

Augmented Reality Driven Design and Fabrication of Shading Devices

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ABSTRACT: The issue of sun exposure in urban settings in relation to placemaking is being studied by city planners and architects. Placemaking, which is both a physical and psychological concept, takes into account the severity of outdoor conditions and how people perceive what is considered normal, as these factors can affect the usage of space. However, many urban spaces still need to be equipped to handle increasing temperatures and broader placemaking needs. This paper proposes an augmented reality-driven design process that utilizes mobile devices to generate shading structures accessible to non-experts. The generative algorithms simplify the creation of design iterations and use material simulation to develop shading devices based on looped surfaces. Moreover, incorporating AR into the fabrication process simplifies construction, making it more accessible and engaging for a diverse range of participants. The research presents an accessible design approach and a fabrication methodology suitable for non-construction professionals, which can be applied in various contexts to provide shade with minimal infrastructural demands. This study contributes to the expanding discourse on the use of AR in architectural design and fabrication, with a particular focus on shading. The envisaged accessible and engaging approach will promote wider community involvement in shaping urban spaces, offering viable solutions to rising temperatures in urban environments.

KEYWORDS: Augmented Reality in Construction, Participatory Design, Augmented Reality for Design, Digital Fabrication, Shading Devices

1.0 INTRODUCTION

Urban public parks play an increasingly crucial role in providing recreational activities for diverse urban communities. The design of these spaces needs to accommodate social activities and the experience of urban ecosystems, particularly in subtropical cities like San Antonio, where mitigating the impact of direct sun exposure is critical. Predictions suggest that by 2050, San Antonio will endure five months of temperatures exceeding 100.4°F (38°C), amplifying the existing severity of its climate (Boice and Garza 2021). Recognizing these potential environmental challenges, the city council has called for action (Office of Sustainability 2019). San Antonio studies emphasize the criticality of shade in improving thermal comfort in open-air spaces (Patel, 2015), and recent case studies on shading structures underscore the need to integrate climate comfort into design considerations using computational tools (Ameijde et al., 2022).

In the context of architectural production, digital design and fabrication can significantly influence the planning and creation of shading structures in urban parks. By harnessing computational design tools and adopting user-focused fabrication techniques, architects can make well-informed decisions to produce custom-made shading devices. Parametric design in architecture presents a unique opportunity to create numerous iterations of a single concept without requiring extensive human input (Figure 4-5). This approach can significantly accelerate the design process by streamlining the drafting and management of design assets (Monedero 2000). A reconfiguration strategy has been proposed to embed interactive behavior in a shading canopy, ensuring shadows in occupied spaces (Wood et al., 2019). However, the user does not have direct access to configure or design where and what kind of shadow is to be created.

The application of Augmented Reality (AR) – the overlay of digital information onto the real world – offers numerous innovative design opportunities. In architectural design and fabrication, AR finds utility in visualizing plans, monitoring progress, aiding workers, revealing hidden utilities, allowing remote experts to guide on-site personnel in real-time, verifying code compliance of assembled structures, and enhancing the efficiency of construction equipment (Nassereddine, Veeramani, and Hanna 2022; Chi, Kang, and Wang 2013). Additionally, AR has been utilized in crafting complex architectural assemblies (Hahm 2019; Jahn, Newnham, and Berg 2022). However, its application remains limited, primarily due to unfamiliarity with the technology, environmental challenges at construction sites (Kassis et al. 2022), or implementation costs (Ramsey & Hongtao 2022), while industry trends suggest a growing adoption of AR (Noghabaei et al. 2020). The benefits of collaborative AR for interior design have been presented as early as 1995 (Ahlers et al. 1995). An extended reality collaborative design review process has been trialed with promising results, augmenting a physical mockup or an existing environment in situ. This approach has demonstrated its potential to enhance inclusivity and active participation during design and planning processes (Gillespie et al. 2021).

Nevertheless, when it comes to non-experts' engagement in the design and fabrication process via AR technologies, it remains under-researched or not extensively explored. Additionally, the development of AR tools

for user-guided on-site design and production of shading devices, and the use of the material behavior of bendable materials in this context, present unique contributions to this body of research.

