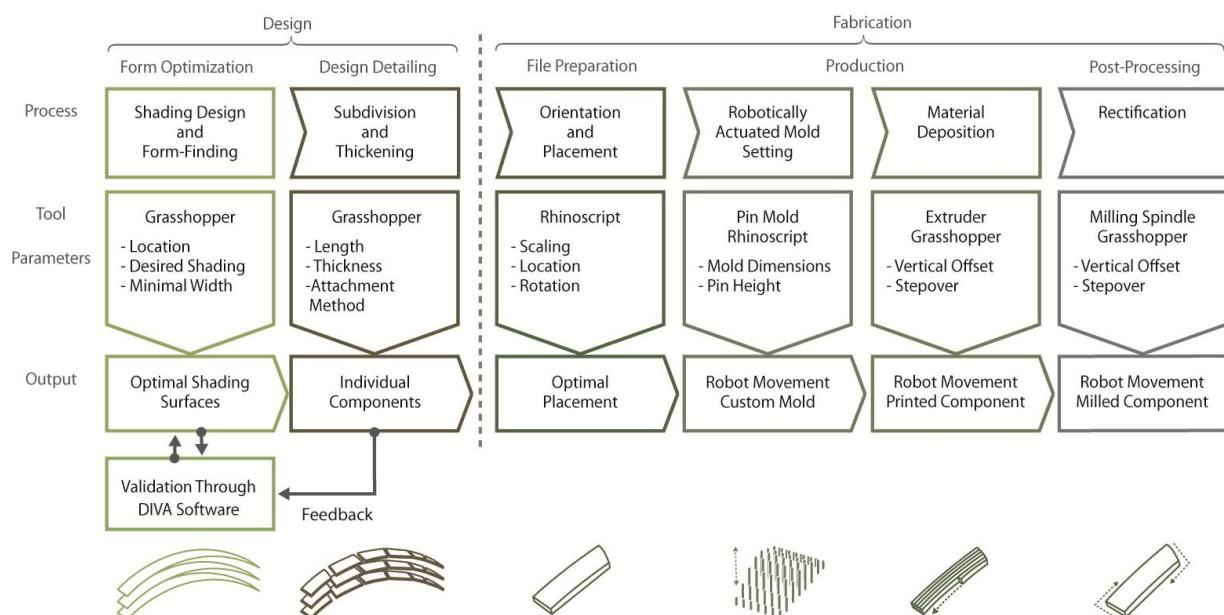


Fig. 5 Integrated workflow with information feedback

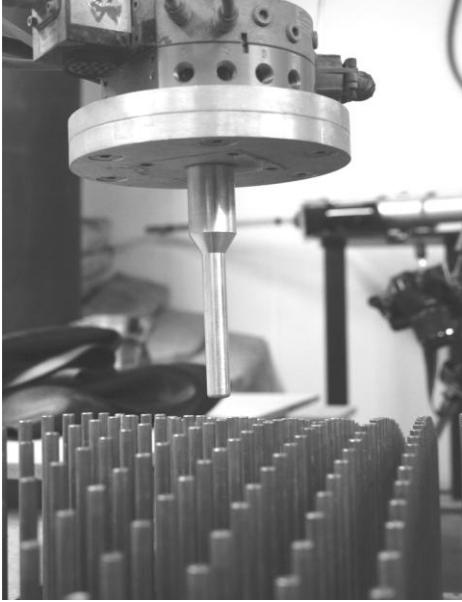


Fig. 6 Robotically actuated variable mold configuration

include material shrinkage during the drying and firing process. The dimensional changes are accommodated within the scripts by a parameter that scales each component based on the precise shrinkage tolerances of the individual clay body. These parameters can be modified to accommodate a wide range of variation and array of material properties, including those of non-ceramic materials.

The material deposition process is facilitated by a custom extrusion system that is carried by the robotic arm. The development of this system referenced Koshnevis's research in contour crafting [6]. In this process specific clay mixtures are deposited normal to the mold surface in overlapping paths to form each individual ceramic component. Proper control of the path overlap, coordinated with the rate of deposition and speed of the robotic arm movement, results in uniform cohesion of the ceramic material into a homogenous part. This process utilizes a parallel tool path that is derived from the production geometry of the louver. This toolpath is different from a milling toolpath that could be readily derived by using a commercially available CAM software. Again Rapid code – a customized version of C language - is exported directly from Rhinoceros using custom scripted components.

