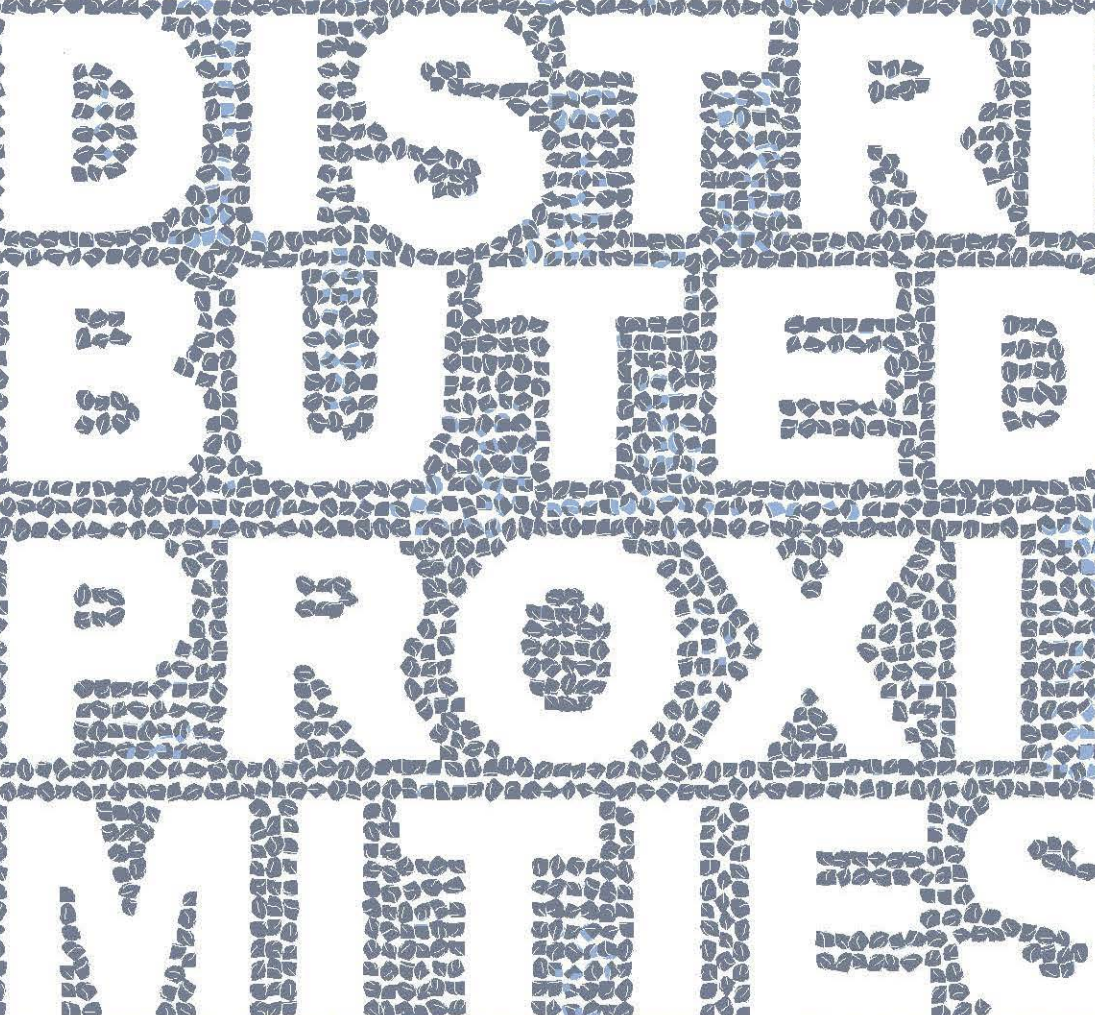


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# Engrained Performance

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Performance-Driven Computational Design  
of a Robotically Assembled Shingle Facade System



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## ABSTRACT

This project presents a novel fabrication-aware and performance-driven computational design method that facilitates the design and robotic fabrication of a wood shingle facade system. The research merges computational design, robotic fabrication, and building facade optimization into a seamless digital design-to-fabrication workflow.

The research encompasses the following topics: (1) a constructive system integrating the rules, constraints, and dependencies of conventional shingle facades; (2) an integrative computational design method incorporating material, robotic fabrication, and assembly constraints; (3) an optimization method for facade sun shading; and (4) a digital design-to-fabrication workflow informing the robotic fabrication procedures.

The result is an integrative computational design method for the design of a wood shingle facade. Environmental analysis and multi-objective optimization are coupled with a variable facade surface to produce several optimal design solutions that conform to the constraints of the robotic setup and constructive system. When applied to architectural design, the proposed integrative computational design method demonstrates significant improvements in facade sun-shading performance while also linking the digital design to the fabrication process.