In response to these challenges, a case study was conducted at Legacy Park in Downtown San Antonio, an urban park grappling with heat-related issues. The choice of location was influenced by past design decisions that minimized shade, leading to lower-than-anticipated visitor engagement during spring and summer. The site's diverse programmatic demands require a response to various conditions. The client intends to install metal wires over the park, allowing for the flexible positioning of shading devices.



Figure 1: Placement of a shadow area via the AR application. Source: (Author 2024)

2.0 METHODS

This research introduces a method of creating user-defined shadow areas on mobile handheld devices via an on-site AR interface (Figure 1). Based on the identified shadows, 3D geometries are projected onto the planned wires above the site. These geometries are further refined through material simulations to define shadow density accurately. An AR fabrication tool has been developed to leverage the properties of bendable materials and enable on-site production of shading devices by participants with minimal construction knowledge. This tool provides detailed fabrication instructions for bending and securing a polycarbonate film into the desired shape. The proposed methods are designed to heighten engagement and inclusion in shade creation, deploying human-centric AR tools during the design and fabrication stages. This approach was validated through the design and construction of a full-scale prototype.

This research followed the case study approach and was conducted in an academic setup at the University of Texas at San Antonio in collaboration with Weston Urban and Dunaway. The design team comprised a Building Design Studio with fourteen students at the University of Texas at San Antonio from January 18th to May 4th, 2022. This study involved implementing and testing climate simulations, parametric design, and AR-assisted fabrication.

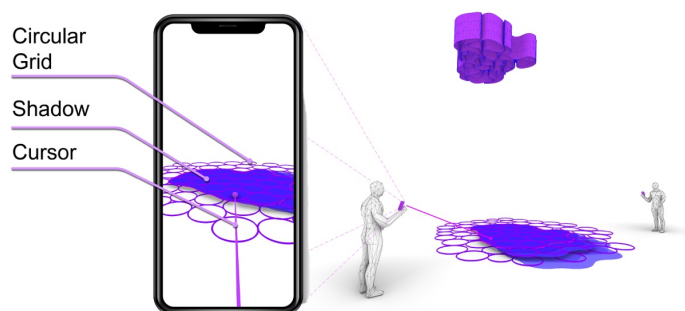


Figure 2: Mobile app concept diagram. Source: (Author 2024)

2.1. Design Methods

An augmented reality tool was developed to assist with on-site positioning and evaluation of shading devices using Fologram in Grasshopper for Rhino 3D (refer to Figure 2). This tool enables users to specify the desired times for shadow by pointing a cursor on the ground, adding a circle to the shading with just a click on the mobile device screen, and projecting the shading device up into the air. The projected shadow is then visualized at fifteen-minute intervals, distinguished by various shades of blue in the application.

The AR tool's geometric system is based on a bendable material, polycarbonate, which is easy to manipulate and weld by non-experts. The placement grid is circular in response to the material system of the bendable sheet. The size of these circles adjusts based on the number of user-proposed shadows at different locations, with more

proposals resulting in larger circles. This feature provides users with insights into previous shading proposals, enabling them to either reinforce existing proposals or suggest other shadow locations. This dynamic circular grid was realized using a particle-spring simulation, specifically Kangaroo for Grasshopper, in which the circle's radius reflects the frequency of user-placed points at the location. A threshold restricts the number and size of the circles to maintain a manageable visual representation.

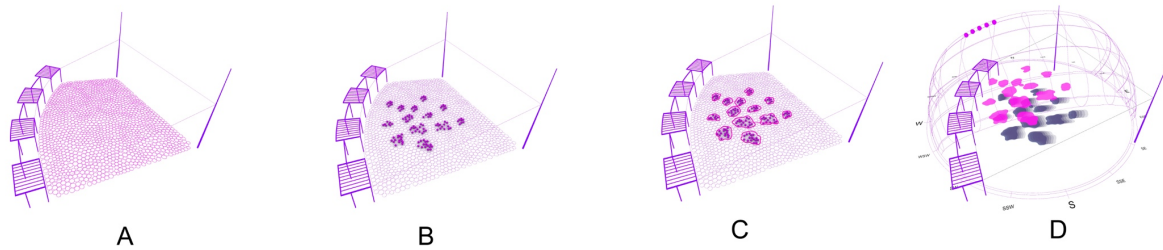


Figure 3: The site constraints: the possible space (A), the adapted grid (B) for the placement of shading devices (C), and a layout option with shading devices placed between the wires with shadow from 15:00 - 16:00 on the 15th of July (D). Source: (Author 2024)

