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ASSESSMENT OF OUTDOOR THERMAL COMFORT IN HOT ARID ZONE

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Abstract: The globe witnessed a rapid development of the concepts of sustainability, smart architecture, and intelligent buildings during recent decades. The Healthy environment, particularly thermal comfort, is an essential concern for planners, urbanists, and architects to produce a healthy and thermally comfortable environment. A better understanding of the parameters that affect the Outdoor Thermal Comfort (OTC) will enable urbanists and environmentalists to control the microclimate and to enhance environmental performance. Several parameters affect the thermal comfort of human-being such as air temperature, mean radiant temperature (MRT), air velocity, humidity, metabolic rate, and clothing insulation. Assessing the MRT is considered the most challenging parameter in outdoor spaces. Recent research recognized several approaches to determine the OTC in different climatic zones. The influence of different climates and user groups has significantly altered the range of responses for thermal comfort. This paper focuses on reviewing the current state of knowledge on how to assess the OTC and the MRT in the hot arid climate. Results confirmed the integration of the appropriate OTC index with other design tools to evaluate the OTC and the MRT. It also confirmed that Physiological Equivalent Temperature (PET) and Predictive Mean Vote (PMV) are the most common indices. While ENVI-met and RayMan are the most common software to assess the OTC.

Keywords: Outdoor thermal comfort (OTC); hot arid climate; outdoor spaces; comfort indices, mean radiant temperature (MRT).

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INTRODUCTION

Urban projects must consider the climatic conditions to provide a healthy environment, especially in open spaces, as they are the main drivers of a prosperous urban life. Outdoor Thermal Comfort "OTC" is one of the essential complex factors that influence the quality of open spaces and the activities that take place. Thermal comfort is defined as "the status of mind that express stratification with the thermal environment" (Fanger, 1970, Mohamed and Gado, 2009a) quoted in (Mohamed and Gado, 2009a). According to Rakha and Reinhart (Rakha et al., 2017), a better understanding of urban microclimate parameters enables the designers to improve the quality of life in the open spaces. Moreover, an improvement of microclimatic conditions in urban spaces can allow people to spend more time outdoors, with the potential to influence the social cohesion of space and increase economic activities (Aljawabra and Nikolopoulou, 2010). Moreover, they explain that people's choice to walk or cycle depends on their comfort and satisfaction with their thermal environment. Furthermore, convey that designers aspire to create spaces that entice outdoor activities where it is noted that thermal comfort plays a vital role in users' daily interaction and amusement (Kwon and Lee, 2017).

Problem

The assessment of thermal comfort in the outdoor environment is more complicated than the indoor environment, where everything controlled. Thus, any thermal comfort assessment concerning practical design must consider several variables of thermal comfort (Sealey, 1979). These factors include air temperature, mean radiant temperature (MRT), Relative humidity (RH), air velocity, clothing rate (clo.), and metabolic rate (Mohamed, 2009, Mohamed and Gado, 2009b, Mohamed, 2018). Hence, a scale is needed to measure the combined effect of all factors. This scale is referred to as the thermal index. Many indices have been developed to measure thermal comfort in general and OTC in particular. However, each index demonstrates different indications of heat or stress. It has been noted that people's preferences and thermal perception vary widely in regard to outdoor temperatures, which results in a broader acceptable range of thermal comfort (Walls et al., 2015). Moreover, people's preferences are comprehended to be influenced by geographic location, and acclimatization of users to certain conditions (Giridharan et al., 2007, Johansson et al., 2014, Brown et al., 2015) quoted by (Walls et al., 2015). While there's a lack of a universal tool to measure the OTC suitable for all climatic conditions. This paper focuses on finding the most suitable index and tool to assess the OTC in the hot arid climate.

This study aims to identify the most suitable OTC assessor for the hot arid climate with consideration for assessing the Mean Radiant Temperature (MRT) as it is one of the leading challenges urban designers face during the assessment of OTC. The objectives of this study are: (1) to systematically analyze a collection of recent studies that applied the OTC indices in an outdoor environment; (2) to identify the most common ways of assessing the MRT in outdoor environments; and (3) to identify the most common tools or software that are compatible with the concluded OTC indices.

Methodology

This study follows the procedure of a systematic literature review to achieve the aim of this research. It is a stand-alone literature review that is defined as "systematic, explicit (Štrukelj, 2019), and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners" (Okoli and Schabram, 2010). The search process to retrieve the relevant studies included using topic-related keywords as well as exploring the list of references found in the already chosen articles. A collection of hundreds of articles was screened and classified to provide the necessary data. The acquired data were recorded into three matrices: 'Climatic Region & OTC Indices', 'Aim of OTC Indices,' and 'Assessment Tools.' The process of performing a systematic literature review has six steps, which can be seen in **Fig. 1**.

Thermal Comfort Models

Thermal comfort is an impression used to demonstrate whether a person does not feel too hot or too cold regarding a given thermal environment (Attia and Hensen, 2014). Recent researches (La Roche, 2012, Sanborn, 2017) recognized two main approaches to assess the thermal comfort: the heat-balance approach or the physiological approach and the adaptive approach. The heat balance approach is simply based on the concept that the heat loss from the body is equal to the heat gained, permitting the body to reach thermal

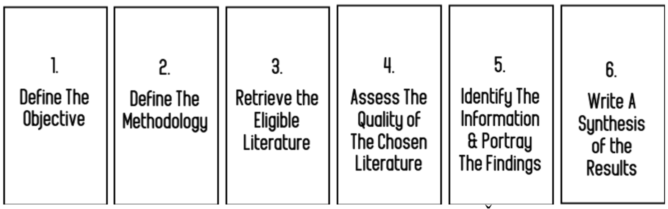

Fig. 1 Systematic Literature Review Process (Štrukelj, 2019)

equilibrium (Sanborn, 2017). If all people are the same, and the comfort of all individuals can be explained by the physiological approach (La Roche, 2012). The adaptive approach relies on people's perception of comfort, where psychological factors, cultural background, and people's preferences are involved (Sanborn, 2017). The best way to evaluate outdoor thermal comfort (OTC) is using thermal indices dependent on the heat-balanced approach of the human body (Santos Nouri et al., 2018).