1 Performance-driven, fabrication-aware wood shingle facade.

## INTRODUCTION

Wood light-frame construction accounts for nearly 95% of single-family homes in the United States, resulting in the construction of over one million new structures each year (United States Census Bureau 2019). Despite their popularity, light-frame structures are still designed using construction conventions that have remained mostly unchanged since the mid-19th century (Schindler 2007). However, recent advances in robotic fabrication, computational design, and environmental analysis provide opportunities to evaluate and rethink framing conventions.

Robotic fabrication technologies offer nonstandard variability for wood construction, as shown in the existing research (Adel et al. 2018; Alvarez et al. 2019; Vercruyse 2020). These projects demonstrated that the use of robotic arms in the production of nonstandard wood structures offers the potential to extend beyond the technical aspects of construction to enable integrative design approaches for creating novel architecture. In this way, nonstandard construction can “close the gap between design and making through assembly, which is enabled by integrative computational design methods and robotic manufacturing technologies” (Adel Ahmadian 2020, 3).

Beyond qualitative design criteria, quantitative metrics—such as material use and structural integrity—can be used to guide the architectural design process, assist the designer in navigating the solution space, and develop design solutions that outperform conventional solutions. This idea has been researched and demonstrated in previous research projects, such as *The Sequential Roof* (Apolinarska 2018) and *the DFAB HOUSE* (Adel Ahmadian 2020). Building on the results of these precedents, the research presented in this paper asks: How can nonstandard robotic construction contribute to increased building performance? And how can a prototypical computational design method utilize climate-based performance optimization to accomplish this increase?

To investigate these questions, the research focuses on the building envelope—more specifically, a wood shingle facade system—as a case study. It can be argued that the facade is the most critical component of an architectural design in terms of overall building performance (American Institute of Architects 2019). Thus, the facade can be considered as an ideal application for quantitative performance improvements. *MAS House* (Eversmann 2017; Eversmann, Gramazio, and Kohler 2017) and *Latitudo Borealis* (Junghans et al. 2018) are two examples of projects investigating facade performance using nonstandard variability through water-shedding and radiation analyses.

The presented research seeks to further improve the thermal performance of a wood shingle facade system by incorporating sun-shading analysis and multi-objective optimization into a prototypical fabrication-aware computational design method.

Climate-based performance optimization has become increasingly accessible with the emergence of environmental simulation software and multi-objective optimization solvers. Several recent projects have investigated the use of single-objective optimization in facade design (Junghans et al. 2018; Wortmann 2017), yet the complexity of season-based sun-shading analysis might be better suited for a multi-objective optimization workflow. Whereas single-objective optimizations can be used to search for the minima or maxima of a single performance value, a multi-objective optimization is capable of balancing multiple conflicting objectives (i.e., summer and winter performance values) (Kocabay and Alaçam 2017).

When working with optimization workflows and nonstandard construction, an integrative computational design method ensures that the solution space meets the constraints of the fabrication process. As defined by Menges, integrative computational design is “a computational design approach that synthesizes performance-oriented form generation and physical processes of materialization” (Menges 2011, 73). In the context of robotic fabrication, these physical processes must satisfy the robotic constraints such as buildable volume and orientation, as well as the limitations of the materials and constructive systems (Junghans et al. 2018). By integrating these constraints into the computational model, the presented fabrication-aware computational design method is capable of generating forms satisfying the fabrication requirements of a prototypical robotic setup.

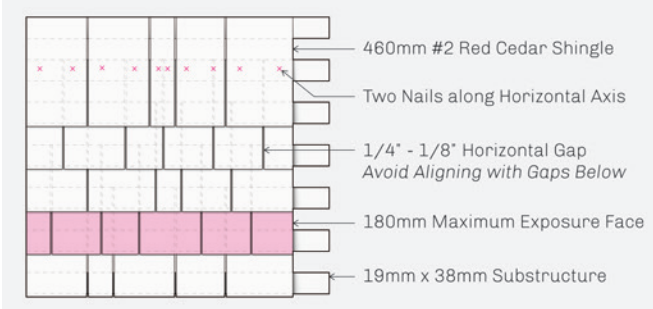
The presented literature review covers a wide breadth of research encompassing robotic fabrication, computational design, and climate-based performance optimization. This paper aims to address gaps in the existing research, specific to the design of nonstandard wood shingle facades. This includes the development of a constructive system for nonstandard shingle facade construction, the use of multi-objective climate-based performance optimization, and the integration of a fabrication-aware computational design method. Each of these topics is integral in the development of a prototypical computational design workflow.