"To meet the site's specific requirements, configured constraints for the application. These constraints included limiting possible locations for shading devices to align with a planned wire layout, which was dictated by two existing posts and a pergola (Figure 3)." The tool prompts users to apply shadows to the site by marking points and generating a metaball polyline encircling these points (also shown in Figure 3). This metaball is then transformed into a mesh and projected to the wire height, roughly between four and five meters (approximately 14 to 16 feet). This mesh is further translated into a pattern of bending and aligning curves that mirror the behavior of the fabrication material. Rhino 7 software was used to generate these patterns, combined with the Grasshopper and Kangaroo 2 plugins. The boundary is then offset inwards and programmed to expand, provided it does not self-collide, thereby simulating the bending behavior of the polycarbonate. Users have the flexibility to select from different pattern densities by altering the total length of the individual curve. The output is a dense pattern that can provide the desired shadow. Generated patterns are user-controllable and can be modified by adjusting the input parameters, such as the offset distance and the line growth rate.

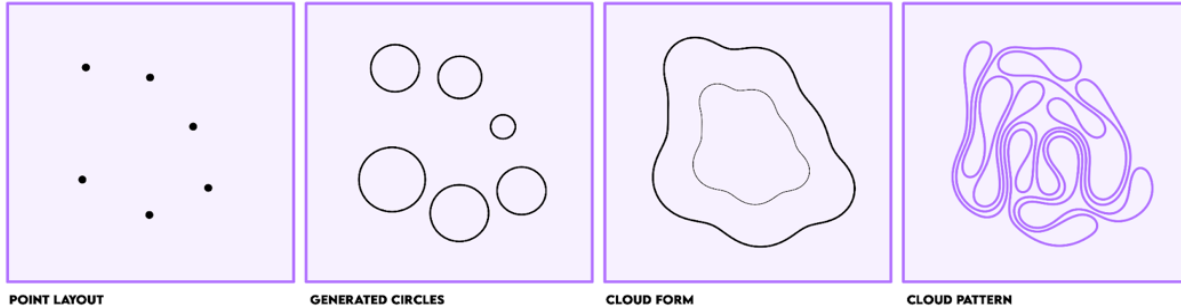


Figure 4: The processes of pattern generation for the ribbon forms. Source: (Author 2024)

2.2. Shadow Analysis

A *Universal Thermal Climate Index* (UTCI) analysis was conducted to create a thermal comfort map of the site, allowing a predictive analysis of the impact of the shading devices. The UTCI calculation considers four main variables: dry bulb temperature, mean radiant temperature, relative humidity, and wind speed. Metrics of human comfort are estimated using universal data on human adaptive behavior, and other essential factors, such as age, height, and weight, are derived from population averages (Mackey et al. 2017). The relevant buildings, site vegetation, and shading devices were input as meshes into the Ladybug plugin in Grasshopper (Roudsari et al. 2013). A mesh was laid over the site with 2009 measuring points (Figure 5). For the measured period on July 15th from 11:00 AM to 2:00 PM, the site had an average air temperature of 32.2 °C and a mean radiant temperature of 54.6 °C based on the weather data from EnergyPlus for San Antonio. The measured UTCI temperatures were averaged and translated into a thermal comfort heat map (Figure 5).

