ComfortCover: A Novel Method for the Design of Outdoor Shades

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ABSTRACT

Over the past few decades, several methods for designing shades to reduce energy loads of buildings have emerged. However, to date there are virtually no agreed upon methods available to assist in the design of outdoor shades to keep people comfortable. Here we present a novel method named ComfortCover to assist in the design of static shades in outdoor conditions using a 3-step methodology adapted from the current state-of-the-art process for the design of building shades.

The first step is an assessment of radiation falling on a person and the calculation of a corresponding solar-adjusted radiant temperature for every hour of the year. Second, this temperature is fed into an hourly calculation of Universal Thermal Climate Index (UTCI). Lastly, this UTCI is fed into an algorithm that projects sun vectors for every hour of the year from the location of a person through a surface where shade design is being considered. Each of the vectors is associated with a UTCI and a temperature difference from a 'comfort temperature' that is summed up for every subdivision of the test shade to color it with shade helpfulness (blue), shade harmfulness (red) and no major effect of shade (white).

Author Keywords

Outdoor; Comfort; Shade; Design; ComfortCover; UTCI

INTRODUCTION

As research into outdoor thermal comfort has progressed over the last decade, there has been a widespread consensus that the presence of direct sun falling on a person can have a large effect on comfort. [1,2,3,4]. Some studies have gone as far to suggest sun as the largest determinant of outdoor comfort as in many cases, having a more significant effect than either wind or humidity [5,6]. As such, many agree that sun and shade are important variables that must be accounted for when designing comfortable outdoor spaces. Notably, studies have stressed both the importance of shading the sun to keep people cool in hot conditions [7,6] as well as making the sun available to warm people in colder conditions [7,4]. Accordingly, in the majority of Earth's climates, where both hot and cold conditions exist, it is important to factor in both the beneficial effects of sun to curb cool conditions as well as the harmful effects of sun in warm conditions in order to design effective shading schemes for outdoor environments.

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Oftentimes, the need to account for both the beneficial and harmful effects of sun is mitigated by the fact that people are usually mobile when they are outdoors. Accordingly, so long as a diversity of shaded and unshaded conditions are provided in a given outdoor space, people are usually able to make themselves comfortable [7]. However, there are also many cases in the outdoor environment where people are expected to sit or remain in a single spot and where this usual strategy of shade diversity will not work. Such cases often arise due to a combination of people not wanting to sit on the ground for sanitary or ergonomic reasons and public institutions wanting to avoid theft of street furniture by bolting it to the ground. Countless cases of this situation can be named from bus stop shelters, to picnic table shading, to placement of shade trees for park benches, to awnings for street-side cafe seating. In spite of the importance of sun to outdoor comfort and the multitude of cases where comfort-sensitive shading would be of benefit, there are virtually no agreed-upon methods currently available to assist in the design of outdoor shades to keep people comfortable.

Existing Methods

At present, if a designer were faced with such a task, they would likely resort to an altered version of the original method developed by Olgyay and Olgyay [8] to size brise soleils for window glazing. Perhaps the first of its kind, this method uses heating and cooling degree days around a balance temperature to select "cut-off dates" with corresponding sun altitude angles that effectively trim the boundary of a rectangular shading plane. In theory, designers could use this method in the design of shades for outdoor comfort by selecting a balance temperature that is indicative of an individual person's energy balance rather than the energy balance of a building. However, because such a human energy balance temperature has never been standardized and the Olgyay method has since been replaced by more precise methods, such an outdoor application would fall far short of the potential accuracy that could be achieved with present technology.

Since the time of Olgyay, there have been large advances in shading design methods for buildings that have factored in criteria such as the azimuth of sun vectors, the thermal lag of buildings, the occupancy schedule of buildings, the buildings' insulation, and much more. Notable among these methods are the Thermal method, the Eco Degree Day method, the Eco Thermal method, and the cellular Shaderade method [9]. In 2011, Sargent et al. demonstrated that the Shaderade method could suggest a shade with the greatest building energy savings of all these methods. The method's success is owed in large part to an underlying EnergyPlus simulation and combines the heating, cooling, and solar beam gains of this simulation with hourly sun vector geometry in order to color a shade's cells with shade helpfulness and harmfulness. With this major advance in building shading, this paper seeks to adapt this current state-of-the-art cellular Shaderade method to create an agreed-upon standard for the design of outdoor shading for comfort.

Proposal for a new Method

Figure 1 illustrates how such a Shaderade adaptation to outdoor shading would progress from the initial selection of a seating area and a surface where shade is being considered to the coloration of the shade surface with shade desirability (blue) or shade harm (red), and finally to the selection of the best part of the shade as a start for design. From here through the rest of the paper, this adaptation of the Shaderade method to the case of outdoor comfort will be referred to as the ComfortCover method.

