robust levels of data output for environmental performance, structural load capacity, and geometric variation enhancement. This will require the use of testing labs working with the engineering labs on our campus and expanding the collaborative nature of this work.

As well, there is a desire to increase the scale of the physical testing. Through our collaborative working partnership with a national leading precast company, we have established an opportunity to work toward mock-ups in their facility that exceed what we have currently been able to produce in our own facility. We feel that the combination of the quantitative and qualitative data will strengthen the research in a very important way. Ultimately it will be the increase in scale and the more precise control factors articulated through the parametric software that will produce enough data for us to assess the viability of our working hypothesis. At the moment our phase one–level investigations have provided proof of concept in linking the working methods at a cursory level to the output possibilities. Phase two will evaluate the testing of larger prototypes with a closer and more rigorous methodology for how the panels perform relative to the issues unique to each panel type.

ACKNOWLEDGMENTS

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WORK IN PROGRESS

FABRICATING SUSTAINABLE CONCRETE ELEMENTS: A PHYSICAL INSTANTIATION OF THE MARCHING CUBES ALGORITHM

Jesse Jackson
OCAD University

Luke Stern
Patkau Architects

ABSTRACT

This paper explores how an algorithm designed to represent form can be made physical, and how this physical instantiation can be made to respond to a set of design imperatives. Specifically, this paper demonstrates how Marching Cubes (Lorensen and Cline 1987), an algorithm that extracts a polygonal mesh from a scalar field, can be used to initiate the design of a system of modular concrete armature elements that permit a large degree of variability using a small number of discrete parts. The design of these elements was developed in response to a close examination of Frank Lloyd Wright's Usonian Automatic system, an architecturally pertinent historical precedent (Pfeiffer 2002). The fabricated results positively satisfy contemporary design criteria, including maximal formal freedom, optimal environmental performance, and minimal life-cycle costs.

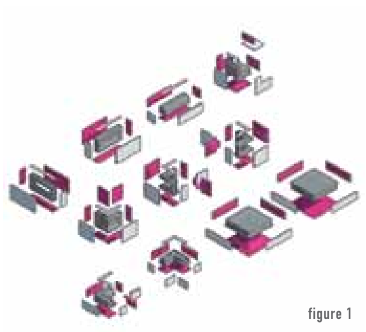

figure 1

1 INTRODUCTION

Our research trajectory began with the observation that computer graphics algorithms used to subdivide a scalar field into a cubic-grid polygonal mesh might have a physical analog in element-based construction. This led to iterative attempts to design an element-based construction assembly derived from Marching Cubes, a seminal example of this type of graphics algorithm. The validity of the most promising design was then tested though full-scale fabrication using contemporary rapid prototyping technology.

An in-depth examination of Frank Lloyd Wright's Usonian Automatic system provided an architectural context for these explorations. The Automatic system, like our proposal, also provided a rule-based means to subdivide a regular, gridded space to create form while also considering the constructional element as a design exercise in itself.

2 A CONCEPTUAL FRAMEWORK: PRIORITIZING THE TECTONIC ELEMENTS

Subdivision into elements, through pixels, voxels, or tessellation, is a fundamental quality of the virtual realm. In the physical realm, the analogous unit parts are commonly referred to as the tectonic elements of built form, and are normally considered to be subordinate components of a greater architectural endeavor. These elements have desired qualities—firmitas, utilitatis, and venustatis—comparable to that of an aggregate assembly, and warrant direct design consideration (Frampton 1995). The parallel between virtual and physical elements was utilized in service of an original design for a unit-based system of construction.

2.1 A Point of Departure: Frank Lloyd Wright's Usonian Automatic System

Frank Lloyd Wright's Usonian Automatic system of concrete block construction is a well-known precedent for the prioritization of the tectonic elements (Frampton 1995). Deconstruction, reconstruction, and replication of this system provided a point of departure for our research. Though much of this work is outside the scope of this paper and has been documented elsewhere (Jackson and Stern 2009), it is summarized here for context.