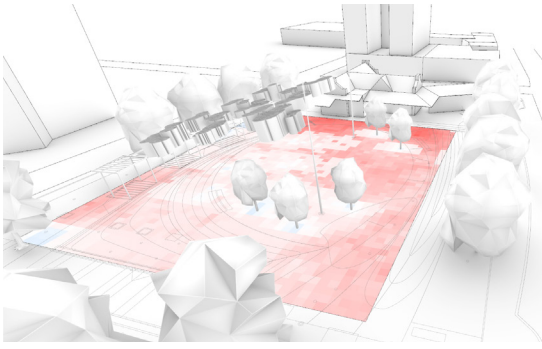


Figure 5: A perspective showing the elevation of the shading devices above the ground and the mesh colored based on the heatmap. Source: (Author 2024)

2.2. AR assisted prototyping

The project's 3D forms were actualized by bending a continuous, thin film to conform to the generated patterns and forming joints at intersections of the film. These polycarbonate films are flexible, UV-resistant, 0.02 inches (0.5 mm) thick, and 48 inches (1219 mm) high. Moreover, the thermoplastic characteristics of the polycarbonate permitted it to be shaped without fracturing or needing a mold.

The Fologram app was used to establish an Augmented Reality (AR) aided construction environment to support the construction of the prototypes. The AR model's primary function was to render the design visible in real-time as it was assembled and to offer a guide for bending the polycarbonate. This ensured that the prototype closely mirrored the intended design. Additionally, the digital 3D model can be loaded onto AR-compatible devices, enabling it to be visualized during the construction process.

Construction tasks were divided into supervisory and building roles. The supervisor monitored the overall model using an iPad handheld device, ensuring the prototype retained its correct form. Additionally, one individual donned an AR headset (Microsoft HoloLens2) to facilitate construction (see Figure 6).



Figure 6: 1:1 prototype assembly process. Supervisors on the left are comparing the built form to the AR model and inspecting it for inconsistencies. Source: (Author 2024)

The builders, equipped with Microsoft HoloLens, guided the clamping and welding of the polycarbonate at a more local scale. A slider interface was implemented to create a more interactive process that allows the builder to alter the percentage of the AR model shown at a time (Figure 7). With this, the builders could visualize prototype segments without the overlay obstructing their vision.



Figure 7: The 1:1 augmented prototype assembly process shows the geometrical overlay and the user interface. Source: (Author 2024)

Small-scale prototypes were created at different sizes to test joint methods and bending behavior. Various heat-based tools were used for the smaller prototypes, including hot air guns, impulse heat sealers, soldering irons, and welding guns. The tested welded joints include punctured fusion welds, continuous fusion welds, circular fusion welds, and W-shaped fusion welds (as shown in Figure 8). From the preliminary tests, intermittent W-shaped fusion welds were determined to be the most robust option. For the 1:1 prototype, W-shaped fusion welds were used to join polycarbonate film at five evenly spaced points along the vertical axis. Each joint connected a maximum of two layers. The prototype joints were roughly aligned along a central axis to strengthen it in the direction of the cables and to allow prototypes to be compressed for storage. On-site, a two-story truss system was constructed, and the 1:1 prototype was suspended in the air for one week to test the feasibility of the joints. Several cameras were used to monitor the prototype during this period, and the effects of the prototype on on-site conditions were also monitored.