Much like the adaptation of the Olgyay method, the key feature that must be changed in order to use Shaderade for outdoor comfort is to replace the building energy simulation with an outdoor comfort assessment. The last decade has produced a wealth of validated methods for assessing outdoor comfort and corresponding comfort metrics expressed as a temperature of what the outdoors 'feels like.' One particular temperature metric that has proven to have a good correlation to outdoor comfort surveys is Universal Thermal Climate Index (UTCI) [10, 4]. In the design of outdoor shades, UTCI is particularly helpful as it was published with ranges defining conditions of 'no thermal stress', 'heat stress', and 'cold stress,' which can be used to identify whether a given set of conditions should contribute positively, negatively, or not at all to shade benefit [11]. The usefulness of UTCI is further enhanced by the fact that it is calculated independent of clothing level and metabolic rate, assuming a natural adaptation of these variables as outdoor climate conditions change. The only required inputs for UTCI calculation are air temperature, mean radiant temperature (MRT), relative humidity, and wind speed, thus making it easy to calculate from publicly available TMY weather data. Because of UTCI's validated accuracy, it's incorporation of ranges that define thermal stress, and its simple inputs, UTCI was selected as the underlying comfort value with which to derive shade desirability or harm.

In order to adapt the original Shaderade method for UTCI, it is first necessary to state the underlying formula that Shaderade uses in order to determine whether a given hour and its corresponding sun vector contributes positively or negatively to shade benefit. This formula is as follows:

$$E_{unwanted} = \begin{cases} E_{beam}, & E_{cooling} <= 0 \\ E_{cooling} - E_{beam}, & 0 < E_{cooling} < E_{beam} \\ E_{beam}, & E_{cooling} >= E_{beam} \end{cases}$$

Where $E_{unwanted}$ is the fraction of the sun's beam gain that is increasing the building cooling load (or the shade helpfulness for that hour), E_{beam} is the solar beam gain through the window at the given hour, and $E_{cooling}$ is the difference between the cooling load and heating load at the given hour (or cooling load - heating load). Note that $E_{desired}$ can be either positive (contributing to shade helpfulness) or negative (contributing to shade harmfulness) depending upon the given conditions. In order to adapt UTCI to this method, a similar approach is taken but the heating, cooling and beam gain are replaced with a temperature difference around a balance temperature. This formula can be written as follows:

$$T_{unwanted} = \begin{cases} T_{hour} - (T_{bal} - T_{offset}), & T_{hour} <= (T_{bal} - T_{offset}) \\ 0, & (T_{bal} - T_{offset}) < T_{hour} < (T_{bal} + T_{offset}) \\ T_{hour} - (T_{bal} + T_{offset}), & T_{hour} >= (T_{bal} + T_{offset}) \end{cases}$$

Where $T_{unwanted}$ is the number of degree-hours for which the additional temperature delta from the sun is unwanted (or the shade helpfulness for that hour), $T_{ba}l$ is the median outdoor temperature that people find comfortable, T_{offset} is the number of degrees away from T_{bal} that people will feel no thermal stress, and T_{hour} is the UTCI at the given hour. Again, note that $T_{unwanted}$ can be either positive (contributing

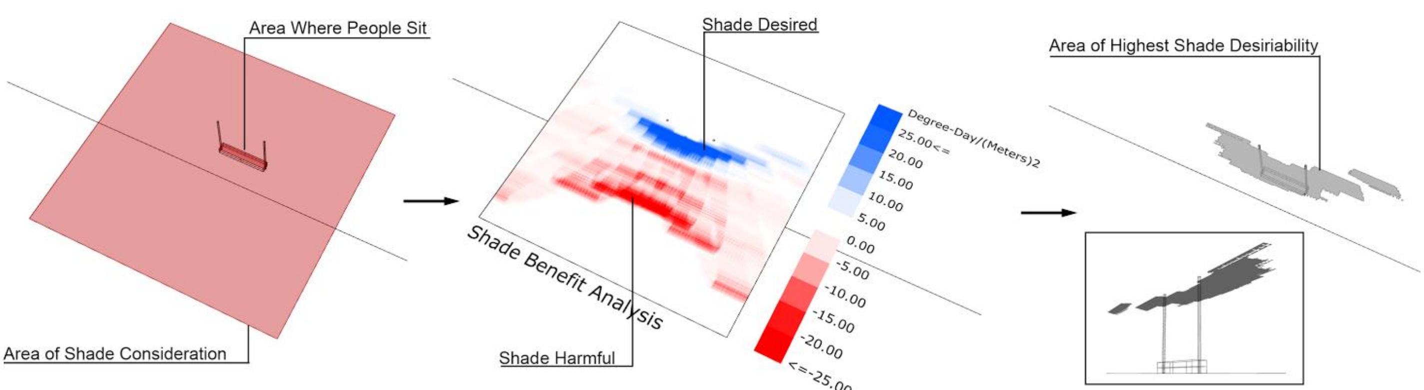

Figure 1. The inputs and outputs of the ComfortCover method.

to shade helpfulness) or negative (contributing to shade harmfulness) depending upon the given conditions. Since UTCI was published with a range of 'no thermal stress' defined from 9 ºC to 26 ºC, T_{bal} and T_{offset} will be defined as 17.5 ºC and 8.5 ºC respectively for the remainder of this paper in order to ensure alignment with these standardized values.

