Designing with thermal comfort indices in outdoor sites

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Abstract: Design of outdoor sites for improved thermal comfort will contribute to greater use and value of these environments. Whilst there are many available thermal comfort indices, the complexity of external sites makes the useful application of these in outdoor site design difficult. This paper discusses two case studies: phase 5 of Masdar City in the United Arab Emirates and the Danginri Thermal City in Seoul, South Korea to illustrate the use of different thermal comfort indices in the design of open space. These case studies highlight the value of using indices when combined with other design tools and processes including multidisciplinary collaborative practices and digital technologies such as Computational Fluid Dynamic (CFD) modelling. Importantly this combination of approaches shifts the emphasis from a focus on achieving specific thermal comfort measures, to a more comprehensive design approach. This shift demonstrates how design can work with relative change to extend the experience and use of outdoor space.

Keywords: Thermal comfort; design; outdoor.

1. Introduction

The design of external space for thermal comfort performance is gaining increased attention. This is most notable in urban environments where enhanced temperatures affect large and growing populations (Chen and Ng, 2012; Norton et al., 2013; Zinn and Fitzsimons, 2014; Brown et al., 2015). Globally, climate change is altering outdoor environmental conditions through temperature increases and heat waves, both of which are linked to severe discomfort, heat stress and mortality (Norton et al., 2013; BOM and CSIRO, 2014). The experience of these conditions limits the usefulness of external open space and is a significant restriction to the value of outdoor environments. Yet at the same time, increased urbanism and density means access to quality open space is of great importance. New land developments are expanding into challenging environmental territories, such as the Masdar city scheme in the United Arab Emirates. As the quality of outdoor space contributes to both human and ecological wellbeing, open space can deliver critical environmental and social infrastructure to urban environments provided that design is able to respond to these needs (VAG, 2014; Brown et al., 2015). This means
addressing the potentials of open space, including improved thermal comfort in a wide range of sites and conditions.

This paper aims to demonstrate the challenges in the use of thermal comfort indices for informing design of external sites. This is developed through an examination of a range of frequently used thermal comfort indices and the variance in the information they provide. This point is expanded through discussion of two case study examples that demonstrate the use of different thermal comfort indices in conjunction with other design tools. The case studies reveal the benefits and limitations of quantifying thermal comfort in design processes. This suggests an alternative use of thermal comfort indices for design as predictive tools of relative change rather than explicitly quantified measurements.

2. Designing for thermal comfort

Thermal comfort is a subjective measure of people’s psychological response to the heat balance of the human body within different environmental conditions. The effects of the thermal environment on different people can vary greatly and this makes assessing the thermal comfort of many users a complex issue. In an outdoor environment the key variables affecting thermal comfort are air temperature, air speed, relative humidity and radiant temperatures (Rose et al., 2010; Jendritzky et al., 2012; Johansson et al., 2014). These principle drivers are shared by indoor and outdoor space, however in external environments they are subject to more extreme, complex and irregular relational changes that vary according to geographic area and climate type, as well as localized physical characteristics. Further challenges of assessing thermal comfort levels in external space include a high variation in individual perceptions and preferences for outdoor temperatures which results in a much greater range of thermal comfort acceptability. These preferences are also influenced by geographic area and acclimatisation of users to certain conditions (Givoni et al., 2003; Johansson et al., 2014; Brown et al., 2015).

For designers attempting to influence the thermal comfort in outdoor environments, there is a lack of control of many of these variables. This challenges the usefulness of different indices for design feedback. For instance, the Pierce two-node model measures the human body at skin and core levels. This measure can give a very accurate indication of an individual’s thermal comfort; however, designers must consider external space as accessible to several users and realistically have limited ability to monitor individual subjects to this level of detail (Chen and Ng, 2012). Further, the influence of design on many meteorological variables is beyond explicit control. For instance, ambient air temperature and relative humidity may be modified through very large scale interventions such as regional parks however, in most design scenarios the scale required to influence these factors is unachievable, particularly within existing urban site conditions (Brown et al., 2015). Factors affecting comfort that are more easily manipulated are air speed, radiant heat and solar exposure, in the conditions set by ambient temperature and humidity. So, whilst design interventions cannot modify all of the conditions related to thermal comfort, the combination of dynamic meteorological properties still needs to be understood and accounted for in influencing thermal sensation in outdoor sites (Rose et al., 2010). Design that aims to influence thermal comfort in external space is faced with these concurrent challenges: an understanding of the relationships of thermal comfort factors in different climatic scenarios; the limited control of these factors and; highly variable responses of users.