Variables that Effect Outdoor Thermal Comfort

Thermal comfort is affected by several factors that affect the rate of heat dissipation from the body. These are either environmental or human parameters; these factors are air temperature, mean radiant temperature, air velocity, humidity, metabolic rate, and clothing insulation (ASHRAE, 2005). To further clarify, the heat exchange between the human body and the surrounding environment occurs through convection, conduction, radiation, and evaporation (Setaih, 2016).

Air temperature, commonly given in degree Celsius, is defined by Barakat et al. (2017) as "the temperature of the air surrounding the human body." It is considered one of the widely known thermal comfort indicators and an essential environmental parameter measured by a dry-bulb thermometer (La Roche, 2012).

Air velocity or wind speed is considered one of the most powerful methods that can cool down a body's temperature, especially in a hot and humid environment (La Roche, 2012, Sealey, 1979). Air movement affects the evaporation of moister from the skin (La Roche, 2012). Air velocity less than 0.1m/s and more than 6m/s causes discomfort (CIBSE, 2006) quoted by (Setaih, 2016). Another detailed investigation (Cheng and Ng, 2006) claimed that the appropriate air velocity for a person under shade to remain in comfortable conditions exposed to solar radiation of about 100 W/m2 and air temperature between 27 and 34 °C is: 0.1to 2.5 m/s for sitting activity, 2.5-4 m/s for a standing activity, and 4-5 m/s for a walking activity.

According to Barakat et al. (2017), Relative Humidity (RH) is defined as "the ratio between the actual amount of water vapor in the air and the maximum amount of water vapor that the air can retain at that air temperature." A low relative humidity enables sweating, whereas a higher relative humidity (above 70%) prevents sweating, which prevents cooling down the skin (Sealey, 1979). The comfort range for RH has been studied in several previous pieces of research (Fanger, 1970) quoted in (Mohamed, 2009) and confirmed between 40 % and 70 %. Anything below the acceptable range will be too dry, and anything above will be too moist and therefore causes discomfort.

The metabolic rate is defined by La Roche (2012) as heat generated by the human body. The amount of energy produced per unit of time is called a metabolic rate, and it is expressed in Watt/ m2 of body surface (Mukherjee and Mahanta, 2014). The metabolic rate ranges from 0.8 Met while sleeping up to 10 Met during sports activities or intensive workouts (INNOVA, 2004).

Clothing acts as a barrier between the human body and the surrounding environment (Mukherjee and Mahanta, 2014). Each clothing type has a different insulation value expressed in Clo Value. The amount of clothing worn by a person significantly influences their thermal comfort due to its influence on heat loss and, subsequently, its influence on the thermal balance. Commonly, the thicker the clothing item, the higher the insulating capacity it has. The clothing insulation and the activity level both present an adaptive opportunity for comfort (Setaih, 2016), however complete adaptation to the extreme thermal microclimates cannot be accomplished, especially for females in the outdoor of the Islamic countries. Females in Saudi Arabia should stay wearing "abaya" (a long black garment that absorbs heat). Therefore, there's a need for urban design support to deal with the environmental parameters and religious and cultural habits.

The mean radiant temperature (MRT) is one of the most critical environmental parameters that significantly influence outdoor thermal comfort. The MRT is defined as the "uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure" (ASHRAE, 2005). The next part of this section will discuss in more detail the assessment of the MRT.

Mean Radiant Temperature

The main factors that influence the value of MRT are mainly divided into short-wave radiation and long-wave radiation, which include direct, diffuse, and reflected solar radiation as well as infrared radiation from the sky and urban surfaces (Rakha et al., 2017, Barakat et al., 2017). According to Kántor and Unger (2011), the MRT values outdoor in an urban setting are much more complicated than in an indoor setting. They continue to explain that the MRT value indoors is approximately equivalent to the air temperature. However, the MRT value outdoors can reach up to 30 °C higher than the air temperature in sunny conditions because the MRT values vary, especially and temporally in an urban environment. There is a wide range of surfaces that absorb, reflect, and emit solar radiation at different rates and intensity (Barakat et al., 2017). A study by Kántor and Unger (2011) mentioned the following as the

MRT's main components: (1) solar or short-wave radiation reaching the lower atmosphere, which includes: (a) I – direct solar radiation, (b) D – diffuse solar radiation, and (c) R – reflected short wave radiation (parts of direct and diffuse solar radiation reflected from the ground and other surrounding surfaces), and (2) terrestrial or long-wave radiation which included: (a) A – atmospheric counter radiation (thermal radiation from the sky), and (b) E – long-wave radiation of the environment (thermal radiation from the ground and other surrounding surfaces).

During nighttime, radiation exchange is limited to long-wave elements. In contrast, the role of short-wave components takes place during sunlight periods only, and their significance increases with the altitude of the sun. On a clear sunny day, solar exposure becomes the main cause of thermal stress. In an urban setting, a standing person is mainly exposed to long-wave radiation derived from the ground, and other urban surfaces, and only 30% is attributed to solar or short-wave radiation during the daytime.

Due to the variety of radiation density spatially and temporally mentioned, obtaining the value of the MRT in an urban environment is one of the leading challenges urban designers face during the assessment of thermal comfort. For example, although shading elements block direct solar radiation, they act as thermal radiators producing diverse levels of long-wave radiation dependent on their emissivity, solid angle proportion, and the person's position under study (Kántor and Unger, 2011). The main concern regarding the MRT calculation is the stipulation of the immediate surfaces with their solid angle proportions and the measurement of the short and long-wave radiation reaching the subject under consideration (Kántor and Unger, 2011).

There are several methods to calculate the value of the MRT. The most accurate method is by integral radiation measurements and the calculation of angular factors, which is the proportion of radiation received by the human body from different directions (Thorsson et al., 2007b). The method requires using a pyranometer and a pyrgeometer (**Fig. 2**) to measure the short and long-wave radiation from six different directions (Thorsson et al., 2007b, Kántor and Unger, 2011, Krüger et al., 2013). However, it is a complicated procedure, but the equipment is costly and challenging to acquire due to lack of availability.