Wright used the term Usonia to denote his vision for a new American landscape characterized by a diffuse agrarian urbanism. In particular, Usonian refers to a series of modest family homes featuring native materials, flat roofs, and large cantilevered overhangs. Early Usonian homes used a wood board-and-batten construction technique, but faced with rising labor costs in the 1950s,

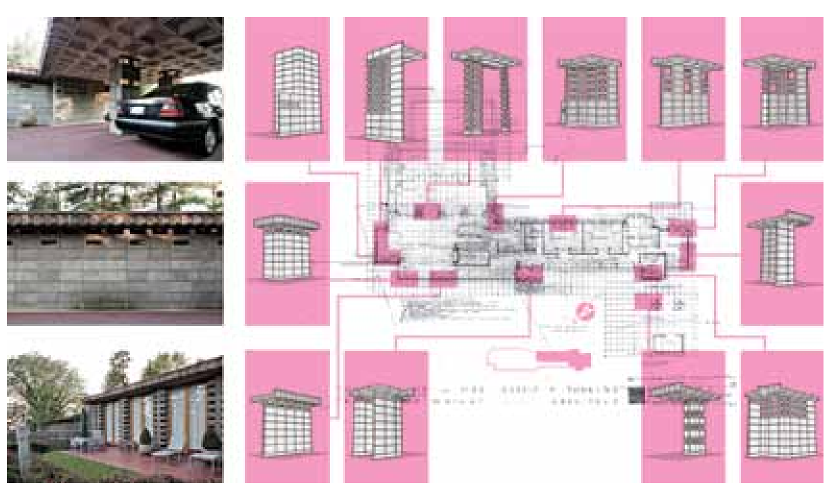

figure 2

figure 1
Frank Lloyd Wright's Automatic elements.

figure 2
In situ use of the Automatic elements.

figure 3

figure 4

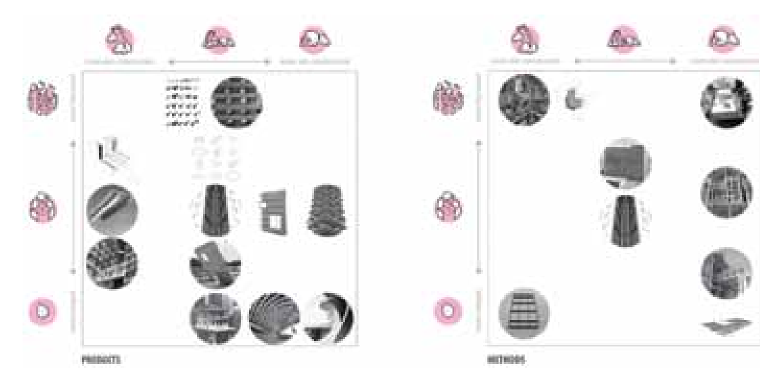

figure 5

Wright turned to concrete. The term Automatic was adopted because the revised design created the potential for end-user assembly and therefore economy, facilitated by a strict grid that determined the dimensions and relative positions of the constituent concrete elements. These elements can be seen as miniature manifestations of the buildings they create, each with a sense of mass and texture that continues to be evident in the assembled whole.

Figures 1 illustrate some of the key results of our deconstruction, reconstruction, and full-scale replication process.

3 DESIGN IMPERATIVES

This detailed examination of the Automatic system helped situate our research in an architectural context, and began to suggest design imperatives that would inform the new design proposal, including:

- innovative concrete materiality;
- environmental, cultural, and economic sustainability; and
- element connectivity and specificity.

3.1 Innovative Concrete Materiality

We anticipated that our new design proposal would continue to be made of concrete. Concrete products can be categorized by the degree to which they are either site-constructed or preconstructed, and by the degree to which they are elemental in nature. An analysis of historical and contemporary

figure 3
Reconstruction of the Automatic formwork.

figure 4
Full-scale replication of the Automatic system.

figure 5
Concrete products and methods.

figure 6
Sustainability imperatives.

figure 7
Universal connectivity.

figure 8
Simplicity versus formal freedom.

figure 9
Marching Squares made graphical.