### Research Objectives

Rather than focusing on the individual areas of research identified in the literature review, the main goal was to



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2 Four wood shingle design prototypes, exploring different patterns, attachment methods, substructure orientation, and substructure attachment methods.

4 Prototypical robotic setup, consisting of two robotic arms with grippers, an arbor saw, and a router table, at the Taubman College of Architecture and Urban Planning, University of Michigan.

3 Diagram of the wood shingle constructive system, noting the rules, constraints, and dependencies established during the prototyping process.

incorporate the constraints and methods of each into an integrative computational design method and a seamless digital design-to-fabrication workflow. Accordingly, we defined the following research objectives:

- Formalize constraints, rules, and dependencies of a conventional shingle facade system for wood light-frame construction and develop a constructive system suitable for robotic fabrication.
- Develop an integrative computational design method for the generation of a shingle facade system, incorporating material, robotic fabrication, and assembly constraints.
- Extend the functionality of the computational design method by integrating sun-shading analysis and multi-objective optimization of the facade surface to maximize sun exposure in the winter and minimize it in the summer.
- Implement a digital design-to-fabrication workflow to seamlessly transfer design information to robotic fabrication procedures.

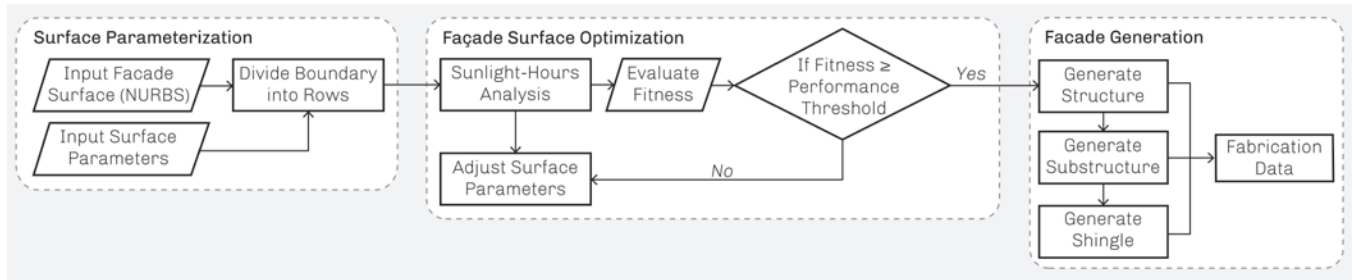
**METHODS**

According to these objectives, the following methods were developed in this research. The first two sections (“Constructive System” and “Fabrication Setup and Process”) inform the development of the computational design method and the constraints that need to be integrated into the process. These are then applied in the design of a demonstrator project. Due to the ongoing COVID-19 pandemic, the construction of the demonstrator project has been delayed. However, the validity of this fabrication data was substantiated through virtual simulation of the robotic processes and preliminary physical prototypes.

**Constructive System**

A constructive system was developed for robotic fabrication from conventional wood shingle-facade construction standards. A shingle-facade constructive system is derived through specific interactions between structure, substructure, and shingle elements. These interactions are defined in conventional facade construction using a series of rules and constraints encompassing substructure placement, shingle lapping, shingle spacing, and attachment methods (Cedar Shake & Shingle Bureau 2020).

To develop, test, and validate the constructive system, the research used an iterative physical prototyping approach (Fig. 2). Several instances of a base unit were prototyped with variations in the shingle placement and substructure attachment rules. We observed and learned the following:



5 Flowchart of the integrative computational design method.

- Methods used for shingle placement require specific positioning relative to the neighboring shingles, as well as the shingles in the course below. Conventional methods dictate an offset of at least 38 mm from the nearest joint below (Cedar Shake & Shingle Bureau 2020).
- Dimensional width of random-width cedar shingles can vary significantly. Further research shows that these widths typically range from 76 mm to 355 mm (Simmons 2007).
- Orientation of the substructure element can lead to unstable shingle courses if the substructure is oriented such that the lower half of the shingle does not contact the course below.
- Substructure elements require a lap joint with the structure elements to maintain their structural integrity. When working with nonplanar elements, the substructure can be notched at attachment points to account for changes in angle and length when spanning between structure elements.

The lessons learned from this iterative approach define the constraints, rules, and dependencies of the shingle facade to be incorporated into the design of the constructive system. This constructive system (Fig. 3) includes details for the shingle type, attachment methods, relative positioning, and maximum exposure face, as well as the sizing and positioning of substructure elements. The robotic setup specified the additional rules and constraints of the tools used for fabrication.