Another method, a more standard approach, used to determine the value of MRT is the globe thermometer. It is combined with air temperature and wind speed measurements, which is considered the simplest and cheapest method. The globe thermometer reacts to the radiation from the surrounding environment; if the global temperature is higher than the dry-bulb temperature, it indicates that the surrounding surfaces are warmer than the air and vice versa (La Roche, 2012). After acquiring the global temperature, the MRT is calculated using the following (Thorsson et al., 2007b).

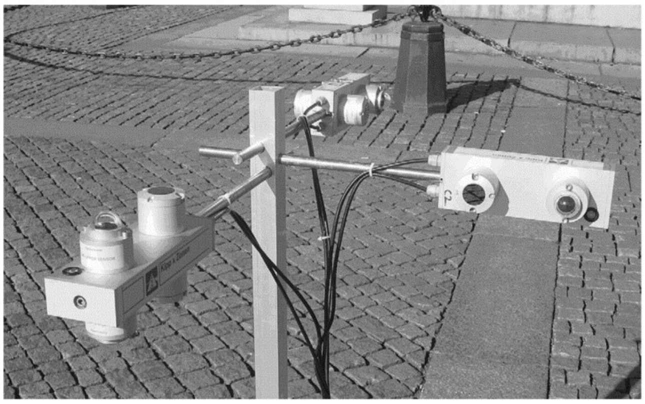

Fig. 2 Instrument setup for measuring both short-wave radiation, using pyranometers, and long-wave radiation, using pyrgeometers, simultaneously from six directions (downward, upward, north, east, south, west) (Thorsson et al., 2007b)

$$T_{mrt}=\left[\left(T_g+273.15\right)^4+\frac{1.335\times10^8 V_a^{0.71}}{\varepsilon D^{0.4}}\left(T_g-T_a\right)\right]^{1/4}-273.15 \quad (1)$$

where T_g is the globe temperature (°C), V_a is the wind speed (ms 1), T_a is the air temperature (°C), D is the globe diameter (mm), and ε is the globe emissivity (0.95 for a black globe).

Practically, the measured value of T_g represents the average of both the T_a and T_{mrt} values (Kántor and Unger, 2011). A typical globe thermometer consists of a black-painted copper sphere 15 cm in diameter (Kántor and Unger, 2011, La Roche, 2012, Johansson et al., 2014). There have been several concerns regarding the use of a standard global thermometer to measure the MRT outdoors. Some of the concerns are the following. Disregard to the black color of the sphere where the absorption of the short-wave radiation is overestimated (Kántor and Unger, 2011). The lengthy duration for the globe thermometer to reach a state of equilibrium where it takes 15 to 20 minutes. The required time presents a challenge, especially as the T_a and V_a tend to change rapidly outdoors, rendering it difficult to reach equilibrium (Johansson et al., 2014, Thorsson et al., 2007b). Hence, the value of the calculated MRT becomes questionable.

Proposed solutions to the previous concerns involve a sphere with a smaller size to speed up the response time; however, not too small where the results become inaccurate (Kántor and Unger, 2011). Thus, an optimum sphere size balances between accuracy and response time. Moreover, the color of the sphere can be changed to a grey color to better present the radiant properties of the skin and general clothing (Johansson et al., 2014). One of the tested grey globe thermometers and proven to be suitable for measuring T_g outdoors is a 38 mm table tennis ball (a hollow acrylic sphere) painted grey (color: RAL 7001) with PT 100 temperature sensor inside the middle of the ball (**Fig. 3**) (Thorsson et al., 2007b). Afterward, Equation 1 was used to calculate the MRT using 5-minute mean values. It has been noted that the results of the equation are valid only when the air velocity is between 0.1 and 4.0 ms−1, and the incoming short-wave radiation range between 100 and 850 Wm^{-2}.

Another method for calculating the MRT (**Fig. 4**) is using simulation software to model the radiation environment within an urban context. However, it is challenging to model the MRT as it relies on heat transfer principles to generate the surface temperatures for the studied period in the chosen site (Rakha et al., 2017). Yet, different software has been developed, such as RayMan and ENVI-met (**Fig. 5**), to determine the MRT. Rayman is considered one of the commonly used tools for thermal comfort researchers. The model calculates the MRT based on Temporal description (date, and time of day), geographical location (longitude, latitude, altitude, and time zone), meteorological input (air temperature, air humidity, global radiation or cloud cover at least, turbidity), the albedo of surrounding surfaces, information regarding horizon limitation such as topography and any form of obstacles including buildings (length, width, and height) and vegetation (type, height, and width of canopy), the Bowen-ratio, and the ratio of diffuse and global radiation (Thorsson et al., 2007b).

It should be noted that the simulation refers to a single point in the examined area, not a continuous surface of the obtained values, as it would increase the duration of the running time (Kántor and Unger, 2011). According to Abdel-Ghany et al. (2013), RayMan is valid for the hot and sunny climate in where the value of the MRT exceed 60 °C at around noon. The software can be further utilized to generate sun path diagrams, sunshine duration, shadow spaces, and various thermal comfort indices (PET, PMV, SET, UTCI).

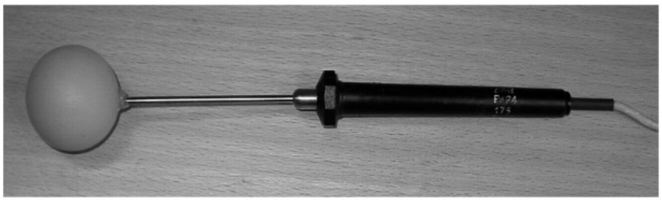

Fig. 3 The 38 mm flat grey globe thermometer (Thorsson et al., 2007a)