Following the Shaderade method, the ComfortCover method will project hundreds of solar vectors from an array of test points over the area where a person is seated and are intersect these vectors with a test shade that has been subdivided into cells. The degree-hours of $T_{unwanted}$ are summed up for each cell of the test shade in order to give a net shade desirability, shade harm, or net minimal shade effect.

In order to ensure that UTCI values for T_{hour} are correctly calibrated for the suggestion of shade desirability, it is necessary to account for the effect of solar radiation falling directly on people by plugging in a solar adjusted MRT into the UTCI calculation. Traditionally, in order to determine this solar adjusted MRT, a radiation study of human geometry is performed and this is then used to produce an Effective Radiant Field (ERF) through the following formula:

$$\alpha_{LW}\ ERF_{solar} = \alpha_{SW}\ E_{solar}$$

Where E_{solar} is the short wave solar radiant flux on the body surface (W/m^2), α_{SW} is short-wave absorptivity, and α_{LW} is the long-wave absorptivity (typically around 0.95). The ERF can then be related to an MRT through the following formula:

$$ERF = f_{eff}\ h_r\ (MRT - T_a)$$

Where f_{eff} is the fraction of the body surface exposed to radiation from the environment (=0.696 for a seated person and 0.725 for standing) [12]; h_r is the radiation heat transfer coefficient (W/m^2 K); and T_a is the air temperature (ºC). To the disadvantage of the design process, this traditional method of performing a radiation study over human geometry is often very time consuming if one is attempting to determine solar-adjusted MRT for every hour of the year. Accordingly, a faster method developed by Arens et al. [13] called SolarCal will be used in this study [14]. SolarCal substitutes this lengthy radiation study with use of weather file radiation values and a few coefficients to account for the geometry of the human body. Specifically, SolarCal works through computing the ERF with the following formula:

$$ERF_{solar} = (0.5\ f_{eff}\ f_{svv}\ (I_{diff} + I_{TH}\ R_{floor}) + A_p\ f_{bes}\ I_{dir}\ /A_D)\ \ (\alpha_{SW}/\alpha_{LW})$$

Where I_{dir}, I_{diff}, and I_{TH} are direct normal radiation, diffuse horizontal radiation, and total horizontal radiation respectively, all of which can be obtained from publicly available TMY weather data. A_p and A_D are geometry coefficients of the human body, which are computed based on sun altitude and azimuth and are described fully in the paper by Arens et al. [13]. R_{floor} is the reflectivity of the ground, which is assumed to be 0.25 by default in this study. Finally, f_{svv} and f_{bes} are the sky view factor and the fraction of the body visible to direct radiation respectively. In this study, these two values are computed by ray tracing from the spot of the seated person and noting intersections with surrounding context geometry. Sky view factor is computed once for the whole year by tracing rays from the location of the person to each of the 145 Tregenza sky patches and dividing the non-intersected rays by the total number. f_{bes} is calculated individually for each hour of the year by tracing the hourly sun vector from each of 9 vertically-arranged points at the location of the person and noting the fraction of these that do not intersect context geometry. As such, the time-consuming radiation study of human geometry is replaced with a much faster calculation that assumes that the body as a set of points (Figure 2).

Together, with the SolarCal method accounting for solar adjusted MRT, a UTCI calculation that factors in this MRT, and a means of incorporating such UTCI in a Shaderade-style analysis, this paper outlines a new workflow that can produce a high-accuracy suggestion of where outdoor shading should be provided and where it may be harmful.

SCRIPTING ENVIRONMENT OF THE NEW METHOD

This study merges the three aforementioned steps together by integrating them through the Grasshopper visual scripting platform, making each step available as a separate Grasshopper component.

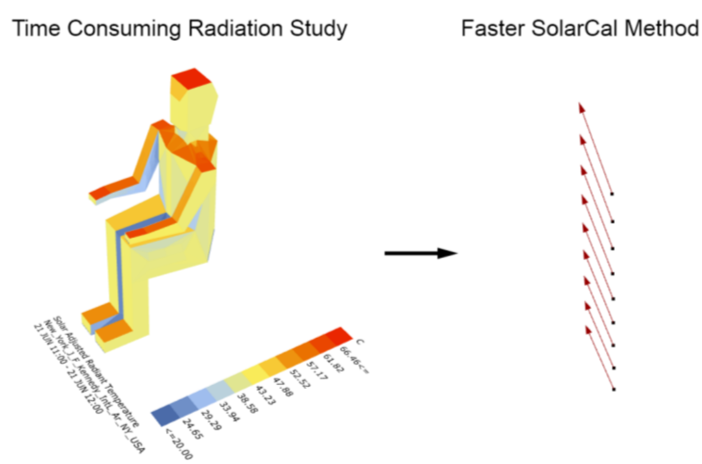

Figure 2. Depiction of the time consuming radiation analysis of a human geometry mesh in comparison to a faster method that treats the body as a set of points and projects sun vectors from those points.