### Fabrication Setup and Process

The fabrication sequence follows a just-in-time fabrication method (Adel et al. 2018; Thoma et al. 2018), where individual elements are picked, cut, and placed in a single robotic sequence. This method of fabrication eliminates the need to label and organize nonidentical elements, thus reducing the complexity of the fabrication sequence. This was achieved using a prototypical robotic setup (Fig. 4) consisting of two six-axis industrial robotic arms<sup>1</sup> equipped with pneumatic gripper and vacuum gripper end effectors.

Two pickup stations were located on opposite sides of an elevated build platform, while a table saw and stationary router table were positioned between the two robots.

Using this robotic setup and fabrication sequence, several tests were performed to identify the constraints of the fabrication setup. The following constraints were measured and documented: wood elements minimum and maximum profile dimensions (38–89 mm width, 19–89 mm height), minimum and maximum length (400–1300 mm), maximum cut angle (60° off square). These constraints are incorporated into the integrative computational design method, which is described in more detail in the following sections.

### Computational Design

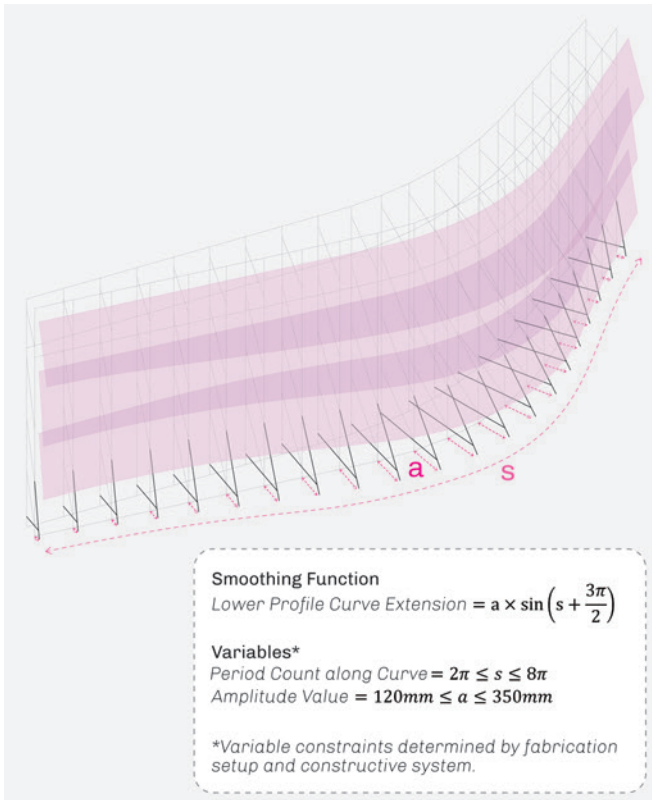
The main steps of the developed computational design method are illustrated using the flowchart shown in Figure 5. This method consists of a sequence of three main steps, beginning with the surface parameterization, where the input variables are defined and facade surface generated. Next, the facade surfaces are subjected to sun-shading analysis and iteratively adjusted until a set of optimized design solutions are produced. The selected facade surface is subdivided to derive the attributes necessary to generate structure, substructure, and shingle elements. During this generative process, data regarding the size, shape, and position of each element are stored and referenced for the robotic fabrication process.

Each of these computational design steps was explored in further detail by applying them to a building-scale demonstrator project as a case study.

### Demonstrator Project

The demonstrator project consists of a wood light-frame structure sited at the Matthaei Botanical Gardens in Ann Arbor, Michigan. The shingled facade makes up two vertical surfaces, measuring approximately 10 m long and 5 m high, on the north and south faces of the structure.

Situated in a cold-moist climate (Zone 5a), the site is subjected to freezing winters and humid summers (Building



6 Visualization of the facade surface parameterization. Variables  $a$  and  $s$  control the maximum amplitude and number of undulations on each facade surface.

Technologies Office 2015). In climates with significant annual temperature variation, self-shading strategies can be used to reduce the solar gain of the facade surface in the summer while still allowing the lower angle of the winter sun to heat the facade surface. This design strategy was applied to the facade of the demonstrator project in an attempt to increase the thermal comfort of its interior.

Although this case study was tested for a specific site, the computational design method is transferable to any location or climatic region, provided there is historical weather data accessible for the site in question.

### Surface Parameterization

The computational design method begins by defining the facade parameters. A NURBS surface (McNeel 2016), indicating the extents of the shingled facade, is used to generate a set of lofted surfaces spanning the length of the demonstrator project. The angle and height of each surface is constrained by the minimum and maximum element lengths the robot can produce.