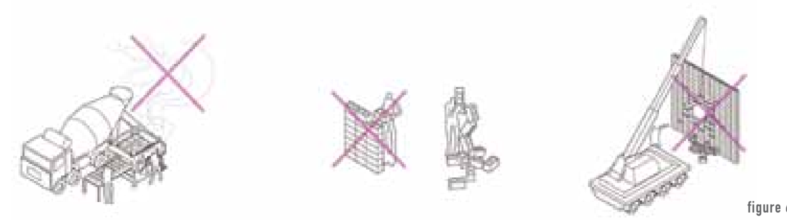
figure 6

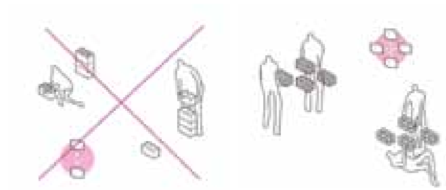
figure 7


figure 8


figure 9

concrete assemblies was conducted, including everyday concrete masonry units; autoclaved aerated concrete building systems (Rastra); proprietary composite insulated concrete panels; contemporary designer concrete elements (Loom); and, of course, Usonian Automatic blocks. Given that concrete always begins in a liquid state, the methods required to fabricate each assembly were also of interest and were similarly investigated, including conventional one-off wood forms; fly-forms; deck systems; modular plastic formwork (Moladi); and more unconventional techniques, such as Edison's single-pour system (Bergdoll 2008).

These analyses, summarized in Figure 5, helped position our new design within the spectrum of concrete construction practices, with the specific aim of identifying opportunities for innovation and how existing systems failed to address our design imperatives. Notably, many of the existing systems failed to overcome a) their predetermined orientation, because their structure and form reflect the forces they will be subjected to; and b) the inherent tension between simplicity and specificity, by subscribing to one of the "one-size-fits-all" or mass-customization extremes.

3.2 Environmental, Cultural, and Economic Sustainability

Wright's system was designed when resources were believed to be infinite. Given our acknowledgment that resources are indeed finite, we sought to make our proposal respond to contemporary environmental, cultural, and economic sustainability concerns, including:

- Impact mitigation: employing advancements in constituents and techniques that mitigate some of the deleterious effects of concrete production.
- Formal flexibility: providing maximal freedom of expression.
- Life-cycle optimization: maximizing the potential for reuse. (Typical concrete elements require permanent assembly methods that inhibit reuse.)

These imperatives are represented in Figure 6.

3.3 Element Connectivity and Specificity

Like Lego™, both Wright's system and conventional concrete blocks are designed with a specific orientation and position in mind. In order to achieve more formal flexibility, the new proposal was designed to permit universal connectivity to facilitate both stacking and spanning, as shown in Figure 7.

The design also sought to permit the freedom to generate a significant range of forms while remaining simple enough to understand and organize. An important parameter in this potentially conflicting desire, represented by Figure 8, is the number of discrete parts: too many, and the system becomes onerous to use; too few, and the system has a potentially limited application..

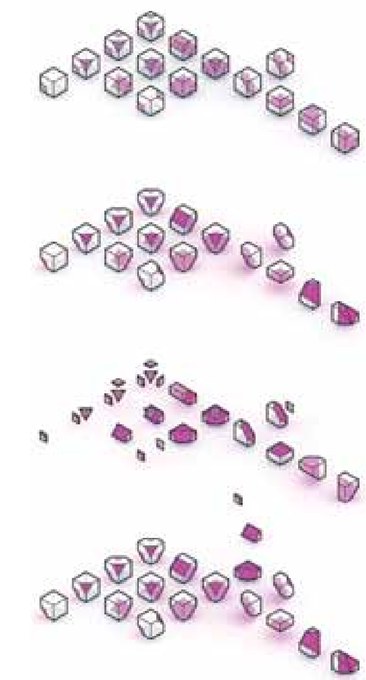
figure 12

4 ONE PHYSICAL INSTANTIATION OF MARCHING CUBES

Universal connectivity and a balance between simplicity and formal freedom can be achieved by leveraging the results of a set of form-finding rules. These rules have their origin in a pair of computer graphics algorithms developed for constructing polygonal meshes in two- and three-dimensional space: Marching Squares and Marching Cubes.