In design, it is necessary to understand the different types of output that outdoor thermal comfort indices will provide. For instance, the measurement of thermal comfort is different from thermal stress. As Spagnolo and De Dear explain, the “application of indices from the hazardous periphery to the comfortable central region would seem to be a case of applying a tool with the wrong resolution.
Comfort is about subtle, finely graded perceptual details, whereas thermal stress is at the gross margins”(Spagnolo and De Dear, 2002). Here the understanding of what is being measured forms a critical judgment on the usefulness of an indices and how it might be applied in design.

The further challenge for design is the proposal of new spatial arrangements, which implies the need to predict future change as well as measuring existing site conditions. The limitations of design of outdoor sites suggest that in many scenarios desirable comfort levels may not be achievable. Similarly, large scale climatic factors may make it impossible to avoid thermal stress at all times. An indication of difference or relative change may be more useful for designers than a precise measurement. This shifts the emphasis of design using thermal comfort indices from measurement of conditions or people to the performative qualities of specific sites (Rose et al., 2010; Brown et al., 2015). Thus, designers need an appropriate index for use as a predictive tool that will suggest relative differences on how a site will perform in relation to variable conditions (Givoni et al., 2003; Chen and Ng, 2012).

The range of frequently used thermal comfort indices offer several ways for informing design, however these vary in how they address specific demands of site, scale, existing conditions and resources. There are many examples of arguments for the need for standardization of thermal comfort assessment methods and indices (Jendritzky et al., 2012; Johansson et al., 2014). There are currently no recommendations for suitable thermal comfort indices for specific conditions or guidance on how to integrate these into design, thus the use of indices as predictive design tools remains an area for further research (Chen and Ng, 2012; Johansson et al., 2014; Brown et al., 2015).

3. Thermal comfort indices

There are over 100 indices developed to represent thermal comfort in hot and cold conditions. Many of these are simplified versions of air temperature combined with a secondary parameter, though the complexity of these indices has increased in recent years (Jendritzky et al., 2012; Johansson et al., 2014). Thermal comfort indices tend to be divided into either rational or empirical guides. The rational are based on heat transfer and energy balance of a typical human body in relation to spatial conditions. Many of these indices have been developed specifically for internal environments where it is possible to maintain constant conditions. The second type of indices is based on empirical studies of subjective experience of thermal comfort in relation to meteorological phenomena. Many examples of both of these types are based on steady state models which assume that users have reached a thermal equilibrium within an ambient climatic environment. Steady state models such as the commonly used Predicted Mean Vote (PMV), Outdoor Standard Effective Temperature (OUT_SET*) and Physiologically Equivalent Temperature (PET) can be problematic when used in external environments where it is difficult to account for the dynamic aspects of adaptation to external environments (Chen and Ng, 2012; Johansson et al., 2014). However, the alternative adaptive assessment methods are largely based on the Pierce Two-Node model of the human body that requires extensive monitoring of subjects which is not feasible in most outdoor scenarios (Chen and Ng, 2012). Based on the practicality of working in external space, commonly used thermal comfort indices for outdoors environments often make a necessary number of assumptions or standardise variables. Table 1 summarizes some of the more commonly used thermal comfort indices which are applied in outdoor environments.
Table 1: Common thermal comfort indices used in external space studies. (source: Fanger, 1970; Steadman, 1984; Spagnolo and De Dear, 2002; Davis et al., 2006; Rose et al., 2010; Chen and Ng, 2012; Johansson et al., 2014).