The individual surfaces are generated using an upper and lower profile curve. The upper profile remains aligned to the primary structural elements, and the lower profile is offset horizontally from the face of the input NURBS

surface to produce a shading effect on the surface below. By adjusting the offset values of the lower profile curve, the self-shading properties of the facade increase or decrease. These offset values are defined using a sinusoidal smoothing function for the lower profile curve of the facade surface (Fig. 6). The number of periods and the maximum amplitude of each sine curve are determined by variables  $s$  and  $a$ , respectively. The values for the number of periods ( $s$ ) are constrained by the maximum curvature radius of the shingle constructive system, while the maximum amplitude ( $a$ ) is constrained by the robotic reach specific to the fabrication setup.

In the case of the demonstrator project, the number of periods ( $s$ ) could be an integer between one and four, while the maximum amplitude ( $a$ ) could be an integer between 120 mm and 350 mm. With a total of 16 surfaces, the facade surface had 32 parameters, 16 of each variable, which are utilized in the sun-shading optimization process.

### Facade Surface Optimization

The optimization step of the integrative computational design method requires the interaction of several computational tools to produce a sun-shading analysis and optimized solutions (Fig. 7).<sup>2</sup> This process begins by providing the inputs for the facade surface and its parameters. Environmental analysis is then used to generate an average sun exposure value for this input surface for both winter and summer analysis periods (Roudsari and Pak 2013).

Sunlight hours analysis is used to determine the average hours of sun exposure on a facade. Both winter and summer sun exposures are measured to evaluate and compare the sun-shading performance of different facade surface options. To calculate the sunlight hours for the facade, the surfaces are subdivided and a matrix of quad mesh faces is generated. An average quad mesh size of 150 mm × 150 mm was used for the demonstrator project, as determined by a parameter study weighing processing time and mesh resolution. The sun angle is simulated for each hour of the winter (December 21 to March 20) and summer (June 20 to September 22) analysis periods to determine the sun exposure at each mesh face. The sum of these values is then normalized by dividing it with the number of days in each analysis period. The normalized value for each period is fed to the optimization engine.

The optimization is performed using a multi-objective evolutionary algorithm with Pareto optimality<sup>3</sup> (Fonseca and Fleming 1995). Early tests were performed using a single-objective evolutionary algorithm; however, the

results were inconsistent, and the algorithm would often get stuck in local optima. Reviewing the literature, we learned that a Pareto-optimal multi-objective method<sup>4</sup> could solve this by removing the search bias that is inherent with using a single weighted-sum objective for both winter and summer performance (Ashour and Kolarevic 2015). Employing the multi-objective approach on the demonstrator project with unique winter and summer objective functions produced several Pareto nondominated solutions—solutions where each objective can only be improved by lowering the other objectives—that vary in performance trade-offs, favoring one objective or the other.

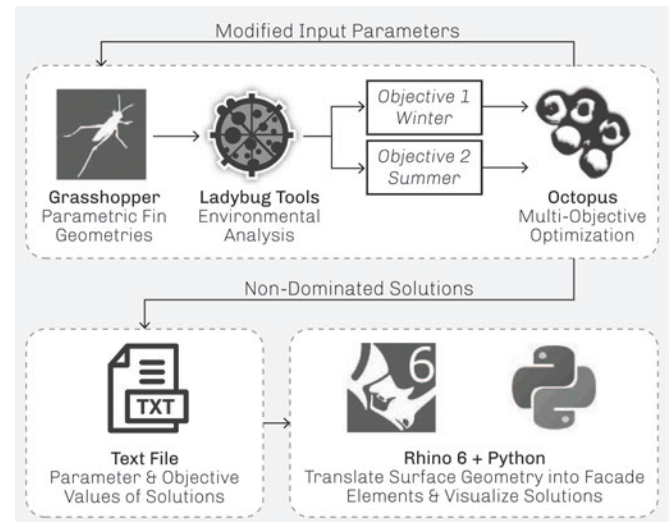
Precise formulation of the objective functions is critical for the optimization to be effective. For the demonstrator project, the overall objective was to improve the thermal performance of the facade using a self-shading design strategy. Therefore, sunlight-hours analysis and local weather data (Energy Plus 2020) were used to formulate two distinct objectives. The first objective was to maximize sunlight hours during the winter, and the second was to minimize sunlight hours during the summer (Fig. 8).

With these equations formalizing the fitness criteria for the evolutionary algorithm, a multitude of facade configurations are evaluated by adjusting the surface parameter variables ( $s$  and  $a$ ). The optimization uses the following characteristics: population size of 200, 80% elitism, 20% mutation probability, 90% mutation rate, and 80% crossover rate. The optimization of the demonstrator project was run for 24 hours.<sup>5</sup> The solution set was exported from the optimization engine as a text file (consisting of 16 parameter values and two fitness values for each solution) and visualized using a 3D modeler.