4.1 Marching Squares Made Graphical

Marching Squares can be made graphical by dividing a plane into quadrants, intersecting this plane with any arbitrary region, and finally approximating this region as shown in Figure 9. The approximation is determined by the quadrants through which the arbitrary region passes.

There are six quadrant/region intersections possible, each of which can be approximated and, in combination, used to approximate a closed region of any size and shape, as shown in Figure 10. The resolution of the approximation is dependent on the size of the quadrants: smaller quadrants provide higher resolution.

4.2 Marching Cubes Made Elemental

The same logic can be applied in three dimensions in order to make Marching Cubes elemental. Any arbitrary surface, intersecting a cube divided into quadrants, can be approximated as shown in Figure 11. Again, the approximation is determined by the quadrants through which the arbitrary surface passes.

There are 15 quadrant/surface intersection approximations possible, which can be interpreted reciprocally as either positive or negative volumes, generating 18 unique elemental forms. These elements can be used in combination to approximate any closed surface, as shown in Figure 12. Again, smaller quadrants create more resolution.

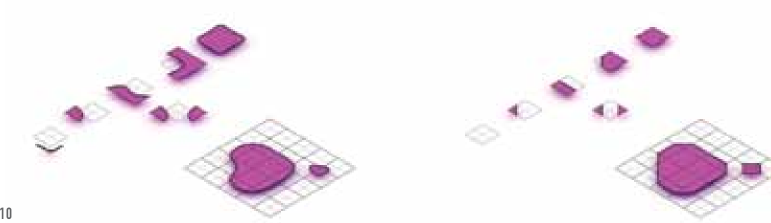
figure 10

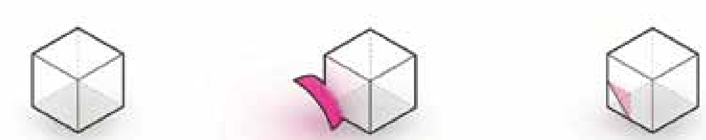
figure 11

figure 10
All permutations of Marching Squares.

figure 11
Marching Cubes made elemental.

figure 12
All permutations of Marching Cubes made elemental.

