Convertible Urban Shades for Climate Resilience
A Holistic Evaluation

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ABSTRACT: Cities with high building density increasingly suffer from urban heat islands (UHI) due to climate change, as sealed surfaces retain heat and limited ventilation proves inadequate for cooling. To counteract these effects, our study investigates the potential of Convertible Urban Shades to mitigate UHI by offering a diurnally or seasonally adjustable shading solution for urban areas, thereby fostering resilient urban microclimates. Utilizing a physical mock-up in Stuttgart, Germany, we compared the impact of no, fixed and convertible shades. Results from the measurement campaign carried out during a heatwave period showed that by using the no-shade scenario as baseline, convertible shades outperform fixed shade, by providing peak reduction of street surface temperature of ~16°C during daytime, and up to ~3°C colder at nighttime. The study also explored the architectural impacts of different shading structures in a street canyon. A scaled mock-up of the street canyon was used to involve stakeholders in a participatory design process to discuss design and implementation policies. The findings highlight Convertible Urban Shades' role in promoting resilient urbanism.
KEYWORDS: Convertible Urban Shades, Outdoor Comfort, Urban Microclimate, Sustainable Urban Design, Lightweight Tensile Structures

1. INTRODUCTION

In the face of escalating climate change impacts, urban areas stand at the nexus of both vulnerability and opportunity. Rapid urbanization has led to reduced green cover, compromised air quality, and amplified building energy consumption [1]. Especially for cities with high building density, the high degree of sealed / impervious surfaces retain heat longer while limited urban ventilation often proves insufficient in cooling these surfaces [2]. This affects the quality of public spaces and poses adverse health risks.

This paper presents an introductory, yet holistic, investigation into “Convertible Urban Shades" as a scalable design solution for locally reducing temperatures in high-density urban areas. "Convertible Urban Shades" are lightweight, tensile shading structures designed for urban spaces, such as plazas, courtyards, and wide street-canyons, offering adjustable shade as needed.

These shading structures respond quickly to leverage the diurnal swings of temperature and radiation-balance in the Urban Canopy Layer (UCL). During daytime they deploy to minimize solar gains and retract at night to allow for cooling through long-wave radiation exchange with the night sky and increased convection. Thus, they serve as an agile response to the urgency of stabilizing urban microclimates amidst climate change and intensifying heatwaves.

The research presented in this paper focuses on the applicability of these shading structures in high-density, central and southern European cities, using Stuttgart, Germany, as a case study. It explores three interconnected factors: (i) the potential for improvement in the urban microclimate through the reduction of air and surface temperatures (at the pedestrian and façade level) in the Urban Canopy Layer compared to traditional fixed shading; (ii) the structural and architectural evaluation; (iii) and an integral component focusing on communication and participation strategies. The latter is dedicated to understanding stakeholders' perceptions and facilitating their direct involvement in the design and implementation process.

2. LITERATURE REVIEW

The field of urban climatology has historically concentrated on adaptation strategies that emphasize the influence of blue-green infrastructure [3], and the surface properties of the built environment (albedo, thermal heat capacity) [4]. However most existing sidewalks in dense central European cities like Stuttgart have existing infrastructure such as sewage and electrical systems underneath sidewalks. This urban sub-surface infrastructure poses a hard limit on easy integration of dense tree plantations necessary to achieve required canopy thickness for sufficient shade [5]. Hence alternative adaptation strategies need to be explored for such situations.

In recent years a growing body of research shows that shading of public urban space has also proven to be an effective strategy for reducing the urban heat island (UHI) effect on the macroclimate level [6], as well as for improving the pedestrian comfort on the microclimate level [7] [8]. Hence urban shading is regarded as an effective strategy for climate adaptation. However, most urban planning research on shading is primarily concerned with the effects of self-shading street canyons and trees, such as the works of [3] [9] [10]. Limited studies focusing on specifically designed urban shading devices are found in literature. [11] [12] [13] investigate the impact of colour, material and geometry of fixed shading structures deployed in streets and plazas and found improvement in the outdoor thermal comfort. The city of Seville, Spain is one example of successful implementation of such seasonally fixed shading devices in urban areas of Europe.