The resulting solutions represent the highest-performing design solutions. A design is selected by looking at both the performance impacts of parameter weights and qualitative properties of the facade surface, like surface morphology, formal expression, and aesthetics. Once one of the solutions is selected, its parameter data is passed on to the facade generation process.

### Facade Generation

After a facade surface design is selected, the individual elements of the facade are generated algorithmically. The developed constructive system is applied to facade surfaces to generate the topology of the shingle facade. The structure and substructure elements are generated by subdividing the facade surface to derive the attributes necessary for fabrication. Structure elements consist of three data categories: frame at element centroid, cut



**Objective 1: Winter**

$$\text{maximize } \sum_{i=1}^{1872} \sum_{j=1}^p \text{SunlightHours}(i,j) + \sum_{i=8520}^{8760} \sum_{j=1}^p \text{SunlightHours}(i,j)$$

**Objective 2: Summer**

$$\text{minimize } \sum_{i=4128}^{6336} \sum_{j=1}^p \text{SunlightHours}(i,j)$$

$i$ : Hour-of-Year  
 $j \in D \subseteq \mathbb{R}^2$   
 $j$ : Point on  $D$  ( $p$  = total number of points on  $D$ )  
 $D$ : Facade Surface Domain  
 \*Objective function applied to all surfaces of the

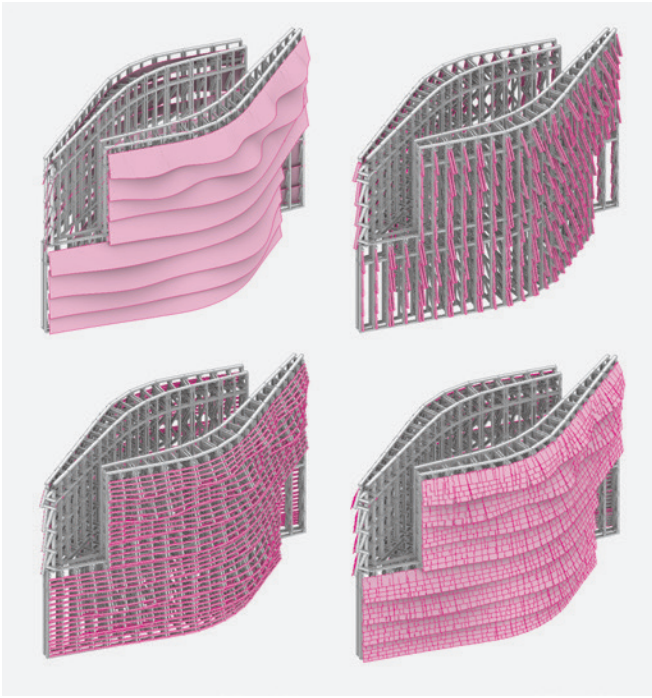
7 Workflow illustrating the sequence, processes, and software used in the multi-objective optimization process.

8 Formulation of two performance objectives that determine the fitness of a specific design solution using sun-shading analysis for the winter and summer seasons.

planes of each end of the element, and frame indicating assembly position and orientation. The substructure also includes these three attributes with the addition of information required for notching the ends of the element. The shingles are positioned onto the substructure elements, completing the facade system (Fig. 9).

## RESULTS

When applied to the demonstrator project, the computational design process returned 41 Pareto nondominated solutions derived from 6,000 tested permutations. There was a measurable performance improvement in the solutions as the optimization progressed, with the average ratio of winter sun-hours to summer sun-hours increasing from 0.87 to 0.95. This improvement was mirrored in the result of both performance objectives, with the average summer sun-hours decreasing by 0.21, and the average winter sun-hours increasing by 0.15. These results support



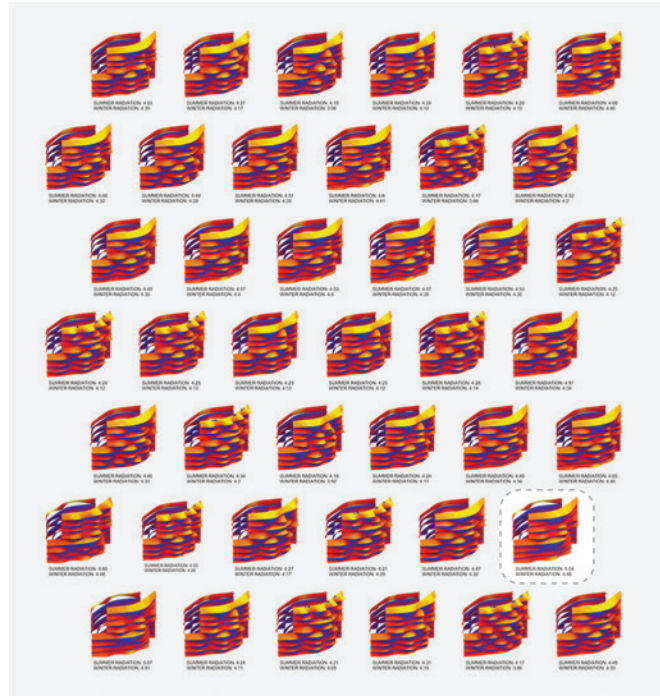
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the use of Pareto-based multi-objective evolutionary algorithms in season-based shading analysis, even when the solution space is determined by the constraints of the constructive system and robotic setup.