<table>
<thead>
<tr>
<th>Index</th>
<th>Usage</th>
<th>Description</th>
<th>Expressed</th>
<th>Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent Temperature</td>
<td>Outdoors</td>
<td>AT = T + 0.33e – 0.7</td>
<td>U</td>
<td>-4 T = dry bulb temperature e= vapour pressure derived from dew point</td>
</tr>
<tr>
<td><strong>Predicted Mean Vote (PMV)</strong></td>
<td>Indoors</td>
<td>Meteorological Variables: Air Temp, humidity, wind speed, mean radiant temp + clothing and activity</td>
<td>Scale between -3 to +3</td>
<td>Quantifies Discomfort</td>
</tr>
<tr>
<td><strong>Standard Predicted Mean Vote (SPMV)</strong></td>
<td>Outdoors</td>
<td>Adjusted PMV to include more extreme humidity</td>
<td>Scale between -3 to +3, where 0 is neutral Temperature Degrees Celsius</td>
<td>Quantifies Discomfort</td>
</tr>
<tr>
<td>Physiologically Equivalent Temperature (PET)</td>
<td>Outdoors</td>
<td>Four meteorological variables. Standardized clothing and activity for indoor activity.</td>
<td>Air temperature required to reproduce a comfortable indoor setting</td>
<td></td>
</tr>
<tr>
<td>Outdoor Standard Effective Temperature (OUT_SET*)</td>
<td>Outdoors</td>
<td>Derived from SET with simplified mean radiant temperature. Assumes activity and clothing value for outdoor uses.</td>
<td>Temperature Degrees Celsius</td>
<td>As with SET*</td>
</tr>
<tr>
<td><strong>Thermal Sensation Index (TSI)</strong></td>
<td>Outdoors</td>
<td>Air temperature, Solar radiation and Wind Speed</td>
<td>Scale between 1 – 7, where 4 is neutral Temperature Degrees Celsius</td>
<td>Quantifies discomfort</td>
</tr>
<tr>
<td>Universal Thermal Climate Index (UTCI)</td>
<td>Outdoors</td>
<td>Air temperature, Mean temperature wind speed, water vapour pressure or relative humidity. Can be coupled with clothing model.</td>
<td>Indication of physiological thermal stress under a wide range of conditions and climates.</td>
<td></td>
</tr>
</tbody>
</table>

3.1. Predicted Mean Vote (PMV) and Standard Predicted Mean Vote (SPMV)

One of the most widely used indices of thermal comfort, the Predicted Mean Vote (PMV) calculates the mean thermal response of large groups of people (Fanger, 1970; Chen and Ng, 2012). This equation uses heat transfer to calculate the equilibrium thermal balance between a person and their surroundings based on meteorological variables (air temperature, air humidity, wind speed and mean radiant...
temperature) as well as clothing insulation and activity levels. Despite being developed as a measure of indoor thermal comfort, PMV has been frequently applied in outdoor studies (Chen and Ng, 2012). PMV is measured across a scale of 7 with -3 being cold to +3 being hot. This scale was developed to describe thermal discomfort which is more precise in indoor conditions than variable outdoor environments and may not be appropriate for assessment of outdoor thermal comfort (Spagnolo and De Dear, 2002; Chen and Ng, 2012). The PMV model has been adjusted for the outdoor environment to include the effects of extreme humidity. This version of the PMV model is the Standard Predicted Mean Vote (SPMV) which takes into account the standard effective temperature (SET*) in the heat balance (Gagge et al., 1986; Rose et al., 2010).

### 3.2. Physiologically Equivalent Temperature (PET)

Developed specifically for outdoor environments the Physiologically Equivalent Temperature (PET) is the air temperature required in an outdoor environment to reproduce a standardized indoor setting, for a standardized individual. This is the air temperature required to balance the heat budget of the human body with the same skin and core temperatures in complex outdoor conditions (Höppe, 1999; Matzarakis A and B, 2008). The calculation of PET is based on four meteorological variables (Höppe, 1999; 2002). As with SET* and OUT_SET* this measure standardizes clothing and activity values. Here, the standardized individual is assumed to have a work metabolism of 80 W of light activity in addition to basic metabolism and 0.9 clo of heat resistance from clothing (Matzarakis A and B, 2008). The indoor reference climate is based on the following; mean radiant temperature equal to air temperature, air velocity (wind speed) is fixed at v = 0.1 m/s and water vapour pressure is set to 12 hPa (approximately equivalent to a relative humidity of 50% at 20°C). The thermal conditions of the body are then calculated using the Munich energy balance model for individuals (MEMI), which in turn are substituted in to the energy balance equation system to produce the PET air temperature measurement.

