THERMAL COMFORT BASED PERFORMANCE APPRAISAL OF COVERED WALKWAYS IN SINGAPORE

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Abstract. This paper describes an ongoing research project to establish a thermal comfort based walkway performance analysis that embodies the effect of context and climate. This study combines the survey data (perceived comfort) from walkway users and thermal sensor data (actual thermal comfort) collected at various covered walkways across Singapore. One contribution is the combination of subjective and objective comfort measurements in a tropical context. We work with descriptive statistical measures to help better understand the ranges of thermal comfort offered by covered walkways. This research highlighted that the comfort offered by current walkways were identified to have no significance, and the walkways are unable to reduce the heat stress into the moderate range at all times of the day. A key contribution of this research project identified missing datasets and help improve our data collection methodology for the future expansion dataset that employ machine learning.

Keywords. Biometeorology; Data analytics; Informed design.

1. Background and Motivation

Urban planning has evolved to address some of the issues of sustainability and climate change through a resilient design approach. However, urban microclimates and outdoor thermal comfort, which are key to designing better urban places, are given little emphasis in urban design and planning processes [1][2][3]. Research since 1980’s has addressed a relational affinity between urban planning regulations and local microclimates. Various temporal and spatial factors influence microclimates. Continuous monitoring and recording of local meteorological data are thus required to understand them. Two main parameters that define microclimate conditions of a space are the local climate regime, and the urban context at the very location [4][5].

Understanding microclimates improves space planning and program allocations of urban spaces. A few case studies over the years have identified critical factors such as the importance of shade, the influence of radiation heat, and the ratio of sky view factor which have a direct influence on the outdoor thermal comfort [6][7][8][9]. However, these case studies are focused on oceanic...
and continental climate zones, which are different than the tropical climate of Singapore. Identifying the influence of the combination of above parameters is challenging in Singapore, as it is very densely built, with a large quantity of concrete structures. Very few case studies pertaining to tropical conditions discuss the effect of shading on thermal comfort, by means of areas that need more plantation, walkways, or other type of interventions to improve the overall thermal comfort index of the built environment [10].

Covered walkways are of great importance to tropical contexts (including Singapore) for shielding pedestrians from rain and sun. While they constitute a key outdoor typology of transitional spaces in Singapore, they have hardly been worked upon during their design phase and also hardly monitored for performance during usage. It is interesting to note that Singapore, being a small island of 720 km², contains covered walkways covering 46 km, and this length is planned to be extended to 200 km by 2019 [11]. This research investigates existing microclimates prevailing under covered walkways across Singapore using descriptive statistical methods to quantify the thermal performance offered by various walkways.

2. Problem Statement

The foundation of a covered walkway is to offer protection from rain and sun. We focus on the latter aspect, having in mind better thermal comfort. Hence the null hypothesis (H₀ Sensor) we formulate is that the thermal comfort offered under the walkway as measured by the sensor data is significantly better than the thermal comfort without it. The alternate hypothesis we formulate (H₁ Sensor) is that the difference in thermal comfort offered by current walkways is not statistically significant. We employ statistical analysis on the pilot dataset (quantitative data from sensors) from 10 walkways to verify if the null hypothesis holds, and if not, understand the possible causes to support the alternate hypothesis. Going through the process in our methodology also helps us identify missing data and improve on the applicability of the methodology.

A similar approach of hypothesis testing is followed with the qualitative data of survey users. The null hypothesis (H₀ Users) we formulate is that the perceived comfort of users falls into the same range of objective comfort (Universal Thermal Climate Index (UTCI) scales, Figure 1). Testing this hypothesis yields findings which help us to understand the thermal comfort acceptance bands of users based on various criteria.

![Figure 1. UTCI (universal thermal climate index) Scale (source: http://www.climatechip.org/your-area).](http://www.climatechip.org/your-area)
3. Research Methodology

This research establishes a multi-disciplinary framework combining the domains of architecture, urban design, human thermal comfort, and data analytics for a climate resilient and informed design approach. A detailed research methodology was formulated that establishes an understanding of the thermal performance of existing walkways in Singapore, identifies ways to improve this performance, and facilitates the design of better walkways for the future (Figure 2).