The resulting solution set contained a diverse range of sun-shading performance values. Solutions with a bias towards summer performance achieved sunlight-hours analysis values as low as 4.17 hours per day; solutions prioritizing winter performance achieved values as high as 4.51 hours per day. All solutions fell within a 10% range when comparing their winter-to-summer performance ratios (0.89–0.98). Additionally, the solution set exhibited noticeable variations in formal expression and surface morphologies (Fig. 10).

Upon qualitative evaluation, a shingle facade design solution was selected and applied to the overall design of the demonstrator project. The selected design solution exhibited a 16–17% increase in the ratio of winter to summer sun-shading performance over nonoptimized solutions, with an increase of up to 0.27 sun-hours in the winter and a decrease of up to 0.79 average sun-hours in the summer (Fig. 11).

The generated facade consists of 2,795 wood light-frame elements and 3,371 cedar shingles, and satisfies the robotic fabrication and assembly constraints as these constraints were already integrated into the computational design process.

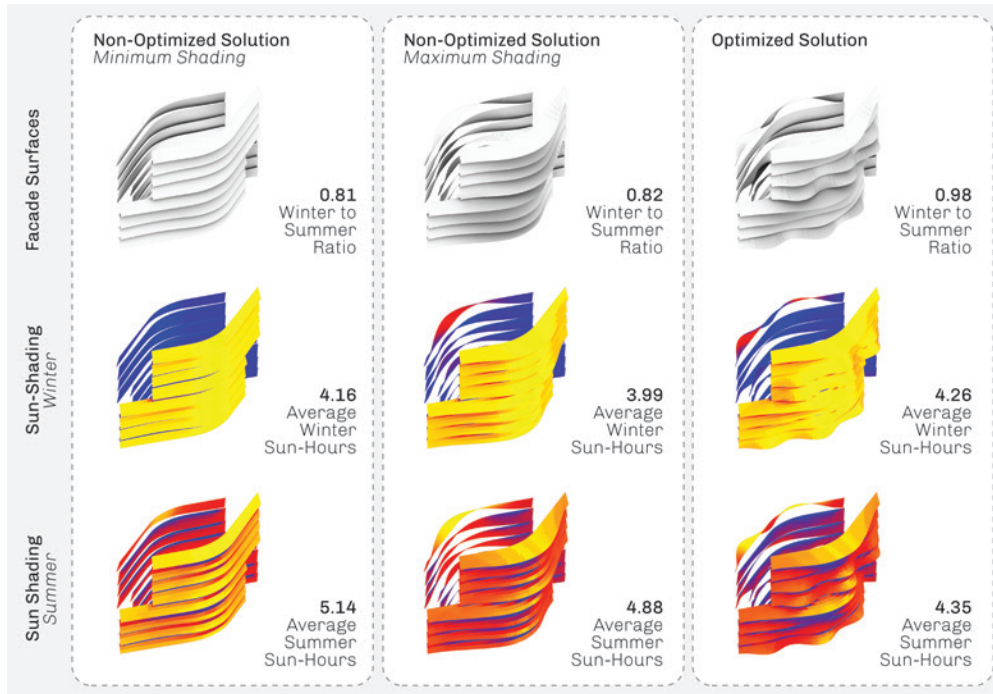


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## CONCLUSION

The product of this research is an integrative computational design method for translating NURBS surfaces into a shingle facade system composed of interdependent elements, embedded with the necessary data for robotic fabrication. This paper attempts to further existing research into spatial assemblies and thermal performance optimization by incorporating fabrication-specific constraints into the computational design method. Nonstandard variability and robotic fabrication enable a traditional shingle facade constructive system to be adapted for use on undulating surface geometries. These geometries can provide a self-shading functionality and have the potential to increase thermal performance as illustrated by the demonstrator project. The increase in thermal performance as a result of this integrative method could have a significant impact on energy use in wood light-frame applications. The use of climate-based performance optimization with nonstandard facade geometries is a common design method (Junghans et al. 2018; Wortman 2017). This research adds to existing methods by connecting fabrication criteria, solar analysis, and form-finding into a single design-to-fabrication workflow. This approach establishes a more accurate solution space by eliminating design solutions that do not satisfy the fabrication constraints, reducing the amount of processing required to run an optimization. It can be argued that multi-objective optimization is an effective approach to solving for the conflicting objectives of season-based sun-shading analysis by generating a solution set of





- 9 Sequence showing the generation of the selected facade design solution into structure, substructure, and shingle elements.
- 10 Visualization of the 41 Pareto nondominated design solutions, with the selected design solution highlighted.
- 11 Comparison of the selected design solution with nonoptimized alternatives. The gradient mappings in the second and third rows represent the results of the sun-shading analysis.