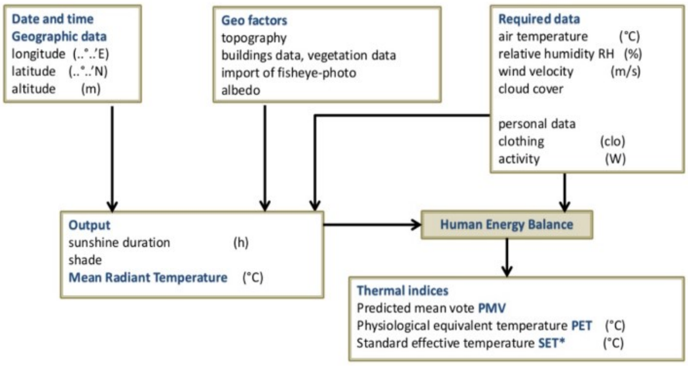

Fig. 4 Modelling of mean radiant temperature within urban structures (Fontanesi, 2013)

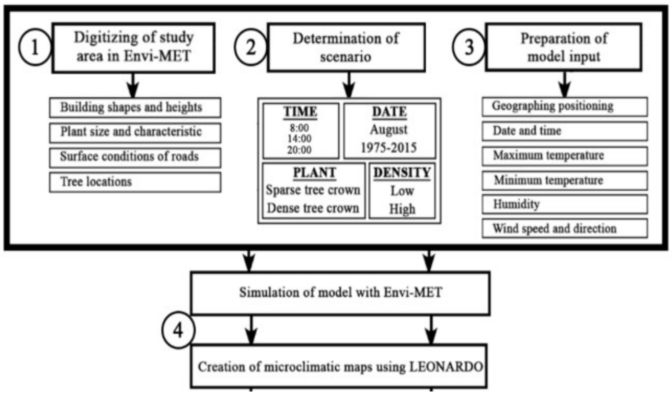

Fig. 5 Envi-met Simulation Process (Unal et al., 2018).

As for ENVI-met, it is a 3-dimensional grid-based tool that can calculate wind flow, turbulence, temperature, humidity, comfort indices (PMV), radiation fluxes, as well as the MRT with a high spatial resolution of 0.5-10 m horizontally and temporal resolution of up to 10 s (Rakha et al., 2017). The software enables the user to create a detailed 3d model within a 250x250x25 grid layout that contains buildings (height, shape, and design), vegetation (type, dimension, physiological process), and soil type.

The software simulates the microclimate parameters for each grid; therefore, the duration of the running time can take several days to generate accurate and comprehensive output variables (Kántor and Unger, 2011). The ENVI-met calculates the MRT at a surface level, whereas RayMan calculates it at one point. Hence, the broad difference in running time. According to Rakha et al. (2017), some of the limitations of ENVI-met software are the extensive workflow, the duration of the running time, which takes 24 hours to simulate a 24-hour simulation, and the restriction in calculating the long-wave radiation fluxes.

Designing for Outdoor Thermal Comfort

Designers with the intent to enhance thermal comfort in an outdoor environment are faced with several challenges, such as the lack of control over the concerned variables (**Fig. 6**). It's complicated to examine or identify the impact of a certain design on the various meteorological variables. Moreover, Brown et al. (2015) explain that some environmental parameters, such as air temperature or relative humidity, are difficult to change or control, requiring large-scale design interventions like a regional park. They continue to explain that other environmental parameters such as air velocity, radiant heat, and solar exposure are more easily adjustable or controllable and can be modified through small-scale design interventions. Although not all meteorological factors can be manipulated, there's still a need to understand how the manipulation of certain environmental parameters can influence the thermal sensation outdoors (**Fig. 7**). Also, according to Sealey (1979), it is crucial to recognize the subjective nature of comfort, where it is challenging to reach a condition where everyone feels comfortable. He further explains that the best comfort conditions are known as optimum conditions where 50 to 75% of people feel comfortable. Another concern for outdoor spaces is the more extreme climatic fluctuations where comfortable conditions cannot always be expected; therefore, more logical design is to increase the frequency of comfortable conditions throughout the year (Rose et al., 2010).

OTC indices

There are tens of indices developed to evaluate thermal comfort. Some of them are very simple depends on air temperature and a secondary parameter while others are more complex (Jendritzky et al., 2011). Many examples of these types are based on steady-state models, which assume that users reach a thermal balance with the surrounding environment. A negative point that the dynamic aspects of adaptation to the environment is not considered when using steady-state models. Predicted Mean Vote (PMV), Outdoor Standard Effective Temperature (OUT_SET*), and Physiologically Equivalent Temperature (PET) are examples of the steady-state models (Yahia and Johansson, 2013, Ng and Cheng, 2012). The adaptive assessment methods depend on the Pierce Two-Node model of the human body that needs intensive monitoring of subjects, that could be difficult in most outdoor scenarios (Ng and Cheng, 2012).

Predictive Mean Vote (PMV)

One of the most used indices for thermal comfort is the Predictive Mean Vote (PMV). It investigates whether a given thermal environment abides by the criteria of comfort by calculating the mean thermal response of a large group of persons on a seven-point scale ranging from +3 (cold) to -3 (hot) (ISO7730, 2005) (Fanger, 1970) (**Fig. 7**). The equation depends on the heat balance approach, where it uses heat transfer to calculate the equilibrium thermal balance between individuals and their surrounded environments. Although the PMV index was initially developed to measure thermal comfort indoors, it has been utilized to assess the thermal comfort outdoors in many studies.

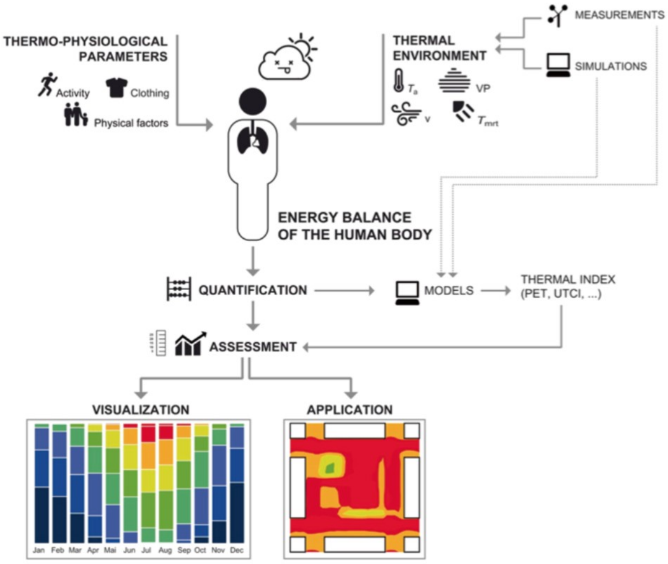

Fig. 6 Flowchart of the human-biometeorological assessment of the thermal environment (Matzarakis et al., 2016)