The effectiveness of these shading devices in a plaza typology could also be further improved by making them diurnally adjustable to limit the solar heat gain during daytime and allowing for cooling through radiation to the night sky by retracting these shades at night, as shown by [14]. The large folding umbrellas in the Holy Prophet's Mosque in Medina, KSA are a famous demonstration of this strategy in a plaza typology [15]. While such convertible urban shading devices are also listed as a basic strategy against UHI in [16], limited evaluation of the improvement of thermal environment in a variety of urban typologies is provided. This paper attempts to bridge this gap on convertible urban shades (CUS) by providing measured data on their thermodynamic effectiveness, and by calibrating a TRNSYS thermal simulation model for further analysis of these devices.

3. HOLISTIC EVALUATION

3.1 Proof-of-Concept & TRNSYS calibration

A proof-of-concept mock-up was constructed on the rooftop of the ABK Stuttgart building to collect measured data for air and surface temperature for three configurations – no-shade, fixed shade, and convertible urban shade (CUS). The measurement campaign was carried out in Stuttgart, Germany during the period of summer heatwaves (July to September 2023).

The experimental setup consisted of lightweight boxes with an overall outer dimension of 104 x 136 x 94 cm (width/length/height). The floor consisted of three layers of massive bricks, for a thermodynamic representation of the top layer of a common street surface (brick specification: 240 x 115 x 71 mm, 2000 kg/m^3, 0.96 W/m·K). The brick layers were placed in an OSB wooden box (internal dimension of brick volume: 60 × 60 × 21.3 cm), insulated with an 10 cm layer of hard polystyrene. Such a setup allowed to mimic an isolated section of an infinitely large urban plaza, with negligible heat exchange to surrounding surfaces. Surface temperature sensors were fixed at the top surface of the brick volume, as well as depths of -7,1cm and -14,2cm. Air temperature sensors (rain-protected) were placed in the box. The setup is illustrated in Figure 1.

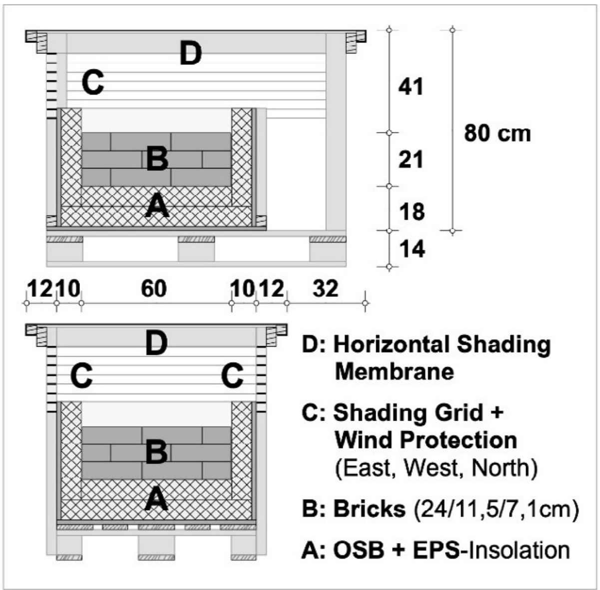

Figure 1: Mock-up cross and longitudinal section.

For the two boxes with shading (fixed and CUS), an identical shading material was used – a white PVC fabric from SergeFerrari (Flexlight Advanced 902-S2; Tsol = 0.07; Rsol = 0.80; ABSsol = 0.13). Additionally for the box with CUS, the shading was retracted everyday around sunset and activated again next morning.

For interpreting sample results of the floor surface temperature measurement campaign presented in Figure 2, the no-shade scenario serves as the baseline, representing status quo. For the fixed shade, it was found that it provides peak reduction of ~14°C during daytime but can get ~1°C warmer at nighttime. The CUS was found to outperform the fixed shade, by providing peak reduction of ~16°C during daytime, and up to ~3°C colder at nighttime, when compared to the baseline no-shade scenario.

Finally, a detailed TRNSYS micro-climate simulation model was setup for the experimental setup, with the goal to calibrate the model with the measured data. Figure 3 shows the final calibrated model achieved an average R2 of over 0.94. This validation sets the ground for more detailed simulations in the future.