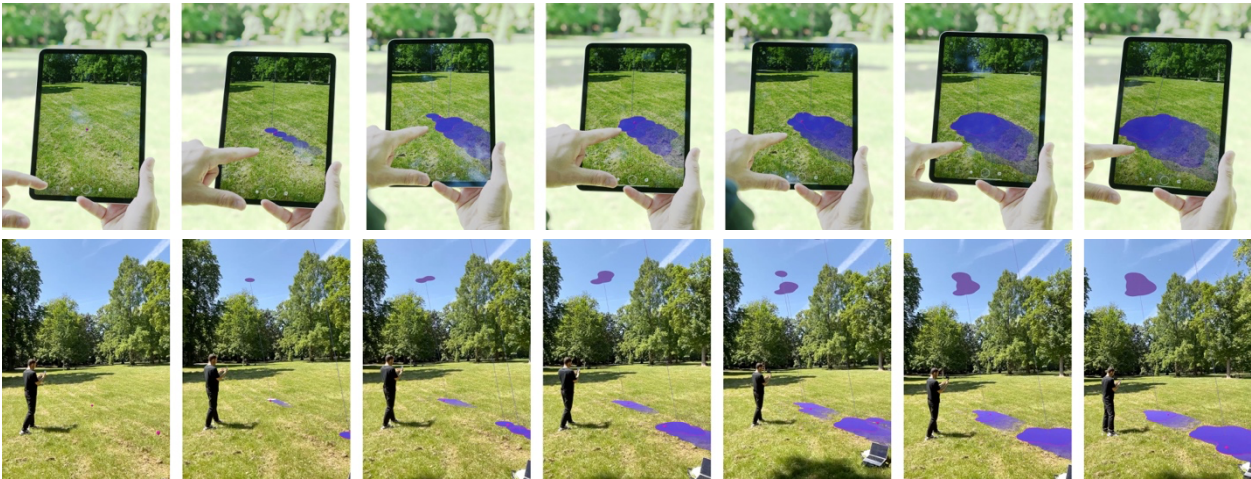
Figure 8: The W-shaped fusion welding tool and its application for the 1:1 prototype. Source: (Author 2024)

3.0 RESULTS AND REFLECTIONS

This research presents AR-based on-site design and fabrication processes for shading devices based on computational design and shadow simulation guided by human decisions. Each step of the design process informs the following process. Collecting the necessary shadow analysis generated a design that efficiently responds to reducing direct sun exposure and improving thermal comfort.

3.1. AR-based design

The AR design tool enabled non-experts to place shading areas as desired within the existing circular grid. Figure



9 shows a user during the process of using the cursor to select the shading areas while being able to get a view of the shading devices projected along the sun vector.

Figure 9: Stills from video capture during the placement of shaded areas via the AR application. The top row shows the placement on an iPad, and the bottom row shows the placement from a second device. Source: (Author 2024)

The layout and pattern generation scripts streamlined the iterative phases of the design process. With it, a single designer could produce and test numerous designs within a limited time frame. Additionally, the introduction of limited randomness contributed to the final design's aesthetic, which incorporated both material properties and functionality. A final design was achieved through a material-based design system that leveraged the properties of polycarbonate. In the context of shading structures, this process was used to find the pattern that maximizes shade while considering the material and fabrication constraints of the film material.

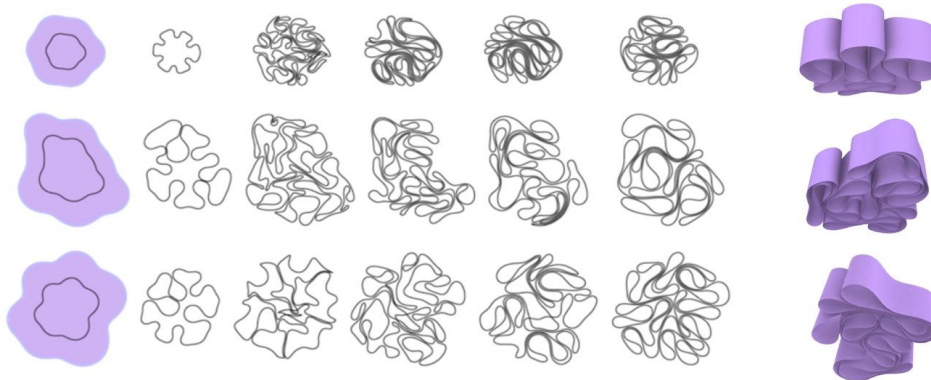


Figure 10: Examples of the script generating patterns of differing complexities and densities Source: (Author 2024)

3.2. Sun hours

Monochromatic shade models were constructed to calculate the concentration and total area of the shade cast by the structure (Figure 11). The location and area of the smallest and largest possible shadows cast were also determined. Control tests were run using solid blocks of equal dimensions for both models. Outputs were converted into percentages and used to gauge the effectiveness of the given forms.