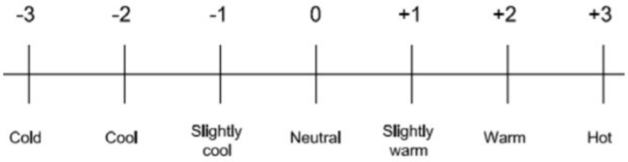

Fig. 7 Seven point thermal sensation scale (Beizaee et al., 2012)

Physiological Equivalent Temperature (PET)

The Physiological Equivalent Temperature (PET) index was developed, especially for outdoor environments. It is based on the Munich Energy-balance Model for Individuals (MEMI). The PET was developed by (Höppe, 1999) to compare the outdoor thermal conditions with the indoor thermal conditions to assess the outdoor thermal environment with a standardized indoor condition for a standardized individual. The PET, expressed in degree Celsius, is defined by (Höppe, 1999) as "the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed." Therefore, it enables a layperson to compare the integral effects of complex thermal conditions outside with his or her own experience indoors. The PET index takes into account the four environmental parameters (air temperature, MRT, air velocity, and relative humidity); however, the human parameters are fixed (metabolic rate of 80 W (light activity, and clothing insulation of 0.9 clo) (Höppe, 1999). The following assumptions are made for the indoor reference climate: mean radiant temperature equals air temperature ($T_{mrt} = T_a$), air velocity is set to 0.1 m/s, water vapor pressure is set to 12 hPa (approximately equivalent to a relative humidity of 50% at $T_a = 20°C$). There are several advantages to the use of PET (Deb and Alur, 2010): It is a universal index, and it is calculated regardless of clothing and metabolic rate. Due to its thermos-physiological background, it provides the real effect of the sensation of climate on human beings. It is measured in °C, which makes it relatable and easier to comprehend. It does not rely on subjective measures. It is suitable in both hot and colder climates.

Simply, PET was designed in a physiologically relevant way to model the thermal conditions of the human body in any given environment (Setaih, 2016). **Table 1** presents the variation of PET in different climatic conditions. For example, in warm and sunny conditions, the PET value is equal to 43 °C, which means that an occupant of a room with an air temperature of 43 °C reaches the same thermal state as in the warm and sunny outdoor conditions. If the person moves to a shaded area away from direct solar radiation, the PET value will be reduced to 29 °C. Thus, the same outdoor air temperature will result in a different thermal strain that can be clearly quantified with the PET index. It should be noted that the PET index does not indicate if the thermal environment causes thermal stress or discomfort (Höppe, 1999); it merely presents what the thermal environment feels like by considering all the influential meteorological data. **Table 2** shows the ranges of PET for various levels of thermal perception and physiological stress.

Table 1. Variation of PET in different scenarios. (Deb and Alur, 2010)

Scenario	T_a	T_{mart}	v	VP	PET
	(°C)		(m/s)	(hPa)	(°C)
Typical room	21	21	0.1	12	21
Winter, sunny	-5	40	0.5	2	10
Winter, shade	-5	-5	5	2	-13
Summer, sunny	30	60	1	21	43
Summer, shade	30	30	1	21	29

Table 2. Different PET Ranges referring to thermal sensation as well as grade of physiological stress (Brosy et al., 2013)

PET (°C)	Thermal perception	Grade of physiological stress
< 4.1	Very cold	Extreme cold stress
4.1–8	Cold	Strong cold stress
8.1–13	Cool	Moderate cold stress
13.1–18	Slightly cool	Slight cold stress
18.1–23	Comfortable	No thermal stress
23.1–29	Slightly warm	Slight heat stress
29.1–35	Warm	Moderate heta stress
35.1–41	Hot	Strong heat stress
> 41	Very hot	Extreme heat stress

German guidelines for urban and regional planners recommended the PET Index, which is used to predict changes in the thermal component of urban or regional climates (Honjo, 2009). PET is the most commonly used index in outdoor thermal comfort studies (Johansson et al., 2014), and it has been proven suitable for the warm, humid climate (Johansson et al., 2018). The PET values can be easily calculated by the software RayMan (freely available online). The RayMan Software requires six parameters to calculate the PET Values. These are Air temperature (C), Vapor Pressure (hPa), RH (%), Wind Velocity (m/s), Cloud Cover N (Octas), Global Radiation G (W/m2), and MRT (C) that influence thermal comfort.

The Outdoor Standard Effective Temperature (OUT_SET) index was developed by de Dear and Pickup (1999). It is a modified version of the Standard Effective Temperature (SET) to suit the outdoor environment (**Table 3**). The SET is defined as "the temperature of an imaginary enclosure at 50% RH in which a sedentary human occupant, dressed in standard clothing [0.09m2 K/W or 0.6 clo] in still air, would lose the same total heat by sensible and insensible heat transfer as he would in the actual environment" (Gagge et al., 1986). Therefore, the 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.

This assessment gives an equivalent air temperature measurement to compare thermal sensations in a range of conditions. From this, the effective temperature can be related to a subjective thermal comfort response (Walls et al., 2015). However, the OUT_SET involves a simplified mean radiant temperature and assumes activity and clothing value suitable for outdoor conditions (Walls et al., 2015).