![Research methodology for walkway comfort analysis.](image)

The methodology is comprised of walkway site selection, site analysis, subjective and objective data collection on site, modeling and data analysis, and derivation of findings. This is an iterative process that aims to improve the methodology for future data collection. The site selection is performed according to the following parameters around walkways: Green to built-ratio, shading ratio, walkway orientation, building density, building heights, building aspect ratio. The site analysis involves a solar shading study, immediate vegetation mapping, macro-scale and micro-scale built-to-green ratio, and the sky view factor. Data collection involves a continuous monitoring and recording of thermal comfort factors, as these factors change with great temporal frequency. We employ compact heat stress sensors and radiation measurement devices across various walkway locations in Singapore. At each walkway location we measure thermal comfort factors during five days, with a data timestamp for every 1 minute, for three 1-hour time spans per day (9 AM -10 AM, 1 PM- 2 PM, 5 PM- 6 PM). These specific time slots have been identified during pilot observations as the most active usage time intervals of walkways. We conduct surveys with users to record their self-reported thermal comfort responses, in addition to their tolerance factor to changes in thermal conditions (air conditioning vs. outdoor activities).

We work with statistical modelling on the current pilot dataset from 10 walkways. We do clustering analysis to identify relationships between various parameters regarding thermal comfort, walkway context, and walkway design. We are currently expanding our data set through data collection across 30 walkways,
with the intent of having a larger sample size permitting to evaluate machine learning approaches to extract predictive correlations between variables. The results of the statistical modelling aim at a better evaluation of the necessity for a covered walkway in a given location, and at identifying design factors which may improve thermal comfort in a given context.

4. Approach

The context and walkway design analysis was conducted at different scales, namely, macro modelling and micro modelling. In the following we describe these two approaches. Macro modelling intends to map the overall context of a walkway location and the urban setting it is located in (on a scale of 50 m radius from data collection point). The micro modelling aims at understanding the influence of a walkway’s immediate surroundings on thermal comfort (scale of 2.5 m radius from data collection point).

Macro modelling: We use a tool (www.gmapgis.com) relying on google maps satellite imagery to extract an aerial view within a radius of 50 meters from the walkway measurement location. The image of this view contains information which areas within the 50 meter radius are covered by buildings and by vegetation (Figure 3.a). We employ an image processing tools available online to calculate the percentage of green to paved surfaces from this image (mkweb.bcgsc.ca/color-summarizer?analyze). The building heights are calculated by employing standard trigonometry on google street view images (www.mroctopus.net/e845uehj223jd/streetview-measure.html) at the walkway location.

Micro modelling: Here we are interested to extract information about the immediate surroundings of a walkway on the scale of approximately 2.5 meters around the walkway. In particular, we are interested in the amount of vegetation, visible sky, paved surfaces, and visible building surfaces. This can be achieved by performing a deep-learning based semantic segmentation on Google street view images of the walkway. We employed Segnet tool developed by University of Cambridge to help generate labels [13]. The labels of interest to us are green, sky, building, paved surfaces, etc. (Figure 3.b). Semantic segmentation produces one label per pixel. From these predictions we computed the percentage of each of the above labels visible in an image.

Quantitative data measurement setup: Three sensors were employed per
location, two sensors inside the walkway five meters apart and one sensor outside the walkway. The sensor data collection setup has a Kestrel heat stress meter 5400, set up at a height of 1.2 meters, which is the common height at which thermal sensation is measured as per literature [14]. This setup measures the actual outdoor comfort under the walkway and outside of it which serves to simulate the conditions in the absence of the walkway. The measured parameters include air temperature, wind speed, globe temperature (average surface temperatures for radiation heat transfer), relative humidity, wind chill, wind direction, etc. UTCI (Figure 1), a widely accepted outdoor thermal comfort metric, is used to determine the extent of thermal comfort offered.