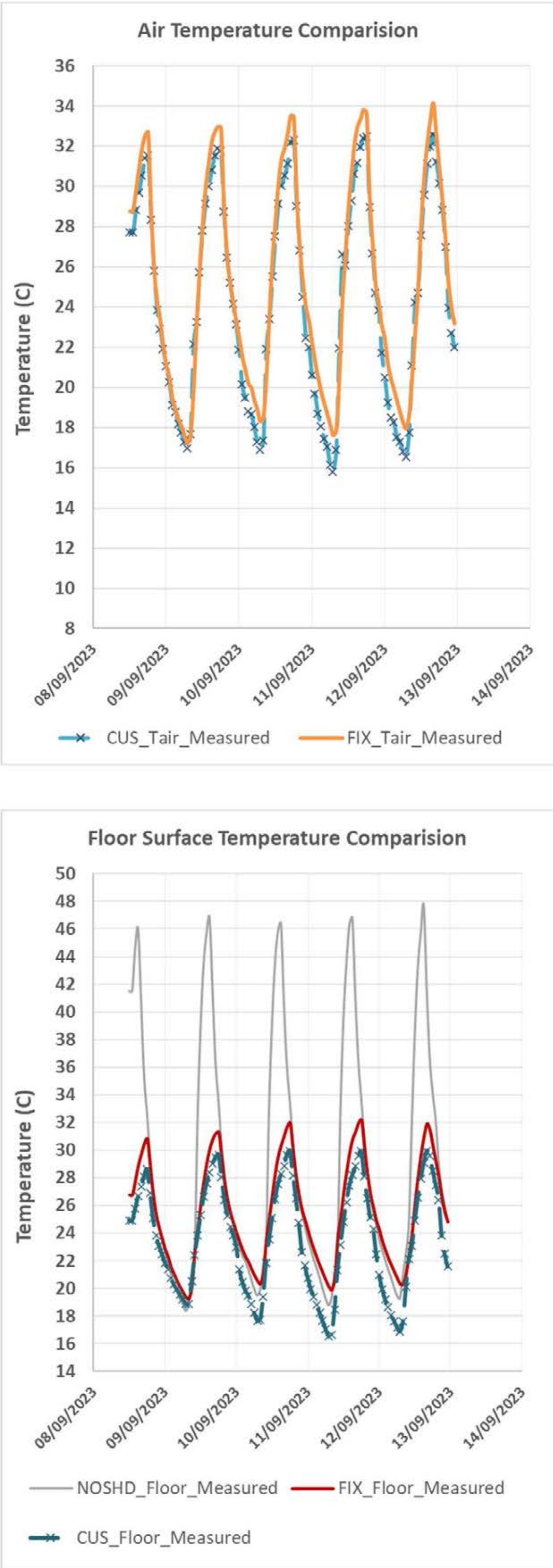

Figure 2: Measured Temperatures – No Shade, Fixed and Convertible Shade.