Table 3. Correspondence between SET, Sensation, and Physiological State (Gherraz et al., 2018)

SET (°C)	Sensation	Physiological state of a sedentary individual
> 37.5	Very hot, uncomfortable	Failure of regulation
34.5–37.5	Hot, very unacceptable	Abundant sweat
30–34.5	Hot, uncomfortable, unacceptable	Low sweat, vasodilatation
25.6–30	Slightly warm, slightly unacceptable	Sweat
22.2–25.6	Comfortable, uncomfortable	Low sweat, vasodilatation
17.5–22.2	Slightly cool, slightly unacceptable	Neutrality vasoconstriction
14.5–17.5	Cool, unacceptable	Slow body cooling
10–14.5	Cold, very unacceptable	Thrill

Universal Thermal Climate Index (UTCI)

The Universal Thermal Climate Index (UTCI) was developed by a commission established by the International Society of Biometeorology and the World Meteorological Organization (Setaih, 2016). The main purpose was to create an index suitable for all climates, seasons, and scales, where personal characteristics such as age, gender, clothing, and activity were dissociated (Jendritzky et al., 2011). The UTCI, expressed in °C, indicates how the weather feels, considering all climatic factors (air temperature, mean radiant temperature, air velocity, and relative humidity) (Mukherjee and Mahanta, 2014). The UTCI thermal comfort classification includes ten categories that range from extreme heat stress to extreme cold stress.

UTCI is the newest thermal index and is considered the most advanced rational thermal indices. **Table 4** shows the concept of UTCI. The parameters that are considered for calculating UTCI involve dry temperature, mean radiation temperature, the pressure of water vapor or relative humidity, and wind speed (at the elevation of 10 m) (Zare et al., 2018).

According to Johansson (Johansson et al., 2018), the UTCI considers the reduction of clothing insulation due to wind speed. Moreover, the clo value has an inverse relationship with the air temperature. As for the value of the metabolic rate, the UTCI has a fixed value for walking, as developed for outdoor studies. One of the advantages of UTCI is that it can be easily calculated online. The following table (**Table 5**) compares the four indices in terms of their thermal ranges.

The most common Index for Hot Arid Climate

After examining hundreds of case studies concerned with the outdoor thermal comfort indices, 59 case studies were reviewed thoroughly. The selection criteria were based on the study being conducted in the hot, humid region like the area of the selected field study, the use of the outdoor thermal comfort indices, and the use of tools to measure the MRT. The schedule containing all the thoroughly reviewed case studies is seen below in **Table 6**.

Table 4. Ranges of UTCI thermal comfort classifications (Walls et al., 2015)

Above 46	38 to 46	32 to 38	26 to 32	9 to 26	9 to 0	0 to –13	–13 to –27	–27 to –40	Below –40
°C									
Extreme heat Stress	Very strong Heat stress	Strong Heat stress	Moderate Heat stress	No Thermal stress	Slight Cold stress	Moderate Cold stress	Strong Cold stress	Very strong Cold stress	Extreme Cold stress

Table 5. Comparing thermal perceptions in various bio-climatic indices.

Thermal perception	Indices				
	UTCI	SET	PMV	PET	
Very cold[1] (extreme cold stress[1,2])	< –40		–3	< 4	🟦
Very strong cold stress[2]	–40 to –27				🟦
Cold (strong cold stress[1,2])	–27 to –13		–2.5	4–8	🟦
Cool (moderate cold stress[1,2]/moderate hazards[3])	–13 to 0	< 17	–1.5	8–13	🟦
Slightly cool[1] (slight cold stress[1,2])	0 to +9		–0.5	13-18	⬜
Comfortable[1,3] (No thermal stress[1,2]/no danger[3,4])	+9 to +26	17–30	0	18-23	
Slightly warm[1] (slight heat stress[1])			0.5	23–29	🟧
Warm[1,3,4] (moderate heat stress[1,2]/caution[3,4])	+26 to 32	30–34	1.5	29–35	🟨
Hot[1,3,4] (strong heat stress[1,2]/extreme caution[3,4])	+32 to +38	34–37	2.5	35–41	🟧
Very strong heat stress[2]	+38 to +46				🟥
Very hot[1,3,4] (extreme heat stress[1,2]/danger[3,4])	> +46	> 37	3	> 41	🟥
Sweltering[4] (extreme danger[4])					🟥

[1] PET; [2] UTCI; [3] SET; [4] PMV.

Table 6. Reviewed case studies

No.	Source, Year	City, Country	Climate	Index	Tools	MRT Calculation
1	(Thanh Ca et al., 1998	Tokyo, Japan	Humid Subtropical	PMV	N/D	Pyranometer & Pyrgeometer
2	(Nikolopoulou et al., 2001)	Cambridge, England	Oceanic	PMV	N/D	N/D
3	(Thorsson et al., 2004	Göteborg, Sweden	Humid Continental	PMV	RayMan	N/D
4	(Gulyás et al., 2006)	Szeged, Hungary	Oceanic Continental	PET	RayMan	RayMan (Global Radiation)
5	(Ali-Toudert and Mayer, 2006)	Ghardaia, Algeria	Hot Desert	PET	Envi-met	Envi-met
6	(Johansson, 2006)	Fez, Morocco	Mediterranean	PET	N/D	RayMan
7	(Hodder and Parsons, 2007, Thorsson et al., 2007a)	Tokyo, Japan	Temperate	PET	RayMan	Globe Thermometer, Pyranometer & Pyrgeometer
8	(Knez and Thorsson, 2008)	Goteborg, Sweden & Tokyo, Japan	Maritime	PET	RayMan	Globe Thermometer, Pyranometer & Pyrgeometer
9	(Andrade and Alcoforado, 2008)	Lisbon, Portugal	Subtropical Mediterranean	PET	N/D	Pyranometer, Pyrgeometer, RayMan
10	(Lin and Matzarakis, 2008)	Sun Moon Lake, Taiwan	Tropical	PET	RayMan	Globe Temperature & Global radiation
11	(Lin, 2009)	Taichung, Taiwan	Tropical	PET	RayMan	Global Radiation & Globe Temperature
12	(Kwon and Parsons, 2009)	United Kingdom	Temperate	PMV	N/D	Globe Thermometer & Pyranometer
13	(Aljawabra and Nikolopoulou, 2010)	Marrakech, North Africa & Phoenix, Arizona	Hot Semi-arid & Hot Desert	PMV	N/D	Globe Thermometer & Pyranometer
14	(Lin et al., 2010)	Yunlin, Taiwan	Tropical	PET	RayMan	RayMan
15	(Bröde et al., 2011)	Curitiba, Brazil	Subtropical	UTCI	N/D	N/D
16	(Hwang et al., 2011)	Yunlin, Taiwan	Tropical	PET	RayMan	Globe Temperature
17	(Mahmoud, 2011)	Cairo, Egypt	Hot Desert	PET	RayMan	N/D
18	(Boumaraf and Tacherift, 2012)	Biskra, Algiers	Subtropical Hot Desert	PMV	N/D	Globe Temperature
19	(Ng and Cheng, 2012	Hong Kong, China	Humid Subtropical	PET	N/D	Globe Temperature
20	(Andreou, 2013)	Tinos, Greece	Mediterranean	PET	RayMan	RayMan
21	(Cohen et al., 2013)	Tel Aviv, Israel	Coastal Mediterranean	PET	RayMan	Pyranometer
22	(Pantavou et al., 2013	Athens, Greece	Mediterranean	UTCI	N/D	Globe Temperature
23	(Setaih et al., 2013)	Medina, Saudi Arabia	Hot Desert	PET	RayMan	Globe Temperature
24	(Yang et al., 2013)	Singapore	Tropical	T_{op} (Operate Temperature)	N/D	N/D
25	(Yahia and Johansson 2013)	Damascus, Syria	Desert	PET, OUT_SET, PMV	RayMan (PET) ASHRAE Thermal Comfort Program (OUT_SET & PMV)	Globe Temperature
26	(Pantavou et al., 2014	Athens, Greece	Mediterranean	UTCI, PET, PMV, OUT_SET	N/D	Globe Temperature, Pyranometers, Pyrgeometer, & Infrared Thermometer
27	(Lai et al., 2014)	Tianjin, China	Topical Monsoon	UTCI, PMV, PET	RayMan	Globe Temperature