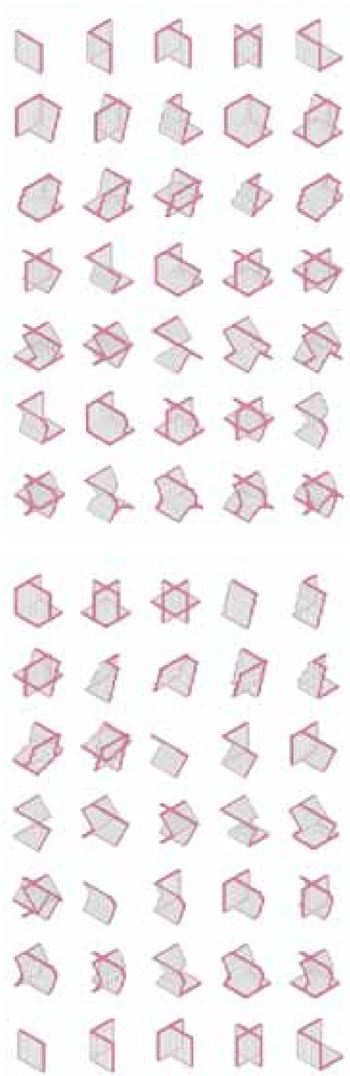

figure 13

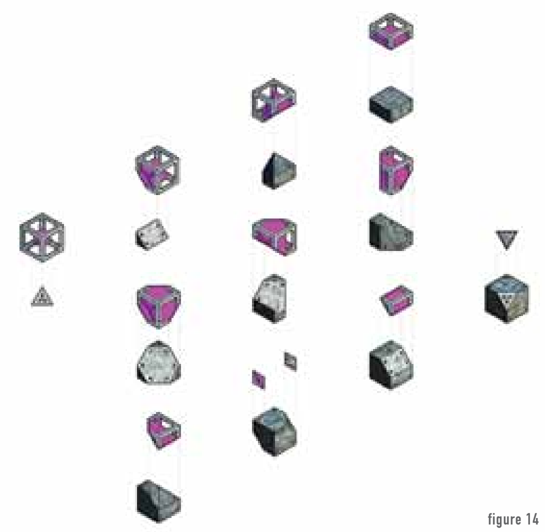

figure 14

figure 15

4.3 The Elements Made Architectural

While the Marching Cubes algorithm can be used to approximate any surface, the 18 unique elements can also create aggregate forms with architectural relevance. Typical enclosure configurations, such as walls, floors, and roofs, and intersections of the three can be produced utilizing this system of construction elements. These elements, like Wright's Automatic blocks, encode their strong formal vocabulary and character on any design to which they are applied. Sixty-four sample aggregations, ranging from normative orthogonal configurations to more complex forms, such as kinked and curved configurations, are shown in Figure 13.

An important parallel between the positive/negative nature of the individual elements and concrete products is that concrete products also have a reciprocal negative: the mold or formwork. When the positive is rendered in concrete, the reciprocal negative of each element becomes its formwork. Understanding this, it was possible to eliminate redundant or nonessential elements from the system, as shown in Figure 14. This reduced set of elements creates an equally complete but substantially less complex system, at the expense of the resolution of some kinked and curved configurations.

The use of this reduced set of elements to approximate an enclosure surface, as shown in Figure 15, results in two design variations: a system of elemental modular formwork for cast-in-place construction (Figure 16), and a system of elemental precast concrete units (Figure 17).

In the cast-in-place variant, shown in Figure 16, the elements become two-sided modular formwork which, when concrete is poured between them, creates an architectural enclosure. An offset grid of reinforcing steel is required on each side to resist tension, the size and quantity of which is determined by the enclosure's loading and orientation. The formwork is reusable, permitting a small number of formwork elements to create a large variety and quantity of architectural enclosures without the difficulty and waste normally associated with the cast-in-place construction of complex geometry.

In the precast variant, shown in Figure 17, the elements become factory-produced concrete units. These units require triaxial post-tensioning, which is provided by a system of connection rods and couplings, and which simultaneously facilitates the one-by-one assembly of the units and eliminates the need for elaborate shoring. Unlike the cast-in-place variant, the development of tensile capacity in the precast variant is orientation-independent and reversible: the system can be disassembled and reassembled into new configurations as desired.

figure 13
Sixty-four architectural configurations.

figure 14
Eleven essential elements.

figure 15
Enclosure surface approximated.

figure 16

figure 17

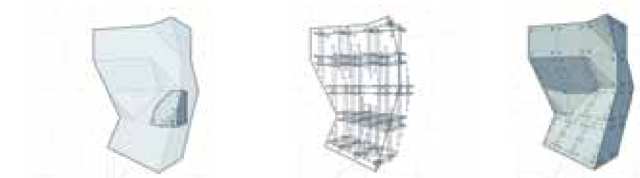

figure 18

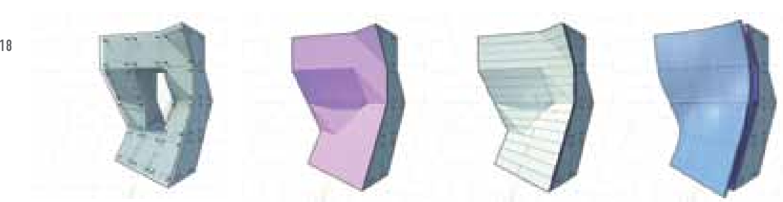

figure 16
Cast-in-place variant.

figure 17
Precast variant.

figure 18
Cladding the armature.

figure 19
Proposed gallery installation.