User data (survey) setup: We employ a free to use online survey tool (kobottoolbox) with the ability of offline data storage. A survey records the thermal responses of walkway users to existing conditions under the walkway. We aimed at conducting on average 3-4 surveys for each hour of data collection. The survey aimed at recording the immediate thermal responses of users to conditions under the walkway, their clothing level, and more importantly, the time of outdoor exposure they have had coming from an air conditioned space prior to using the walkway. These factors help us interpret the acclimatization differences amongst the walkway users.

5. Analysis and findings:

In order to discover patterns from the data that reveal temporal and spatial comfort distribution across the selected walkways, based on selected attributes, we adopt a clustering technique of data mining. In this model, UTCI (comfort) is the dependent variable.

Figure 4 presents the box and whisker plot of the distribution of measured UTCI comfort values under the various walkways. It is interesting to note that 5 walkways located at Simei, Eunos, Marsiling, Downtown, and Somerset have exposure to very strong heat stress during most part of the recorded time. In order to understand the reasons underlying their poor performance, we have specifically looked further into three of them. The comfort distribution at Simei, Eunos, and Somerset are influenced by three major variables: walkway orientation, vegetation next to walkway, and lack of shading from buildings/trees. The walkway located at Somerset is exposed to strong heat stress for more than 77% of the time. Firstly, the orientation of this walkway, which is 100 degrees from true north, reduces shading opportunities from buildings and maximizes solar exposure in tropics (typical building massing to reduce heat absorption is North-South orientation in tropics). Secondly, close proximity to paved surface (arterial road) within 5 meters increases the radiant heat. Lastly the lack of trees to shade the walkway for most of the time increases solar gain.
The walkway located at Simei is exposed to strong heat stress for all the time with the mean UTCI being 35.13 °C. Even though this walkway has a best orientation of 50 degrees from true North, the morning and afternoon sun are not restricted by buildings and trees with sparse leaf spacing. This walkway has advantage of shading only from evening sun by neighboring buildings. The worst condition should naturally be exhibited by the walkway located at Eunos, as it is a stand-alone walkway unshaded by any buildings or vegetation. However, the data highlighted the walkway to have performed better and kindled a need for investigation. A further detailed investigation on the walkway dataset highlighted that majority of the data recorded for Eunos was during overcast and rainy conditions and thus highlighting the need for missing sunny datasets to help draw better conclusions.

Figure 5 presents the clustered UTCI values according to the three measurement times in the morning, afternoon and evening. The percentage of measured time when the comfort under the walkways were in the extreme heat stress zone was distributed as 2.09% for morning, 9.01% in the afternoon, and 0.22% in the evening. The afternoon has the highest median UTCI and the highest 75% quantile. The median of the other two times is in the moderate heat stress range. While this is not surprising in hindsight, it shows that there is a significant impact of the timing on the comfort distribution. This points to three conclusions. Firstly, the walkways are unable to reduce the median heat stress into the moderate range at all times of the day. Secondly, the need for walkways is most pronounced during the afternoon time. Thirdly, if one needs to limit data recording to one time per day, the afternoon is the most relevant time, which allows to guide the expansion of future data collection to a larger number of walkways.
Figure 5. Comfort distribution for morning, afternoon and evening clusters.

Figure 6 presents the distribution of UTCI measurements clustered into two groups. UTCI lower inside the walkway denotes the case when UTCI measurements under the walkway are lower than the UTCI measurements outside of it. UTCI higher denotes the opposite case. The walkways located at Simei and Somerset have more comfort outside the walkways than under them, contradicting a sole purpose of a walkway, i.e., to offer better thermal comfort. A further investigation of these walkway datasets highlighted the dominance of data collected during overcast conditions. Overcast conditions reduce the ability for sky cooling and radiate more heat under the walkway surface and hence cause the reduced comfort under the walkway. A critical finding was to investigate more on the material properties of the walkway for their ability to influence comfort as they differ in their thermal properties.