### 3.3. Standard Effective Temperature SET* and OUT_SET*

Also developed for indoor environments, the Standard Effective Temperature (SET*) is a model for calculating the dry-bulb temperature which relates the real conditions of an environment to the (effective) temperature assuming standard clothing, metabolic rate and 50% relative humidity. SET* uses skin temperature and skin wettedness as the limiting factors (Blazejczyk et al., 2012). This assessment gives an equivalent air temperature measurement to compare thermal sensations in a range of conditions and from this the effective temperature can be related to a subjective thermal comfort response. OUT_SET* is the outdoor variant of SET* which simplifies the complex mean outdoor radiant temperature conditions down to a mean radiant temperature with all other variables maintained as in SET* (Pickup and de Dear, 2000; Jendritzky et al., 2012).

### 3.4. Thermal Sensation Index TSI

The Thermal Sensation Index (TSI) determines a measure between 0 and 7, with 4 as the most comfortable condition (Givoni et al., 2003). TSI was developed from research in Japan through formalized testing of subjects positioned in outdoor environments for set periods of time. Subjects were asked to complete a questionnaire of thermal sensation indicating discomfort, neutral and pleasurable conditions. These experiments were conducted under various solar and wind conditions to quantify the experience of outdoor climatic variables in relation to the subject’s experience. Regression analysis of
the data from this experiment led to the development of an equation expressing thermal sensation as a function of five variables including surface temperatures of surrounding materials and humidity. This was further analysed to produce a simplified equation to be used as a predictive formula taking into account air temperature, solar radiation and wind speed (Givoni et al., 2003). This predictive formula was used in the Danginri case study discussed below.

3.5. Universal Thermal Climate Index UTCI

In 2000, the Universal Thermal Climate Index (UTCI) was developed by a commission established by the International Society of Biometeorology. The primary aim was to create an index that would be accurate in all climates, seasons and scales, and be independent of personal characteristics such as age, gender, specific activities and clothing (Jendritzky et al., 2012).

The UTCI is defined as the air temperature in the reference condition (50% humidity, still air and full shade) that causes the same physiological response as the actual observed conditions. The range and classification of UTCI is given in Table 2.

<table>
<thead>
<tr>
<th>Above 46°C</th>
<th>38°C to 32°C</th>
<th>26°C to 20°C</th>
<th>14°C to 8°C</th>
<th>4°C to -4°C</th>
<th>Below -8°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate Heat Stress</td>
<td>Moderate Cold Stress</td>
<td>Strong Cold Stress</td>
<td>Very Cold Stress</td>
<td>Extreme Cold Stress</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 summarizes the UTCI if a person were to be in full sun or full shade in open ground for a warm, low wind speed day in Adelaide. In addition, the probable UTCI rating using 4m/s wind at ground level (the limit for acceptable wind speed for long periods of sitting based on the Lawson criteria) is also provided for reference. This higher wind speed is likely to result in the most comfortable conditions for the simulated air temperature and associated level of shade.

<table>
<thead>
<tr>
<th>Case</th>
<th>Air Temperature (°C)</th>
<th>Wind Speed at 10m (m/s)</th>
<th>Global Solar Radiation (W/m²)</th>
<th>UTCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshaded, low wind</td>
<td>36</td>
<td>1.5</td>
<td>1045 (full sun)</td>
<td>46.5°C</td>
</tr>
<tr>
<td>Shaded, low wind</td>
<td>36</td>
<td>1.5</td>
<td>114 (shade)</td>
<td>38.3°C</td>
</tr>
<tr>
<td>Unshaded, acceptable wind</td>
<td>36</td>
<td>4.0</td>
<td>1045 (full sun)</td>
<td>43.3°C</td>
</tr>
<tr>
<td>Shaded, acceptable wind</td>
<td>36</td>
<td>4.0</td>
<td>114 (shade)</td>
<td>36.4°C</td>
</tr>
</tbody>
</table>

These examples illustrate how different thermal comfort models provide various indications of comfort or stress. Whilst many of these are expressed as a temperature in degrees Celsius, they are incompatible. For example, the PET air temperature for comfort is between 18°C – 23°C whilst SET* (an indoor measure) reports a much greater range of 17°C – 30°C and UTCI suggests between 9°C to 26°C (Blazejczyk et al., 2012). This is because they are each reporting on different things. This highlights the
need for outdoor specific models; however, with the variability of external conditions there remains a
necessity for standardizing certain variables which again limits precise testing in some areas. Further,
the influence of different climates and user groups has been found to greatly alter the range of
responses for thermal comfort calculations (Chen and Ng, 2012; Niu et al., 2015). As discussed above,
the value of different indices for design is in the indication of potential changes within microclimates.
This requires an integration of the appropriate index with other design tools. Following are two case
studies of design of outdoor space for improved thermal comfort using indices through complimentary
design tools.