28	(Amirtham et al., 201	Chennai, India	Tropical	PET	RayMan	N/D
29	(Farajzadeh et al., 2015)	Iran	Mediterranean	PET, SET, UTCI	RayMan	N/D
30	(Zakhour, 2015)	Aleppo, Syria	Semi-Arid	PET, PMV	ENVI-met (PMV) RayMan (PET)	Infrared Thermometer
31	(Acero and Herranz-Pascual, 2015)	Bilbao, Spain	Oceanic	PET	ENVI-met	Global Thermometer
32	(Irmak and Yılmaz, 2015)	Erzurum, Turkey	Humid Continental	PET	RayMan	N/D
33	(Lobaccaro and Acer 2015)	Bilbao, Spain	Oceanic	PET	N/D	ENVI-met
34	(Niu et al., 2015)	Hong Kong, China	Humid Subtropical	PET	RayMan	Globe Thermometer
35	(Taleghani et al., 201	Netherlands	Temperate	PET	RayMan	ENVI-met
36	(Martinelli et al., 201	Rome, Italy	Mediterranean	PET	RayMan	N/D
37	(Wang et al., 2016)	Groningen, Netherlands	Mild Maritime	PET	RayMan	Globe Thermometer
38	(Achour-Younsi and Kharrat, 2016)	Tunis, Tunisia	Mediterranean Subtropical	UTCI	N/D	ENVI-met
39	(Elnabawi et al., 201	Cairo, Egypt	Hot Desert	PET	RayMan	Globe Temperature
40	(Hirashima et al., 2016)	Belo, Brazil	Tropical	PET	N/D	Globe Thermometer
41	(Li et al., 2016)	Guangzhou, China	Humid Subtropical	PET	RayMan	Pyranometer & Globe Temperature
42	(Liu et al., 2016)	Changsha, China	Humid Subtropical	PET	RayMan	Globe Temperature
43	(Maleki and Mahdavi 2016)	Vienna, Austria	Oceanic	PET	ENVI-met	N/D
44	(Middel et al., 2016)	Tempe, Arizona	Semi-Arid	PET	RayMan	Globe Temperature
45	(Perkins and Debbage 2016)	Phoenix, Arizona & Atlanta, Georgia	Hot Desert & Humid Subtropical	PET	RayMan	Sky Cover
46	(Salata et al., 2016a)	Rome, Italy	Mediterranean	PET	RayMan	Pyranometer & Globe Temperature
47	(Salata et al., 2016b)	Rome, Italy	Mediterranean	PMV	ENVI-met	ENVI-met
48	(Zhao et al., 2016)	Guangzhou, China	Subtropical	SET	N/D	Globe Thermometer
49	(Barakat et al., 2017)	Alexandria, Egypt	Hot Arid	PMV	ENVI-met	ENVI-met
50	(Du et al., 2017)	Hong Kong, China	Hot Humid	PET	RayMan	Pyranometer & Pyrgeometer
51	(Irmak et al., 2017)	Erzurum, Turkey	Humid Continental	PET	RayMan	RayMan
52	(Kruger et al., 2017)	Curutuba, Brazil Rio de Janeiro, Brazil & Glasgow, UK	Subtropical, Tropical, & Oceanic	PET	RayMan	Globe Thermometer & Pyranometer
53	(Cheung and Jim, 2018a)	Hong Kong, China	Hot Humid	PET, UTCI	RayMan (PET) Bioklima (UTCI)	Globe Thermometer
54	(Cheung and Jim, 2018b)	Hong Kong, China	Hot Humid	PET, UTCI	RayMan (PET) Bioklima (UTCI)	Globe Thermometer
55	(Gherraz et al., 2018)	Ouargla, Algeria	Hot Desert	PMV, PET, SET	RayMan	RayMan
56	(Sodoudi et al., 2018)	Berlin, Germany	Oceanic	PET	RayMan	ENVI-met
57	(Lee et al., 2018)	London, Canada	Humid Continental	COMFA	N/D	N/D
58	(Johansson et al., 201	Guayaquil, Ecuador	Warm Humid	PET, SET	N/D	Globe Thermometer
59	(Zare et al., 2018)	Kerman, Iran	Arid	UTCI, SET, PET, PMV	Bioklima (UTCI) RayMan (PET, SET, PMV)	N/D