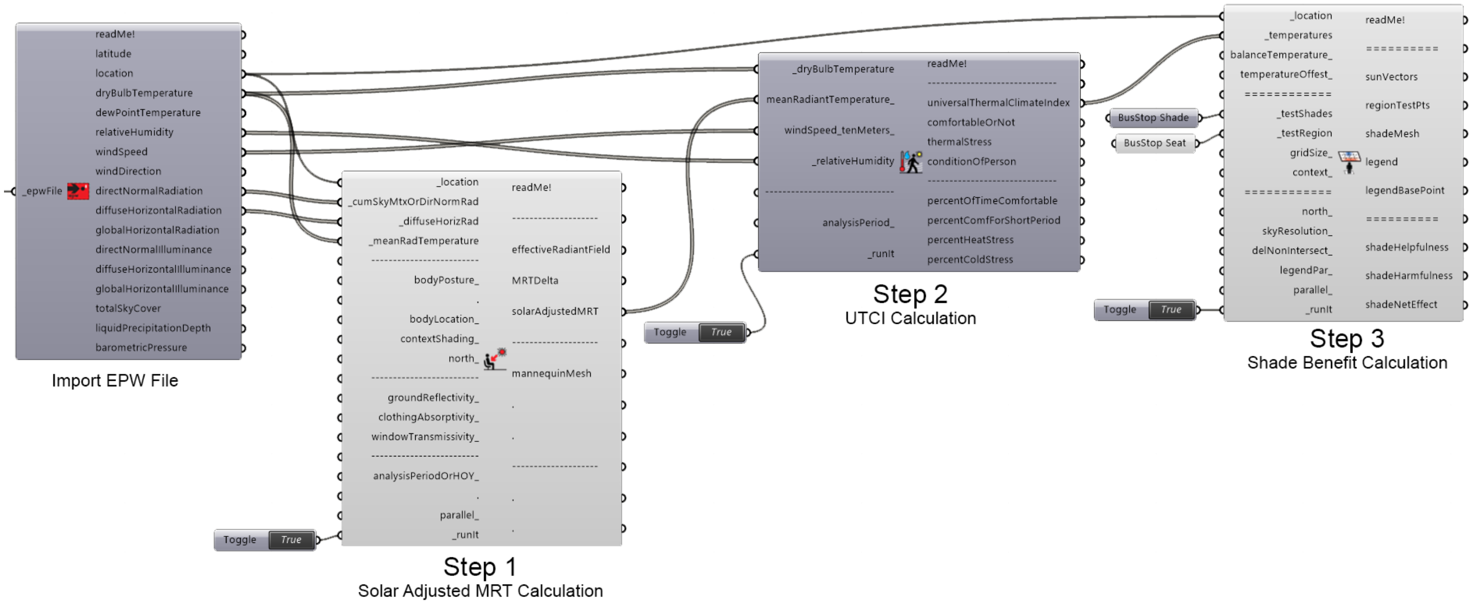

Figure 3. The component-based interface of the ComfortCover workflow. Each of the three main steps of the process are consolidated into three components, each of which include both required inputs as well as optional inputs to customize the model. For more information on the options and how to use the components, see the tutorial videos here: https://www.youtube.com/playlist?list=PLruLh1AdY-Sho45_D4BV1HKcIz7oVmZ8v

As Figure 3 illustrates, the workflow begins by importing the different data types of an EPW weather file into the grasshopper interface, each as a separate list. Next, the radiation and air temperature lists from this EPW import are fed through a second component along with location data from the EPW file that contains information for generating sun vectors such as latitude and time zone. This component computes a list of solar-adjusted MRT for a person in an outdoor space for every hour of the year (Step 1). This list of solar-adjusted MRT is then fed into a third component along with the air temperature, relative humidity, and wind speed lists from the EPW file. This third component computes a list of UTCI for every hour of the year (Step 2). Finally, this UTCI list is fed into a fourth component along with the EPW location data. Importantly, this last step also accepts the required geometry inputs, which are 1) a surface representing an area where people will sit and 2) a surface where shade desirability is being considered (see left side of Figure 1). This final component performs the shade benefit evaluation and produces the colored mesh of shade desirability seen in the middle of Figure 1 (Step 3).