Figure 6. UTCI distribution outside and under the walkway to understand walkway effectiveness to provide comfort.
We defined a statistical test for the mean UTCI for a one hour period. The H0 Sensor hypothesis denotes that their means are equal inside and outside of the walkway. The H1 Sensor hypothesis denotes that their means are different. Note that the statistical test looks at a slightly different quantity than displayed in Figure 8. The statistical test over a sample size of 141 hours of comfort data under and outside the walkway identified the hourly mean of UTCI values to have no significant difference with a standard error of 0.409 and a p value of 0.27 with 95% confidence. Thus we reject the null hypothesis H0 Sensor and accept the alternate hypothesis H1 Sensor that the mean of thermal comfort are different and was found to have a difference in mean of 0.456 C. This difference of just 0.5 C comfort is identified as not a significant contribution of the walkway to offer comfort to its users.

A Pearson correlation analysis was performed using the macro-modelling features (context related features) on the UTCI without walkways and micro-modelling features (walkway design related features) on UTCI under the walkways (Figure 7). This analysis was performed over mean UTCI for each walkway location, across all 10 walkways. Amongst the micro-modelling factors, walkway orientation, walkway height, and walkway width were identified to be key design factors to have a strong negative correlation to the UTCI comfort under the walkway, while vegetation, building and sky view were identified to have a weak positive correlation to comfort.

Figure 7. Pearson correlation of micro-modelling variables to UTCI comfort (design factors).

The results from the macro-modelling correlation analysis highlighted a strong positive correlation existing between comfort and distance to height ratio of buildings within a close proximity. A smaller distance to height ratio suggests tall buildings at close proximity to walkway location, offers a greater influence on shading the walkway for majority of the time. These correlations are established from a smaller sample size of 10 walkways and their significance need to be quantified when working with a larger expansion dataset in the future.

Figure 8 highlights the mean and ranges for the perceived comfort based on survey responses of the walkway users. The appropriate quantitative value for
these perceived comfort was obtained through the actual sensor measurements in the same or nearby time stamp (5 mins average). A t-test of measured UTCI values at time stamps of user survey, revealed the null hypothesis H0 to be true for user identified comfort, as they fall under similar scales of globally accepted metric UTCI (around 29°C for cold and 35°C for hot stress). A further investigation of grouping the sensor measured UTCI values, at time stamps corresponding to user thermal votes as cold comfortable (n=166) vs hot/too-hot (n=56) revealed the corresponding mean UTCI of hot too hot group being greater than the cold/comfortable group. This helps to support the fact that the perceptional user thermal votes fall under similar scales of measured comfort.

![Figure 8. Perceived comfort distribution vs UTCI scales.](image)

**6. Conclusion**

Through the statistical analysis on a smaller walkway dataset (n=10) we have tried to understand how the relative performance of walkways vary over various times of the day. The key finding that was established through this case study was that the difference in thermal comfort offered by current walkways is not statistically significant. In addition, we can draw the following conclusions through descriptive statistical modelling. Firstly, we have identified three major factors that greatly influence comfort distribution across walkways and they are orientation of walkway, vegetation, and shading potential from buildings and trees. Secondly, a correlation study highlighted walkway orientation, walkway width and walkway height to be the key elements to influence comfort directly. Thirdly, walkways are unable to reduce the median heat stress into the moderate range at all times of the day. Fourthly, the need for walkways is identified to be most pronounced during the afternoon time. Lastly, through statistical significance testing, the perceived comfort responses from survey were found to match the scales of UTCI. Additional insights could be made through organizing the data into further clusters based on: solar exposure (sunny and shaded), walkway material, aspect ratio, and sky view factor, etc.
This pilot data study has also identified a few methodological improvements to our existing data collection. Expansion of data collected will be targeted mainly during the afternoon, and the measurement of radiation will help create sunny and shaded clustering, etc. The methodology can further be improved through detailed site modelling with ENVImet or other urban simulation software in order to understand the granularity of shading and wind flow. These findings help us structure the framework for performance based urban infrastructure design in a logical and pragmatic approach.

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