4. Design case studies

Design of external space occurs in numerous contexts from very small interventions to the
redevelopment of existing space and master planning of entirely new developments. Each of these
scenarios provides different constraints and opportunities for thermal comfort control. Following are
two case studies; phase 5 of Masdar City in the United Arab Emirates and Danginri Thermal City in Seoul,
Korea. Masdar City is located in Abu Dhabi, United Arab Emirates. Abu Dhabi experiences very little rain
through the year, with an average of 20mm of rain in February but less than 10mm for every other
month of the year. The dry climate has an average summer temperature of nearly 35°C, with highs
exceeding 40°C for 9 months of the year (Böer, 1997; Islam et al., 2009). In contrast, Seoul, in which
Danginri Thermal City is located, is much cooler. Average winter temperatures fall in January to -4°C and
summer temperatures average between 21°C and 24°C without days exceeding 30°C (NOAA, 2014;
KMA, 2015). Whereas Abu Dhabi is very dry throughout the year, Seoul averages nearly 400mm of rain
in the month of July. These two case studies provide an interesting juxtaposition to one another as
design challenges. These examples demonstrate variance in design processes, and as a discussion
around different strategies for intervention and application of thermal comfort assessment and
feedback into design decision making.

4.1. Design case study 1: Masdar City Phase 5. AECOM

Masdar City in Abu Dhabi has used the fundamental principles of thermal comfort to develop a master
plan that has the best chance of resulting in comfortable conditions for what aspires to be the world’s
most sustainable city. The 6km² developments, when completed, will house commercial, education,
residential and industrial facilities. This case study is restricted to Phase 5 of the master plan which is
mostly residential, consisting of townhouses and villas. However the same principles were used for the
whole development site. With a huge focus on Masdar City being a cycling and pedestrian friendly
neighbourhood, it has been imperative to understand not only the impacts of the local climate, i.e. the
surrounding hot, arid desert, on the development, but also the impacts that a development can have on
the local microclimate.

Although exposure to the sun’s rays is the driving variable for thermal comfort, arguably, the built
form has the biggest impact on wind patterns through any development, particularly at the scale of the
Masdar City development. It has therefore been critical to develop this master plan with wind flows in
mind to ensure that as much air as possible is directed through the site. In terms of the other remaining
comfort variables, the built form provides shading, with local features such as canopies and awnings
incorporated to shade pedestrians from the intense summer sun. The use of low albedo materials in the
construction of the villas and townhouses will reduce the amount of heat stored in the material from
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solar radiation in the day. This heat gets released as soon as the wall temperature is above the outdoor temperature, contributing to high temperatures. Finally, humidity can be influenced by the use of vegetation and water. However, any change in humidity is dependent on the humidity of the incoming air.

At the early stages of master plan design, getting building layout and massing correct is crucial to the success of providing a comfortable thermal environment. If done incorrectly, wind flows through the streets become limited, resulting in stagnant air pockets and excessive heat build-up. An analysis of local meteorological conditions will therefore dictate street orientation and placement of tall buildings. Throughout the year, the winds in Abu Dhabi come mostly from the North West, with occasional winds from the east and south. As the aim is to reduce the impacts of excessive temperatures, winds during summer are most significant; especially those during the afternoon and evening when temperatures are higher and pedestrians are most likely to move from one part of the city to the other. Prevailing winds change throughout the day with overnight and morning winds during summer being easterly to southerly. From noon onwards however, winds predominantly come from the North West. This provides the first design principle of aligning main streets along a north west to south east access. In addition, orienting streets in this way will result in cooler overnight street temperatures as winds purge the heat that builds up in the streets during the day. Building on the encouragement of prevailing winds through the site, much work was done in the early design stages on the importance of urban canyon aspect ratios: street width to building height. The current master plan design maintains wide streets, and uses green infrastructure along these streets to further reduce the temperature of incoming air movement.