Figure 3 depicts the minimum inputs required in order to run the outdoor shade benefit calculation, which are essentially a weather file and the two geometry inputs. However, as one can see, there are many more optional inputs on the components that can be used to adapt this default workflow to the variety of situations that designers might encounter.

Taking a closer look at the solar adjusted temperature component in Figure 3, some of these options are visible along with some assumptions of the required inputs. For example, it is important to note that, in this publication, the air temperature from the EPW file is connected as a starting MRT, which denotes an assumption that the outdoor MRT is the same as that of the air temperature. While this assumption is acceptable for fairly open outdoor spaces, users are advised that they should compute a starting MRT if they have a lot of context geometry that might be at a different temperature. Such a starting MRT can be calculated through observation of outdoor surface temperatures in building simulations or through other tools specialized for producing such values [15]. In addition to plugging in custom versions of required inputs like the starting MRT, users can also adjust a number of characteristics related to the geometry of the person including the posture of the body (seated, standing, or lying down), the location of the body in the 3D Rhino scene and, most importantly, they can input context shading geometries that might block the direct sun to the person. Lastly, users can change reflectivity of the ground and the absorptivity of the person's clothing. It should be noted that this component has capabilities beyond the workflow described in this paper and, notable among these is the ability to compute solar adjusted temperature from a full radiation study of human geometry (left side of Figure 2). This will be used later to help validate the implementation of the SolarCal method.

The component for calculating UTCI does not include any major options that differ from the defaults. However, it should be noted that users may disconnect the wind speed or incorporate dampened wind speeds if they feel that the location where a person will sit has adequate wind protection. Figure 4 includes an hourly plot of UTCI for the Boston weather file in three cases that were chosen to illustrate the effects of different inputs: one with only temperature and humidity considered (signifying outdoor comfort in a shaded space with wind protection), one that incorporates wind speed, and one that includes solar adjusted MRT.

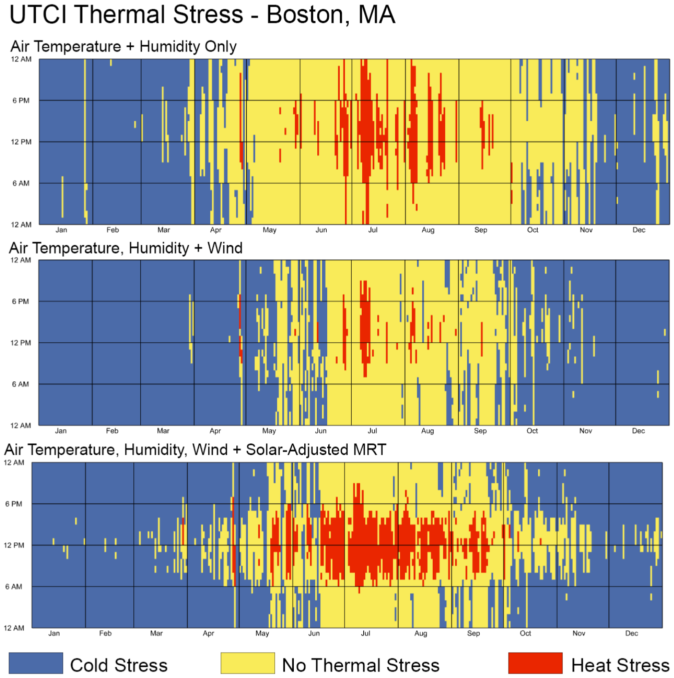

Figure 4. Annual UTCI with Different Weather Criteria

Finally, taking a closer look at the shade benefit component of Figure 3, one notices options to adjust the balance temperature and offset temperature from the defaults of UTCI that define the range of no thermal stress from 9 ºC to 26 ºC. This can be useful in climates where there is a known preference for warmer or colder temperatures that may differ from the 'universal' standard of UTCI. Additionally, users are given the option to adjust the subdivision grid size in order to get either a high-resolution understanding of shade desirability at a slower simulation time or a low-resolution understanding quickly. Importantly, users are also given the ability to set a sky resolution, which can dramatically reduce calculation times by grouping sun vectors and their corresponding UTCI values together based on Tregenza sky patches. For this sky resolution, users can select an integer from 0 to 4, which denotes the number of times that the sky patches are subdivided into a higher and higher resolution. At a resolution of 4, sky patches are no longer used and the sun vector of each hour is intersected with the test shade.

Through the implementation of the method in the Grasshopper visual scripting interface, users are given a high level of flexibility to customize the shade benefit calculation to their unique case and even override parts of the process by inputting their own data.

VALIDATION OF THE NEW METHOD

Since this method is the first of its kind, there was no outdoor shade design tool that could be used to validate the results of the entire process. However, each of the three parts of the workflow was validated against the original methods in order to ensure an implementation that is consistent with the intentions of the original authors.