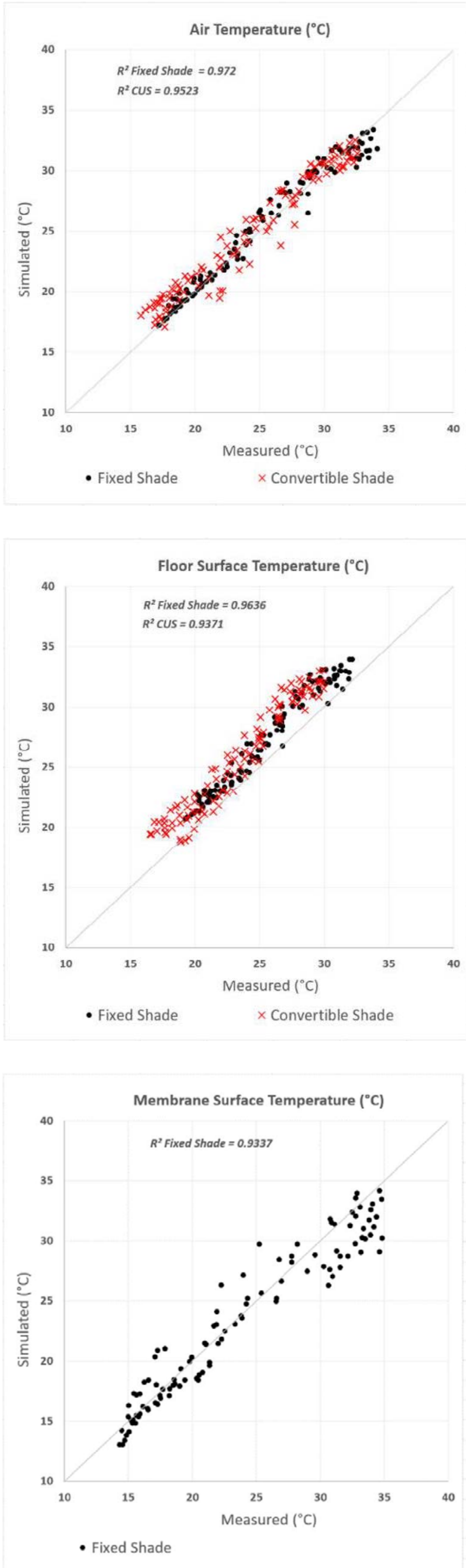

Figure 3: Correlation between Measured and Simulated Temperatures.

3.2 Structural and architectural evaluation

As mentioned in the introduction, "Convertible Urban Shades" are lightweight, load bearing, tensile structures, which allow maximum utilization of the strength of the material (e.g. membranes). They optimize the mechanical characteristics of the material by eliminating inefficient bending stresses etc [17].

The great advantage of such tensile-only load-bearing structures is the “foldability” that they offer, making them ideally suited in applications such as movable and adaptable shading strategies. They offer a simple, reversible, and complete change in the geometry of a load-bearing component, which allows for swift adaptation of the structure to respond to a myriad of stimuli such as weather changes/climatic factors, acoustic boundary conditions, requirements for thermal behavior, lighting and exposure conditions etc [18] [15]. Such shading structures can also cover large spans without needing space-consuming, bulky supporting structures, making them suitable for use in large urban spaces like public squares etc.

From a structural design perspective, Convertible Urban Shades can be broadly classified into two main categories: (A) pneumatically pre-stressed construction and (B) mechanically pre-stressed construction. Both can be used to realize a variety of transformation principles [18] [19] [20].

(A) Pneumatic pre-stressed construction can be further classified into six sub-categories based on the transformation principle: (i) push-through cushions, (ii) inverting hoses, (iii) tires with membrane retraction in beads, (iv) rolled hoses, (v) cushions, and finally (vi) convertible multi-cells [18].

(B) Mechanically pre-stressed construction can also be further classified into three sub-categories based on their transformation principle: (i) membrane as a convertible component within a non-convertible primary system e.g. centrally gathered roof, (ii) membrane that follows the transformation of the primary structure e.g. umbrella, and finally (iii) membrane as a component of a convertible primary system whereby the membranes change their position in space, but not their geometry, when the primary system moves, e.g. movable roof.

Additionally, mechanically prestressed structures can also be classified into four styles based on the direction of movement during the transformation process: (i) parallel, (ii) central, (iii) circular, and (iv) peripheral moving constructions. The textile membranes are either gathered, folded, or rolled [19] [21].

However, Convertible Urban Shades introduce special constraints on the choice of the membrane material due to changes in shape during the travelling process. Hence high-strength fabrics made of organic fibers, PVC-coated polyester fabrics, PTFE fabrics, and Aramid fabrics are needed for such an application.

Convertible shading structures are also significantly more complex in terms of design, construction, and maintenance, as compared to a typical fixed shading structure [17].

Therefore, from an architectural design perspective, fixed vertical textile lamellas were also briefly studied besides adaptive membrane structures for more holistic evaluation. The advantages of fixed lamellas are their comparatively low planning and execution requirements in comparison to adaptive systems, and they also ensure a continuous ventilation of the street.

Three distinct system geometries were conceived and investigated as seen in Figure 4. The underlying consideration was a street in an east-west orientation in Stuttgart, with a total length of 140 meters, a width of 14.5 meters, and buildings with an average height of 14 meters (eaves height). The variants differ in terms of their horizontal distance and the vertical extension of the membrane. Variant 1 features lamellas at a horizontal interval of 2 meters and a height of 3 meters. In Variant 2, the distance increases to 5 meters and the lamella height to 4 meters. Finally Variant 3 has a horizontal distance of 10 meters with a lamella height of 7 meters.

As a preliminary evaluation, a direct sunlight hours study of the 3 variants demonstrates that all show similarly good shading of the street. Future studies will evaluate the detailed microclimate using the calibrated TRNSYS model from this study.