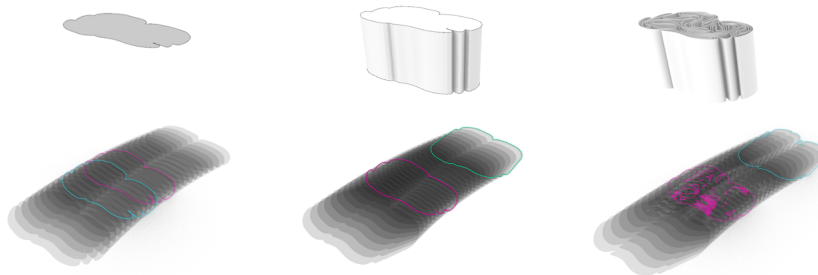


Figure 11: Shadow analysis on July 21st from 11:00 AM to 3:00 PM for a flat surface without perforation (left), a solid geometry (middle), and the generated form (right). Source: (Author 2024)

A direct sun hour analysis was implemented, focusing on the immediate area surrounding a single, suspended structure (Figure 12). Using meteorological data from San Antonio, the hours of solar exposure on July 21st from 11:00 AM to 3:00 PM were calculated in 5-minute increments.

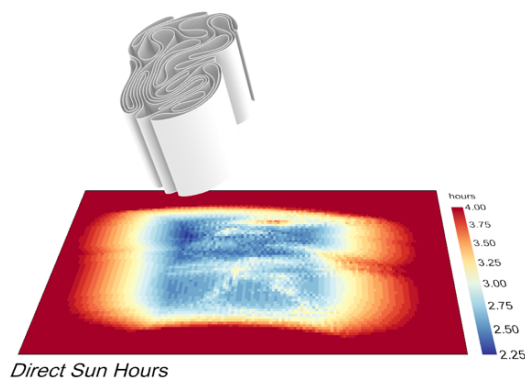


Figure 12: Direct sun hour analysis on July 21st from 11:00 AM to 3:00 PM in 5-minute increments. Source: (Author 2024)

Our measurements recorded both increases in shadow area and reductions in hours of direct sun exposure. As depicted in Figure 11, the pattern generates a maximum shadow of 5.07 m² (cyan) and a minimum shadow of 2.8 m² (pink). In contrast, the solid block generates a maximum shadow of 5.51 m², while the flat surface generates a maximum shadow of 3.38 m². Solar radiation analysis, shown in Figure 10, indicates that only minimal spots remain exposed to sunlight. The total area experiencing reduced solar exposure by more than an hour was 7.5 m², and the

overall area observed to have reduced solar exposure amounted to 16 m². Compared to the 3.4 m² footprint of the polycarbonate form, the maximum area of solar protection is 4.7 times larger.

While the perforations impact the shadow area generated, the combination of orientation and depth in the design made this effect minimal. This is vividly demonstrated by the shading structure's smallest shadow; even though perforation allows some light penetration, the angle ensures this happens during times of the day with less cooling demand and in quantities too minimal to undermine its utility. The layout proposed in the UTCI analysis reduced the average temperature by 3-4° Celsius. The average perceived temperature in the analyzed area transitioned from 36.34 °C without intervention to 35.78 °C with the implementation of shading devices. With the proposed twelve geometries, approximately 50 percent of the site's main lawn underwent temperature reductions significant enough to enhance thermal comfort. These results align with the temperature reductions offered by deciduous trees, as shown in Figure 13. Such results confirm the feasibility of larger-scale applications of the approach for AR-assisted shading design.

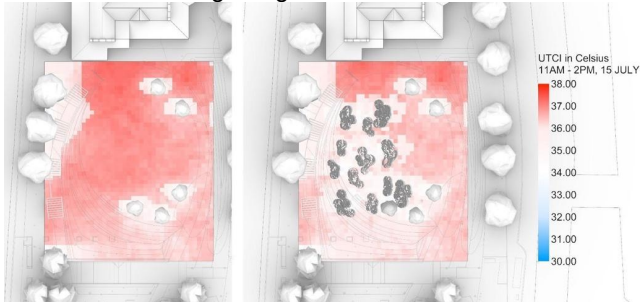


Figure 13: The UTCI heatmap for the site before intervention (left), including the shading devices (right). Source: (Author 2024)