In order to validate the solar adjusted MRT component, the output of the component was compared to that obtained from a detailed radiation study of human geometry consisting of 481 mesh faces. The functions that were used to determine radiation over these 418 faces come from the validated rendering engine, Radiance [16]. Table 1 illustrates the results of the comparison over the course of a single day taken from the Boston, MA Logan Airport weather file. This chosen day is March 20th and this was selected because it included a diversity of both cloudy and sunny conditions. As one can see, the ComfortCover manifestation of the SolarCal method falls short of the higher accuracy human geometry radiation study, especially in cases of very low sun angles right after sunrise and right before sunset. However, it consistently lands within the correct order of magnitude and, as such, this implementation of the SolarCal method seems suitable for most design applications such as that considered in this paper.

In order to ensure a correct translation from the original FORTRAN manifestation of UTCI that is published on the UTCI website [17], the output of the Python Grasshopper component used here was tested against that of the original FORTRAN tool. Table 2 compares these outputs and it is evident that the differences between the two are consistently less than 0.1 C (note that the original UTCI tool rounds all results to the nearest 0.1 of a degree). It is inferred that the slight discrepancies result from differences between how numbers of FORTRAN are stored as full double values while those of Python are stored as smaller float values. Whatever the underlying

	Hour of March 20 (Boston, MA)														
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Human Geo Rad Study (ºC)	0.0	0.19	12.20	28.41	32.97	23.37	23.26	35.18	39.05	27.10	15.30	7.64	6.28	3.92	0.0
SolarCal/ ComfortCover (ºC)	0.0	0.16	12.50	26.21	31.21	21.19	21.61	36.11	40.52	26.24	15.96	7.94	6.34	3.14	0.0
Difference (%)	0	13.0%	-2.4%	7.7%	5.3%	9.4%	7.1%	-2.6%	-3.8%	3.2%	-4.3%	-3.9%	-0.9%	19.9%	0

Table 1. Comparison of SolarCal solar adjusted temperature method to full radiation study of human geometry

	Jun21 9 AM	Jun21 12PM	Jun21 3 PM	Dec21 9 AM	Dec21 12PM	Dec21 3 PM
Original UTCI (ºC)	30.3	37.1	34.1	-15.2	-10.8	-17.3
ComfortCover (ºC)	30.28	37.11	34.12	-15.21	-10.82	-17.31

Table 2. Comparison of Comfort UTCI to the original UTCI calculator for Boston.

cause, it is clear that the error here is small enough that is should not interfere with the overall design application proposed in this paper.

Lastly, to validate the ray tracing functions that ultimately produce the map of shade benefit, the code in the shade benefit component that computes shade desirability from temperature about a balance point was compared to one in accordance with the original Shaderade method using heating load, cooling load, and solar beam gains. Values from the same EnergyPlus simulation were plugged into both the shade benefit functions of the component used in this paper and the most recent version of the Shaderade tool [9]. The best cells of the resulting shade were then used to make a new shade that was then re-run through the EnergyPlus simulation. The energy savings of the shades produced by both methods in the climates of Phoenix, Boston, and Anchorage were recorded and can be seen in Figure 5. Figure 5 also depicts energy savings of various other methods used to design shades prior to the development of Shaderade. As one can see, ComfortCover functions are producing acceptably similar results to other methods including the most recent Shaderade version of 2014. Discrepancies between the functions in this paper and Shaderade 2014 can be attributed to new features that have been implemented in the most recent version that were not a part of the original paper published by Sargent et al. [9]. Specifically, these include a consideration of diffuse solar gains in the calculation of shade benefit as well as thermal lag between incoming sun and eventual building cooling gains. While consideration of diffuse gains would improve the accuracy of the functions in this paper, it is clear that they are still meeting a high standard required in order to give accurate advice in the design process and offer a significantly more accurate alternative than other approaches.

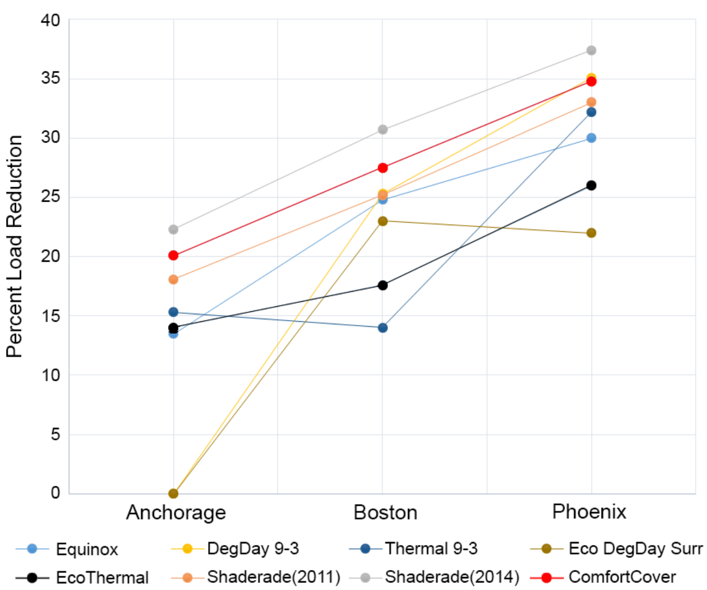

Figure 5. Comparison of ComfortCover's ray tracing to that of other shade design methods by comparing building thermal load reduction of shades.