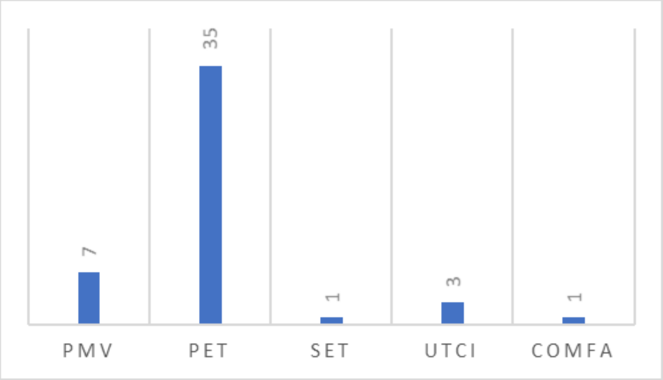

Fig. 8 Type of thermal indices used in the reviewed studied

The following bar chart (**Fig. 8**) created based on the reviewed case studies reveals that the PET is the most commonly used outdoor thermal comfort index in the hot humid region. The collected studies used the outdoor thermal comfort index for one of the following reasons: (1) validation the Index, (2) validate a simulation software, (3) difference between various urban areas, or urban morphology to generate design guidelines or measure influence of different mitigation techniques such as shade, vegetation, material, (4) to identify the influence of one or each climatic variable on outdoor thermal comfort, (5) define neutral temperature, preferred temperature, and acceptable range (calibrate the scale), (6) to view the influence of culture on people's thermal perception, and (7) the influence of an outdoor thermal comfort on the usage of a public space. Most studies used the PET to indicate the influence of design on outdoor thermal comfort or to adjust the scale as there is a need for adjusting proposed comfort/stress ranges of a given index when using it in different climatic contexts (**Fig. 9**) (Kruger et al., 2017).

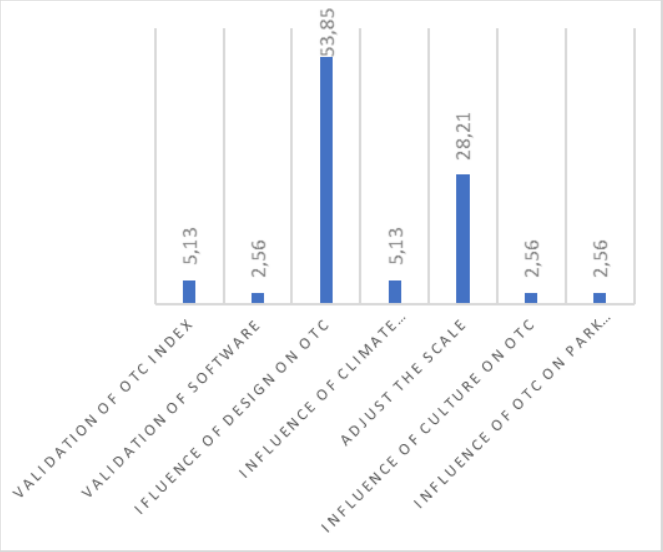

Fig. 9 The different aims for using the PET scale

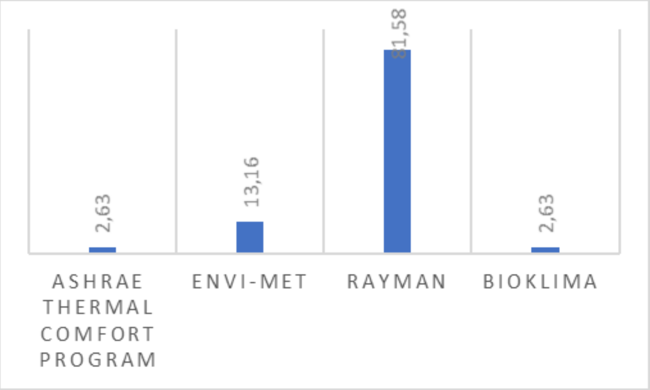

Fig. 10 Different Software and Tools to assess the OTC

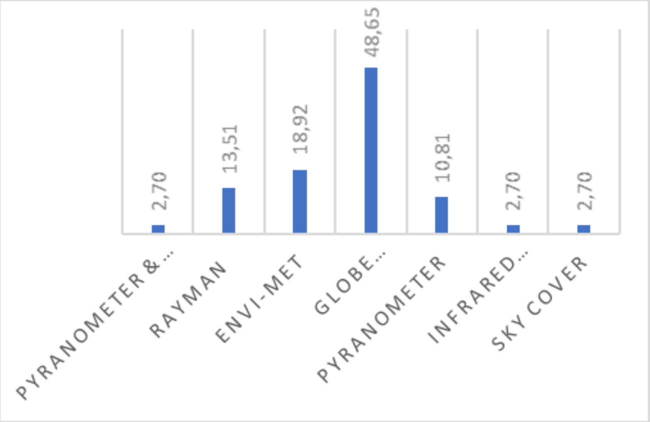

Fig. 11 Different Tools to assess the MRT

As for the tools or software used to calculate the outdoor thermal comfort (**Fig. 10**), few tools can assess either the outdoor thermal comfort or mean radiant temperature in this filed. However, the most common and comprehensive tools that can determine both outdoor thermal comfort and the mean radiant temperature are RayMan and Envi-met. As for the tools used to measure the mean radiant temperature on site (**Fig. 11**), the most common method is using a globe thermometer to measure the MRT using **Eq. 1**.

CONCLUSION

This paper discussed the significance of OTC on the success of designed open spaces. It showed the variables that take part in the model of thermal comfort. It also discussed the different thermal comfort approaches, including the most common OTC indices and the ranges of thermal perception of the most common outdoor thermal indices. For the assessment of thermal comfort in Hot Arid Zone, the PET index is the most used one. The required data for calculating the PET has been discussed, and the mean radiant temperature as the most complicated factor in assessing the OTC was discussed and can be measured by the globe temperature and using Equation 1. RayMan was identified as the choice of software for calculating the

PET index. It has been noted that outdoor thermal comfort (or discomfort) in urban open spaces is a complicated matter. However, empirical data from in-situ measurements on urban microclimate and the subjective human perception level in the outdoor context would provide a broader perspective regarding the thermal comfort of urban spaces.

Future work

The OTC at a selected case study from Effat Campus, Jeddah, Saudi Arabia, will be investigated using the PET, RayMan Software, and the Global Thermometer.

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