The flexible structural armature permitted by either variant offers many possibilities for cladding, including insulation, slatting, glazing, and paneling, as shown in Figure 18. The armature's resolution can either be expressed directly or can be used as a substructure.

4.4 The Architecture Made Physical

Finally, a response to a specific site—a gallery—was proposed, as shown in Figure 19. The precast variant was selected as the most suitable system for this temporary installation, as it could be easily assembled and then demounted to be potentially remounted and/or reconfigured at a later time.

Figures 22–26 show aspects of the fabrication and installation process.

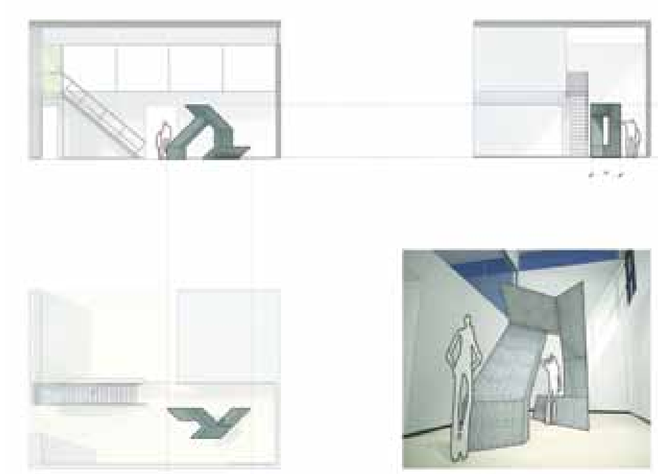

figure 19

figure 20

Full-scale fabrication of the precast variant.

figure 21

Milling procedure required to complete the precast variant.

figure 20

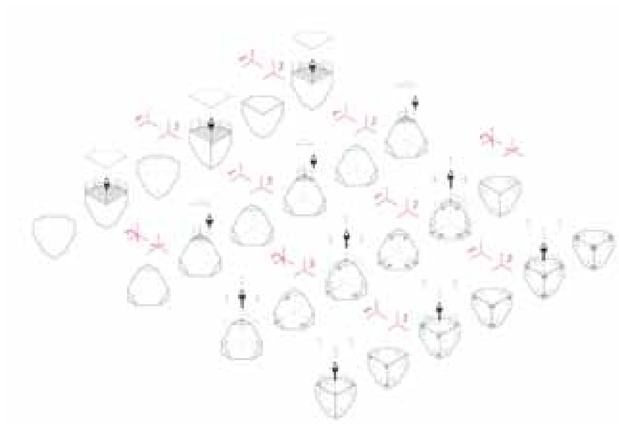

figure 21

5 CONCLUSIONS AND FUTURE DIRECTIONS

The full-scale fabrication of the gallery installation revealed advantages and limitations of the design, which will be discussed in a future paper. However, two preliminary conclusions may be drawn:

- This physical instantiation of Marching Cubes, as a modular system of reusable concrete elements that permit a large degree of formal variability using a small number of discrete parts, convincingly satisfies the established design imperatives.
- The direct consideration of constructional elements and the full-scale fabrication of those elements as a parallel exercise to conventional design activity empower the architect to reclaim problem-solving agency (Kieran 2004).

The synergies between the digital and the physical demonstrated by this body of work validate further exploration into the translation of form-finding algorithms into material objects. The potential to leverage generative algorithms to facilitate design using these elements remains a tantalizing line of research, as does the possibility of addressing non-concrete-based instantiations of the elements.

figure 22

figure 22

Physical instantiation of the Marching Cubes algorithm.

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