CASE STUDY

In order to demonstrate the usefulness of the method, a case study is provided here in the form of application to the design of a bus stop shade. Following in the precedent of the original Shaderade paper, the shade desirability is depicted in 3 different climates that range from hot to cold: Phoenix, Boston, and Anchorage. Figure 6 illustrates the results of this process and, as expected, the hot climate of Phoenix produces a pattern that is dominated by high shade desirability while the cold climate of Anchorage includes one with a high level of shade harmfulness. From such initial studies, designers might make initial selections of materials for the shelter. For example, since the shade desirability of the Anchorage site is so small, designers might opt for a transparent roofing material such as curved acrylic to allow the sun to pass or might opt to not have any shade at all depending on whether rain protection is needed. In the climate of Boston, one might opt for an opaque material and deploy it intelligently over the area where shade is desired since the line between shade helpfulness and shade harm lies a reasonable horizontal distance away from the shelter's seating area. In Phoenix where a large fraction of the sky must be covered to avoid discomfort, designers might opt for a wholly different strategy that deploys an opaque material curving over the sides of the seating area, helping avoid harmful East-West sun. Figure 7 shows how such a design process can be informed by ComfortCover as a designer might begin by inputting a curved box geometry that completely surrounds the seating area. After getting results, they might then make an appropriate judgment call about the height at which the shade could be trimmed in order to allow occupant access underneath and minimize the amount of shade material. After iterating, they might then test their final geometry by running it through ComfortCover and ensuring that they have shaded the majority of harmful hours.