Due to inconsistencies in the clay body, and taking into account variations during the drying and firing process,

high-quality industrial ceramic products are often dimensionally rectified at the end of production to achieve precise tolerances. For the same reason, the developed production process utilizes robotic post processing at the green state that provides consistent thickness and exact part shape. By addressing these dimensions at the green state over 50% of the problematic shrinkage is eliminated and a finish is achieved that is consistent with industrially produced counterparts. Post processing is the final stage in the workflow and prepares the parts for firing. In the case tested, dimensional rectification is achieved through robotic milling. Using the automation tools developed, the model geometry is adjusted for firing tolerances. Rapid code for surface milling tool paths and contour cuts is generated through custom scripts. Without manual tooling all needed code for the 6-axis robotic workcell is created directly from the central Rhinoceros model.

The integration process was tested with the production of the full-scale prototypical façade section. The design approach employed a curved base geometry. Louver divisions were informed by limitation of the ceramic material and production such as kiln dimension and firing times. 30 louvers were produced and tested to be within the fit tolerances of the supporting frame, indicating that the material and construction parameters are adequately addressed by the workflow.



Fig. 7 Ceramic deposition in progress

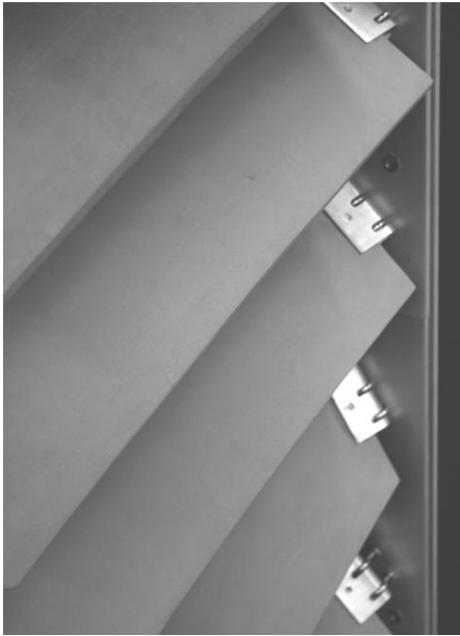


Fig. 8 High performance ceramic shading prototype

## 7. SUMMARY AND CONCLUSION

This paper presents an integrated design to robotic fabrication workflow that, while developed for a high performance ceramic facade system, is easily transferable to other material systems. Custom Grasshopper components and custom scripts integrate all necessary steps within a single software platform. This design automation approach facilitates the collaboration of all team members involved with the conceptual design, design development and design-for-construction of customized, high-performance facades. The digital workflow also directly supports the fabrication environments. It facilitates the iterative simulation of the construction geometry, verifying that geometry created in the early stages of design performs as predicted.

Environmental optimization generated highly customized louver shapes, potentially leading to a visually rich and complex façade pattern. In practice there is widespread interest in the purely formal expressions of parametric design, an interest that often leads to the same need for customization even without performance optimization. Only by re-thinking existing fabrication processes, and by developing related digital design to production environments can highly variable design geometries be

more readily implemented in physical form. Architectural construction has long struggled with the dilemma of customization in the context of costly one-off crafted construction versus inexpensive but relentless high-volume industrial production. Robotic technologies and related design automation approaches may finally offer a third path to escape the age old dilemma. Focusing on environmental performance as a driver of customization does not mean to abandon design – both are no longer mutually exclusive.

## ACKNOWLEDGMENTS

Research was supported by a grant from ASCER Tile of Spain.

## REFERENCES

- [1] K Lagios, J Niemasz, C F Reinhart, "Animated Building Performance Simulation (ABPS) - Linking Rhinoceros/Grasshopper with Radiance/Daysim", *Proceedings of SimBuild 2010*, New York City, August 2010.
- [2] Ward, G. and Shakespeare, R. *Rendering with RADIANCE, The Art and Science of Lighting Visualization*, Morgan Kaufmann Publishers, San Francisco, CA, 1998.
- [3] US-DOE. EnergyPlus V5.0. from. US Department of Energy, Building Technologies Program, <http://apps1.eere.energy.gov/buildings/energyplus/>; 2010.
- [4] Olgay, Olygyay, *Solar Control and Shading Devices*, Princeton University Press, Princeton, New Jersey, 1957.
- [5] Bechthold, M., "The Return of the Future: A Second Go at Robotic Construction", *Architectural Design*, Vol. 80(4), pp. 116-121, 2010.
- [6] Koshnevis, "Experimental investigation of contour crafting using ceramic materials", *Rapid Prototyping Journal*, Vol. 7(1), pp.32-41, 2001.