Phase 5 of Masdar City is bounded to the north and west by ‘Khalifa City A’ – a similar residential development of single and two storey villas and townhouses. As winds flow from the North West, ‘Khalifa City A’ is exposed to the breeze, however this will result in a low speed sheltered wake region behind the development. This is one of the primary reasons that Phase 5 of Masdar City uses graded street levels. By raising streets above the standard ground level (approximately 4m above sea level) by up to 2m in parts, the wind availability is increased, and the likelihood of more comfortable conditions is increased.

With these main principles in mind, four master plan concept designs were worked up by the project architects. High level, coarse CFD models were created at a building massing level of detail (1m – 2m model resolution) to assist the design team in visualizing the benefits that certain features and layouts could have when the development is subject to prevailing north westerly winds. At this stage, only wind flows were simulated, and the ratio of local street level wind speeds to open ground wind speed analysed. Compared to most standard CFD modelling exercise, these concept CFD models were run for less than 12 hours each, and so whilst the accuracy of simulated wind speeds could be questioned, general flow patterns were unlikely to significantly change with a more accurate and refined model.

One of the key outcomes from the early CFD modelling was the effect of location of the taller multi-unit residential blocks within the development. As with the sheltering effect of ‘Khalifa City A’, placing taller buildings at the north west of the site created a slow moving air region behind the building, extending half way through the development in some cases. One of the other options had the multi-residential unit located towards the centre of the site. This resulted in improved air flows throughout the development, as whilst winds skimmed across the lower villas and townhouses, they flowed down the taller building envelopes, drawing air down to ground level. While this can be detrimental in some climates due to highly accelerated winds, the extent of the downwash in Masdar City is unlikely to be as
significant, as the tall buildings are only five to six storeys tall, and therefore do not draw significant air volumes down to ground level.

As well as a CFD model, an analysis of hourly local weather data and thermal comfort metrics was done to demonstrate the impacts of increasing and decreasing wind speed. The apparent temperature metric was used as this enabled approximations to be made based on the variables that were accessible; air temperature, speed and humidity, with two different equations depending on whether comfort is estimated in full sun or shade. Assuming that local features would be incorporated in pedestrian heavy areas, the baseline thermal comfort, i.e. in open ground but fully shaded was calculated at pedestrian head height using the atmospheric boundary layer approximation. Adjustments were then made to account for a 50% increase or 50% decrease in wind. The apparent temperature calculation showed that adjusting wind speeds could achieve a relative thermal comfort difference of ±2°C. This demonstrates that considering thermal comfort during early stage design and manipulation of important metrological variables can make the local microclimate more acceptable than surrounding areas.

Future work on Masdar City will include full thermal comfort simulation using CFD. This will provide guidelines for surface materials, local shade and green and blue infrastructure as the development progresses to individual plot design.

4.2. Design case study 2: Danginri Thermal City. PARKKIM

Thermal Comfort was also a major design consideration for PARKKIM’s entry to the 2013 competition for the Danginri Power Plant redevelopment in Seoul, Korea. Situated in Mapo-gu, Seoul, located next to the Han River the competition brief asked for ecological and cultural significance to be addressed in the landscape design of this post-industrial site. The redevelopment is to move the existing ground level thermal power plant, built in the 1930’s to underground at the same location. The upgraded power plant is due to be completed in 2016 and will be the world’s first large scale combined power station located underground. The above ground space will be transformed into a cultural complex including libraries, museums and 8350m² of public open space (Daesung, 2011).

PARKKIM’s Thermal City scheme was not successful in the final competition; however their strategy provides useful insights into the use of thermal comfort indices in design validation. The scheme proposed to control thermal comfort to increase the use of the open space in both summer and winter conditions. Whilst Seoul’s climate is relatively mild it is changing towards more extreme conditions with hotter and more intense summers and very cold winters (NOAA, 2014). The necessity for open space to be habitable in those extreme times provided an important design consideration (PARKKIM, 2014).