CONCLUSION

This paper presents a novel workflow that empowers

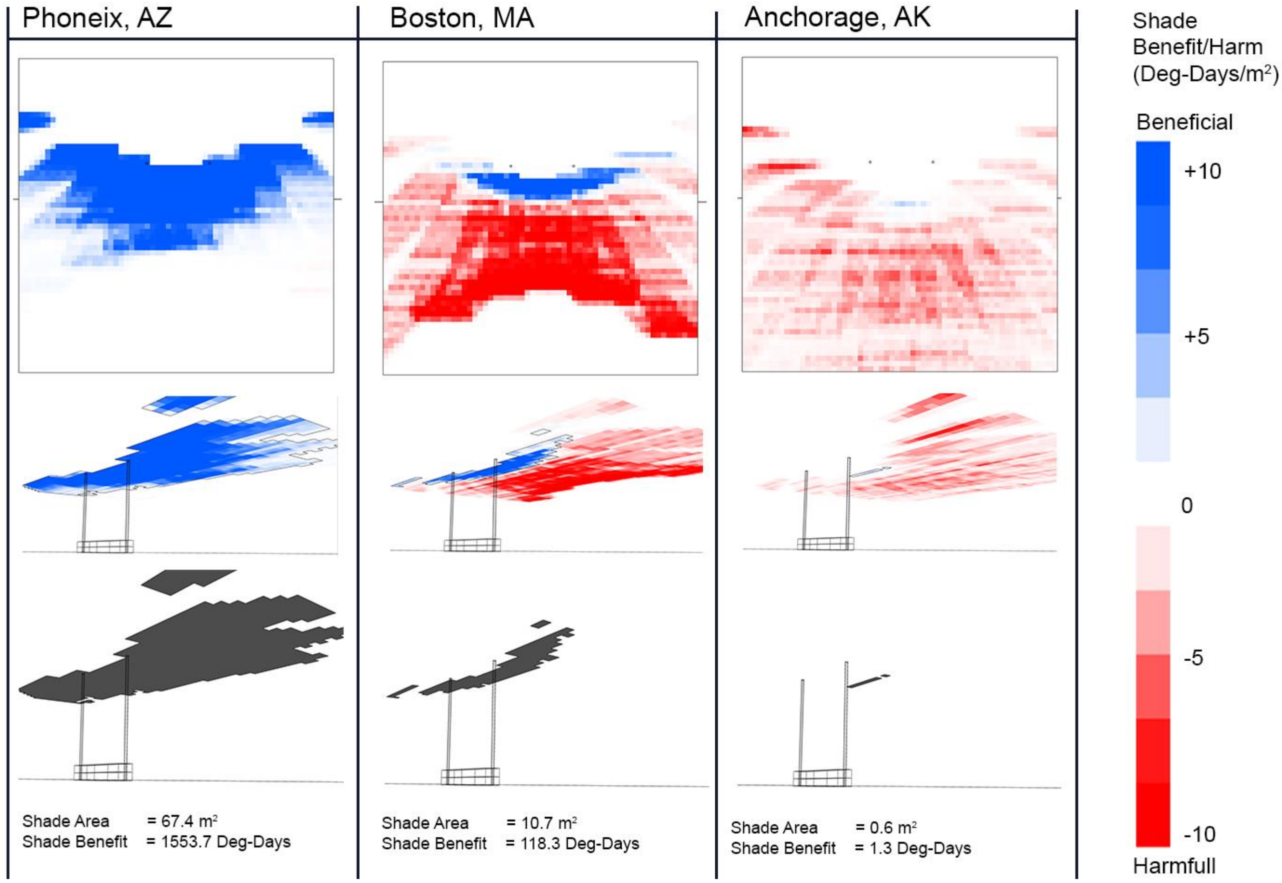

Figure 6. Suggested bus stop shades for Phoenix, Boston, and Anchorage

landscape architects, planners, environmental engineers, and other designers of outdoor spaces to account for outdoor thermal comfort in the design of static shades.

Among the areas for future research and improvement, one must admit the drawbacks of UTCI that come along with the previously-stated advantages. Unlike some other outdoor comfort metrics such as Outdoor Standard Effective Temperature (OUT_SET) and Physiologically Equivalent Temperature (PET), UTCI does not include clothing level or metabolic rate as inputs and this may cause inaccuracies in cases where these criteria differ from normal 'universal' levels. As stated previously, the inclusion of these 'universal' standards can often be an advantage in the design process when such personal factors are not known. However, if a user is given a specific value for clothing or metabolic rate to use in the comfort assessment of shades, he or she will currently be at a loss with the proposed method here. Perhaps the largest limitation of the current proposed method that will necessitate future research is that this paper has assumed that the outdoor radiant temperature before solar adjustment is equivalent to that of the air. While this assumption is suitable for large open outdoor spaces, this can potentially be a high source of error in cases with high thermal mass materials or street geometry with deep urban canyons, both of which will often produce radiant environments that are much different than the air at a given hour. The simulation of these radiant environments within the time frame of design is the subject of much of ongoing outdoor comfort research and the future results of these efforts will be necessary to ensure ComfortCover's relevance to a significant fraction of the cases in which people may wish to use it.

With these limitations noted, it is important to reiterate that the ComfortCover method proposed here uses the most recent and state-of-the-art standards, both in terms of

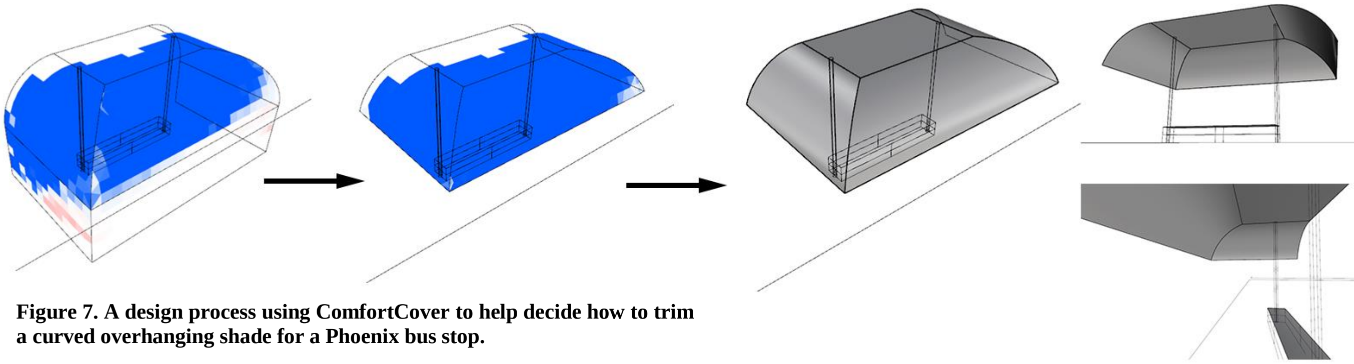

Figure 7. A design process using ComfortCover to help decide how to trim a curved overhanging shade for a Phoenix bus stop.

outdoor thermal comfort and ray tracing processes. It also incorporates the fastest new schemes for estimating solar radiation on the human body in spite of the recognition that these techniques are still under development. Furthermore, the the development and implementation of the method within the visual programming environment of Grasshopper offers parametric design capabilities and flexibility that would not have been achieved had they been implemented in another style. Finally, the method is undeniably novel in that there has historically been no agreed upon means to quantitatively account for outdoor comfort in the design of static shades. Never before have the three individual components of ComfortCover been merged into a single workflow and, as a result, designers of outdoor shades now have a high-accuracy means of designing such comfort sensitive shades.

The components are published as part of the open source plugins, Ladybug & Honeybee for Grasshopper3D [18] and will be accessible to designers working in the 3D software, Rhinoceros.

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