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similar performance values with different fitness biases. From an architectural design standpoint, this method generates several different solutions to the same problem, allowing for subjective input without diminishing the facade performance.

As mentioned at the beginning of this paper, nearly 95% of single-family homes in the United States are fabricated using wood light-frame construction. The presented method could be used to effectively design and fabricate nonstandard shingle facades with a demonstrated increase in sun-shading performance. Such integrative design and fabrication methods could drastically reduce the required energy use for heating and cooling and mark a significant reduction in the carbon footprint of new residential construction.

### Future Work

The presented use case—sunlight-hours analysis for self-shading shingle facades—is narrow in scope and may not be applicable in regions where wood shingles are not available or the climate does not support self-shading strategies. The implementation of additional performance objectives into the multi-objective optimization process is a clear next step in the research. New performance criteria, such as daylighting, ventilation, and view studies would further improve the performance of a wood shingle facade and provide additional value to the design.

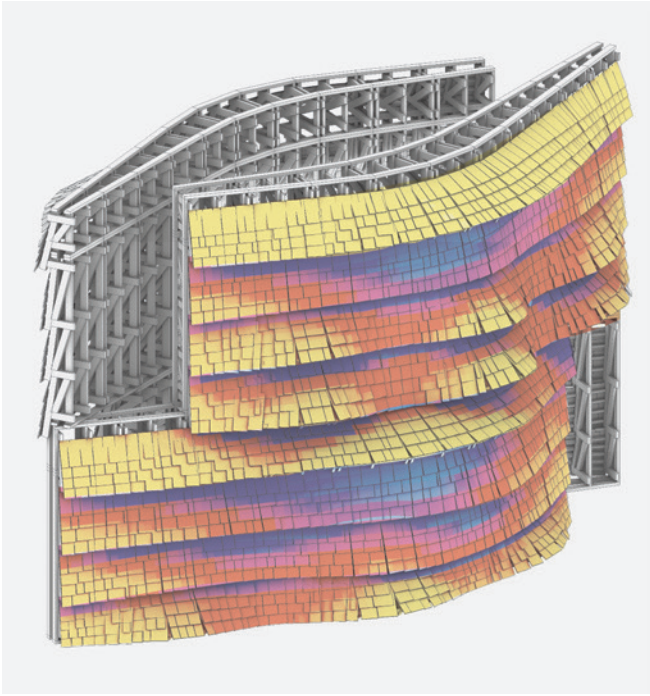
Additionally, the proposed method was partially limited by the use of ready-made plugins for optimization and environmental analysis. The implementation of custom-made algorithms into the integrative computational design method could provide additional opportunities for designer input and improve upon the environmental performance optimization. For example, the use of a genetic algorithm for multi-objective optimization proved sufficient for the research, yet alternative algorithms (i.e., simulated annealing and Gaussian adaptation) may improve the speed and effectiveness of the optimization process.

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### NOTES

1. Kuka KR60 robotic arms.
2. The facade surface optimization was performed using Rhinoceros (Robert McNeel & Associates 2018), Grasshopper (Rutten 2018), and Python programming language (Python Software Foundation 2020), in conjunction with the



12 Rendering of the optimized wood shingle facade system applied to the building-scale demonstrator project. The summer sun-shading analysis is overlaid, illustrating a gradient of shading values, from heavily shaded areas (blue) to sun exposed areas (yellow).

Grasshopper plugins Octopus (Vierlinger 2020) and Ladybug (Roudsari and Mackey 2017). Weather data for the demonstrator project was obtained from EnergyPlus (Energy Plus 2020).

3. Pareto optimality is a condition where each solution cannot simultaneously improve all of its performance objectives (Fonseca and Fleming 1995).
4. The developed multi-objective optimization process uses HypE (Hypervolume Estimation Algorithm for Multi-Objective Optimization) to obtain a Pareto front consisting of several nondominated solutions (Bader and Zitzler 2008).
5. Optimization was run on a desktop computer (Intel i7-4790K, 16GB DDR3).

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## IMAGE CREDITS

All drawings and images by the authors.

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