3.3. Prototyping

The results of the 1:1 prototype test underscored the concept's potential for creating comfortable pockets of shade. The entire construction process, greatly simplified by the use of AR-assisted design, was completed in less than a day by a team of just four builders. The AR technology was an accessible blueprint, providing workers with clear assembly instructions. The segmentation of the AR model streamlined the information delivery to the builders, enhancing efficiency. Among the two devices used, the HoloLens goggles proved superior to the iPads, enabling workers to visualize the model while actively building. The flexibility of this phase permitted modifications to the prototype during assembly. Builders could suggest changes to the pattern or the size of the curves within the constraints of ensuring future connections remain secure and consistent with the pre-established outline. The AR model could be swiftly updated to reflect any alterations and used to set a new endpoint if necessary. During construction, producing W-shaped fusion welds was rapid and cost-effective. While polycarbonate was used in this prototype, other more sustainable, eco-friendly materials could be used in future iterations. For instance, bioplastics or recycled plastics could be considered, reducing the environmental footprint while maintaining the requisite flexibility and strength. Material selection should also consider potential outgassing or chemical release during welding, favoring materials that minimize these risks.

While the prototype's overall stability was satisfactory, it was noted that a single joint failure occurred along the exterior of the prototype. The timing and cause of this break are unclear, possibly due to mishandling during disassembly; however, this incident highlights the need for more robust, reinforced connections in future prototypes. On-site monitoring confirmed the prototype's effectiveness in providing shade during the afternoon, particularly when the sunlight was directly overhead – the most crucial time for shade provision (Figure 14). Even when sunlight struck the prototype at an angle, the cast shadows were large enough to ensure thermal comfort. The prototype balanced its shading function with preserving views of the sky, avoiding the monolithic appearance of a solid shading surface, a testament to the potential of this approach.

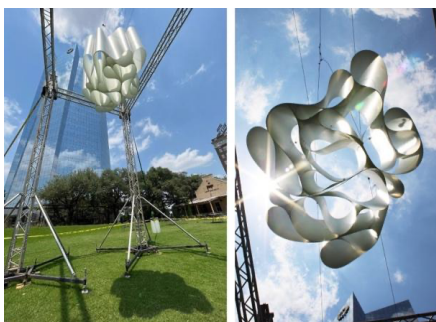


Figure 14: The 1:1 prototype was installed with a provisional truss structure on site, with its shadow cast on the lawn (left) and the view through the perforated shading device (right). Source: (Author 2024)

CONCLUSION

The research presents a comprehensive approach to mitigating direct sun exposure by employing computational and on-site participatory design, shadow analysis, and digitally augmented fabrication, aided by augmented reality (AR). The integrated design process caters to diverse programmatic needs and successfully improves thermal

comfort while addressing essential placemaking necessities. Tests confirm that the innovative structure effectively generates perforated shade, striking a balance between sun protection and unobstructed views.

The on-site design tools provide a comprehensive understanding of each shading intervention at the site scale, allowing users to focus on designing shadows rather than the shading device itself. Tailored computational design tools were developed explicitly for bending-active polycarbonate structures. Combined with the AR-assisted fabrication process, this offers a cost-effective solution that empowers many users to design and construct shading structures.

This research builds upon existing studies that strive to harness AR for design and fabrication, integrating material behavior through computational tools. The workflow developed can be applied to a multitude of projects across diverse sites, utilizing 3D data of the surroundings to generate site-specific shading solutions. The simulation of material behavior within these computational analyses merits further exploration, with the potential to optimize the creation of perforated shading devices. Moreover, incorporating AR into earlier stages of the design process promises to democratize design and enable on-site construction by individuals without professional training.

This case study enriches the repertoire of available methods and tools for creating shade in urban parks experiencing extreme heat, such as those in San Antonio. The approach empowers a participatory design process and simplifies construction, making it accessible even to those without formal training. Overall, the project demonstrates how accessible, technologically supported methods can improve thermal comfort in public spaces, contributing to more resilient urban landscapes.

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