In the final design proposal, topographic features were aligned to capture cool airflows from the bordering Han River for summer cooling. Further vegetation provided both shade in summer and barriers to the winds in winter. During winter it was proposed that the excess heated water from the power plant would be channelled through pipes to stone surfaces within the park. These stone features would absorb the heat from the water to produce warm seating and small microclimates within the park. This process would also cool the water and address the environmental damage of pumping hot water directing into the river. The system of under-surface heating is a reference to a traditional Korean architecture convention of channelling wood smoke through an under floor system to heat sleeping and living areas (Walliss and Rahmann, 2015).

During the design development, PARKKIM used Autodesk Ecotect analysis software to simulate sun, shade and wind behaviour to test new landform and facilitate the siting of vegetation. The initial
simulations were run on test plots which were unable to convey the full complexity of the site. However, this initial testing was able to provide insight into performative qualities for influencing thermal comfort at the early stages of design and suggest tactics for further development.

Once the proposal had been short listed, PARKKIM engaged the consulting engineers ARUP for more detailed analysis of thermal comfort performance of the design against the existing and proposed site conditions (Walliss and Rahmann, 2015). This more advanced stage of the design development used multiple softwares and the Thermal Sensation Index (TSI) equation to calculate and simulate the effects of air temperature, solar radiation and wind speed.

The detailed analysis of the existing site and proposed design undertaken by ARUP was tested for critical times in the height of summer in June between 2-5pm and winter in December between 2-5pm. The results show the design extends the areas measuring closest to 4 (most comfortable) using the TSI in the summer months into the central open space. Whilst in the winter the areas with the most comfortable spaces aligned with the heated stone (Walliss and Rahmann, 2015). This testing facilitated a design process of iterative feedback between the simulation analysis and the designers to further develop the landform and features that would enhance the thermal comfort performance of the scheme (PARKKIM, 2014).

Using a combination of design tools including a relevant thermal comfort equation, the emphasis of the design proposal was focused on the key tactics of wind management, shade, shelter and the warming capacity of the stone seating structures to produce microclimatic change. Whilst the designers were seeking to extend use of the park in the extreme climatic conditions of summer and winter the broader climatic conditions severely limited the ability to achieve a reading of 4 (most comfortable) across the site. This is especially evident in winter where it is most challenging to warm the external environment. However, the designers were able to work with a relative change of conditions specific to the surrounding environment. Through the management of key variables certain microclimate conditions could be enhanced, such as the warm stone benches. Whilst the majority of the park remains unaffected, opportunities for use of the space in the most extreme scenarios emerged in the smaller interventions.

5. Tools for predicting difference

These case studies illustrate the benefits of using a predictive tool to inform design and the usefulness of working with projected relative change of thermal sensation in the design of external environments. The existing site conditions in these examples were already at extreme or very uncomfortable thermal ranges so that the design responses were implicitly restricted in the ability to achieve a desirable thermal comfort range. Whilst in both circumstances the proposals are not always able to achieve a perfect measure of thermal comfort, the design schemes are able to effect relative change at the sites and extend the potential use of the space. This suggests a move away from generalizations of thermal comfort ranges to methods for working with information about existing site conditions and effecting change within those. This shift provides a broader range of outcomes that are more suitable to design in external sites where knowledge of desired thresholds remains valuable but may or may not be precisely achievable depending on the particular site and climate.

Both of the case studies also show how digital modelling and simulation technology can reveal complex environmental phenomena and provide behavioural analysis of climate conditions. In these instances simulation is essential for communicating with the design teams and conveying the relationships between spatial interventions and the critical forces dictating thermal comfort. In both
design of external space can provide important knowledge of the relationships between the key variables which affect thermal sensation. However, the usefulness of these is dependent on the aim in particular situations, the selection of an appropriate measure and the method in which the index is applied. The case studies shown here suggest the use of indices is valuable for designers as a predictive tool for change. This is apparent when used within a design process where designers can test spatial design proposals against different scenarios and predict a result. Here the value of simulation technologies such as CFD modelling is clear, where this tool works as a means for accessing complex information, predicting change and as a communications tool.

6. Conclusion

It is evident that designers need to address the issues of thermal performance in external space to ensure these kinds of sites remain useful in the future. There are many existing and emerging tools and methods through which to work with the variables that impact on thermal comfort, including established thermal comfort indices. How these tools are best applied into design processes is an important and necessary area for further research in the area of performative external space design.

References