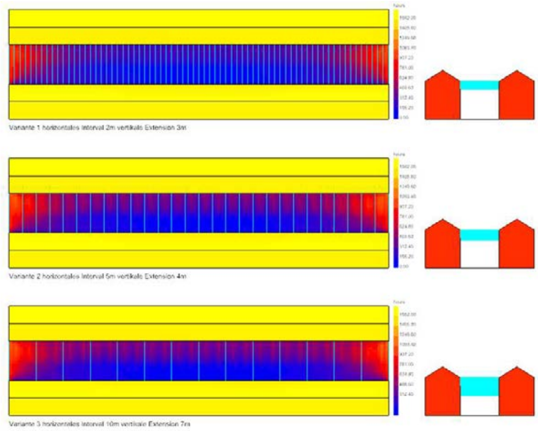

Figure 4: Sun hours study for different vertical lamellas.

Regarding the architectural impact, Variant 3 shows a significant reduction in terms of overall material consumption and assembly effort.

The suspension cable could serve as one of the most efficient structural design solutions that can be used for such fixed shading system – the membrane is simply attached to the suspension cable, and either allowed to hang freely or is stabilized by an additional ballast. Such simple cable structures offer high tensile strength and their low weight enable them to bridge large spans with minimal material use. Such a rudimentary tensile suspension cable structure can also be easily and firmly anchored into the building façade. Common materials used for suspension cables are galvanized steel, stainless steel, and other high-strength modern composite materials, which significantly contribute to the longevity of the constructions. Further structural options such as frames, tensioning of the membrane, or stiffening with battens, will be examined more closely in future publications as part of the ongoing research process.

3.3 Research-related Communication and Participation

The transformation of urban public spaces towards climate adaptation requires broad acceptance in society, considering a large number of different stakeholders. Based on a stakeholder analysis, specific communication strategies were developed for each target group, adhering to the recommendations of the National Institute for Science Communication (NAWik) [22]. The goal was to engage, involve, and facilitate interdisciplinary exchanges among participating stakeholders. Furthermore, insights were gained through interactions with diverse stakeholders affect the development of individual shading strategies.

First, a dedicated project website communicates climate change challenges, provides updates on current research, and allows for idea contributions. It caters to both experts and laypeople. Second, a public symposium was also organized to spread awareness, featuring lectures and discussions aimed to bring together a diverse array of stakeholders and perspectives, including architects, structural engineers, urban climatologists, city officials, and the public. Third, a large-scale physical model and traveling exhibition format – named "U°CA On Tour", was created. This platform facilitated participatory evaluation, allowing various interest groups to interact with different design typologies and collect user preferences, concerns as well as, suggestions. The model informs, engages, collects feedback, promotes transparency, and encourages collaboration. The model proves to be particularly accessible, communicative, and inclusive.

Positive feedback from the implemented formats helped to strengthen the efforts in knowledge transfer and stakeholder involvement. In the next phase, a communication strategy will be employed to further involve the city administration and planning stakeholders. This will enable the collection of additional information regarding implementation and planning processes.

Scientific pursuits on climate change adaptation, often remain inaccessible to the common people due to their highly specialized subject matter. Communication and participation strategies accompanying such research can help counteract this, by engaging in public discourse around the opportunities and challenges related to such measures, as evidenced by the paradigm adopted in this work.

Figure 5: Residents and users interacting with the travelling exhibition of Convertible Urban Shades ('U°CA On Tour') as part of the participatory design process (Stuttgart, Germany).

4. CONCLUSION

This paper presented a holistic investigation of Convertible Urban Shades, encompassing measurement campaigns, thermodynamic validation of computer models, architectural and structural design considerations as well as participatory engagement.

Climate change exacerbates the urgency of rethinking urban spaces. Traditional architectural interventions pertaining to blue-green infrastructure may fall short due to long implementation timelines and potential disruptions to existing infrastructure. Alternative solutions such as Convertible Urban Shades offer a promising avenue, embodying flexibility, and efficiency. Our measurement campaigns showed their potential to reduce ground surface temperatures at day by 16°C and at night by upto 3°C compared to the status quo. By combining architectural innovation with user-driven acceptability, this research contributes to the discourse of sustainable architecture and urban design for climate resilience.

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