THE OPERATIONAL METAMATRIX OF THERMAL COMFORT FOR EUROPEAN AREAS, A GRAPHICAL METHODOLOGY FOR APPROPRIATE SELECTION OF OUTDOOR THERMAL COMFORT INDICES: APPLICATION TO AN URBAN PLANNING STUDY-CASE

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Abstract: In the current climate crisis, safeguarding citizens from thermal strokes without resorting to energy-intensive strategies is a crucial challenge for urban design. More than 200 calculation methods can be adopted to design thermally comfortable outdoor public spaces, but existing literature lacks selection criteria to choose appropriate ones. As resolution, an Operational Metamatrix of Thermal Comfort for European areas has been developed. It is a graphic chart that allows to compare the specificities of thermal comfort indices usable in Europe and that can be computed by available software, capable to simulate the urban climate. The Metamatrix has been applied on a European study-case, to find calculation methods to assess the citizen's thermal comfort in different configurations of the urban space during all seasons.

Keywords: Outdoor thermal comfort; Urban microclimate; Human-biometeorology; Urban planning.

Introduction

In the climate change scenarios, extreme meteorological occurrences, such as heat waves, will be ever-growing (https://meteofrance.fr/). A calibrated coexistence between artificial and natural environments is crucial for the amelioration of urban microclimates, to protect citizens from thermal strokes without resorting to energy-intensive strategies (Kumar & Sharma, 2020). To design thermally comfortable outdoor public spaces, more than 200 calculation methods can be adopted, but selection criteria to choose the appropriate ones is lacking in existing literature. Providing a scientific answer to this problematic is crucial for the development of operational studies, such as the ongoing ADEME's MODEVAL-URBA 2019 research project "MESH 2C" by Franck Boutté Consultants, whose aim is to develop methodologies for the generation and the rapid evaluation of urban morphologies, to optimize outdoor thermal comfort. To overcome this knowledge gap, within the framework of the "MESH 2C" project, an Operational Metamatrix of Thermal Comfort for European areas has been developed. The name has been chosen by adding the prefix "meta", meaning "comprehensive", to the noun "matrix", since the objective is to produce a graphic chart that allows to comprehend and compare the specificities of the most renowned thermal comfort indices, adapted for Europe, that can be computed by the available software capable to simulate the urban climate. This pull of indices has been identified after extensive literature review of the present state of the art of thermal comfort calculation methods and tools. In the following chapters, the list of the selected indices and the description of the methodology adopted for the creation of the Operational Metamatrix are provided. Consequently, the instructions for the use of the tool are presented, with an example of application. Finally, a conclusion highlights the key issues.

1. Methodology

1.1. Examined thermal comfort indices with literature references

As mentioned by Epstein & Moran, 2006, thermal comfort studies often emphasise the academic accuracy of the different methodologies, to the detriment of their practical use. The use of thermal comfort indices outside the academic field is related to the availability of tools that can conveniently calculate them. To promote thermal comfort verification in European urban planning, an Operational Metamatrix of Thermal Comfort was developed, which only includes adapted indices that can be calculated using dedicated software that can simulate the urban climate. The defined pool of indices is presented in Table 1:

Table 1. Thermal comfort indices considered in the current work.

Full title	Acronym	Main publication	Software for calculation
Actual Sensation Vote	ASV	Nikolopoulou & Lykoudis, 2006	Ladybug Tools
Modified Physiologically Equivalent Temperature	mPET	Chen & Matzarakis, 2014	Rayman
Net Effective Temperature	NET	Gregorczuz, 1968 (cited by Landsberg, 1972)	Ladybug Tools
New Perceived Temperature	PT**	Staiger et al., 2012	Rayman, UBIKLIM, PALM-4U, SkyHelios
Outdoor Standard Effective Temperature	Out_SET*	Pickup & de Dear, 1999	Ladybug Tools
Physiological Equivalent Temperature	PET	Höppe, 1999	Rayman, ENVI-met, UMEP-SOLWEIG, Ladybug Tools, PALM-4U, SkyHelios
Predicted Mean Vote	PMV	Fanger, 1970	Rayman, ENVI-met, Ladybug Tools
Predicted Percentage of Dissatisfied	PPD	Fanger, 1970	Rayman, ENVI-met, Ladybug Tools
Standard Effective Temperature	SET*	Gonzales et al., 1974	Rayman, ENVI-met, Ladybug Tools
Universal Thermal Climate Index	UTCI	Jendritzky et al., 2009	Rayman, ENVI-met, UMEP-SOLWEIG, Ladybug Tools, CityComfort+, SOLENE-microclimate, PALM-4U, SkyHelios

1.2. Categories and features for the construction of the Metamatrix of Thermal Comfort

The Operational Metamatrix of Thermal Comfort for European areas provides different categories, starting from "CLIMATIC FACTORS", which includes all major environmental parameters of thermal comfort: air temperature, mean radiant temperature, wind speed and relative humidity. Among the "PHYSICAL FACTORS" are gathered the physical characteristics of the person: metabolic heat production, clothing insulation, sweating and/or skin temperature, and body composition (referring to a multilayer representation of the human body). The category "METEOROLOGICAL CONDITIONS OF APPLICATION" analyses where the application of the index is suitable: hot / cold, humid / dry, highly ventilated / poorly ventilated. "SOLAR EXPOSURE" refers to the ability of the index to provide valuable results in direct exposure to solar radiation or in the lack of direct solar radiation. The "TYPE OF ENVIRONMENT" category describes the precision of the index in different areas, such as a natural landscape, an urban settlement, or an indoor space. The "TYPOLOGY

OF THE RESULT" describes the form of the result: equivalent temperature, which means that the index is expressed in a well-known temperature measurement unit (such as °C), or dimensionless value. Finally, the "USABILITY ISSUES" designate if the index is "suitable for application in human biometeorological studies" according to Staiger et al., 2019, while reporting the number of available software that can calculate it and if, among them, there is at least one that responds to the definition of "user-friendly tool to improve the urban microclimate" by Jänicke et al., 2021.

1.3. Interpretation of the graphics of the Metamatrix

To be able to describe each index comprehensively in regards with the categories identified in Chapter 1.2., each feature may present two graphic symbols: the cross (╳) specify the impossibility to take in account the selected parameter, while the filled circle (⬤) indicates that the feature is considered. In addition, the Metamatrix provide a hierarchisation through different size of the filled circle:

- The large circle indicates that the corresponding feature represents one of the main objectives, according to the declared aims of the index and to the emphasis given by the scientific literature.

- The mean circle states that the analysed feature is widely considered by the index (with no to minor limitations), but it doesn't take priority over other criteria.

- The small circle defines the presence of limits of validity with respect to the analysed feature or inaccuracies in the assessment detected by the scientific literature, bringing the reader's attention to caution.

The symbols corresponding to the features' evaluation have been assigned following the information provided by the scientific community, including the author's statements about their own indices and the feedbacks provided by other researchers after their practical application. This evaluation could be somehow subjective, hence the function of the Metamatrix as a decision aid tool, which doesn't replace the study of the selected indices. No direct assessment of all the classified indices has been performed. Moreover, editable inputs (marked with an "I") are explicitly identified, allowing the user to understand which parameters can be modified, to guide the choice of appropriate indices in relation to the objectives of the assessment.

2. Results

2.1. Operational Metamatrix of Thermal Comfort for European areas and recommendations for its application

The Operational Metamatrix of Thermal Comfort is displayed in Figure 1. It is intended to be an easily read-able graphic chart that allows to quickly compare strengths and weaknesses of thermal comfort calculation methods adoptable in European countries, with respect to pre-identified features.

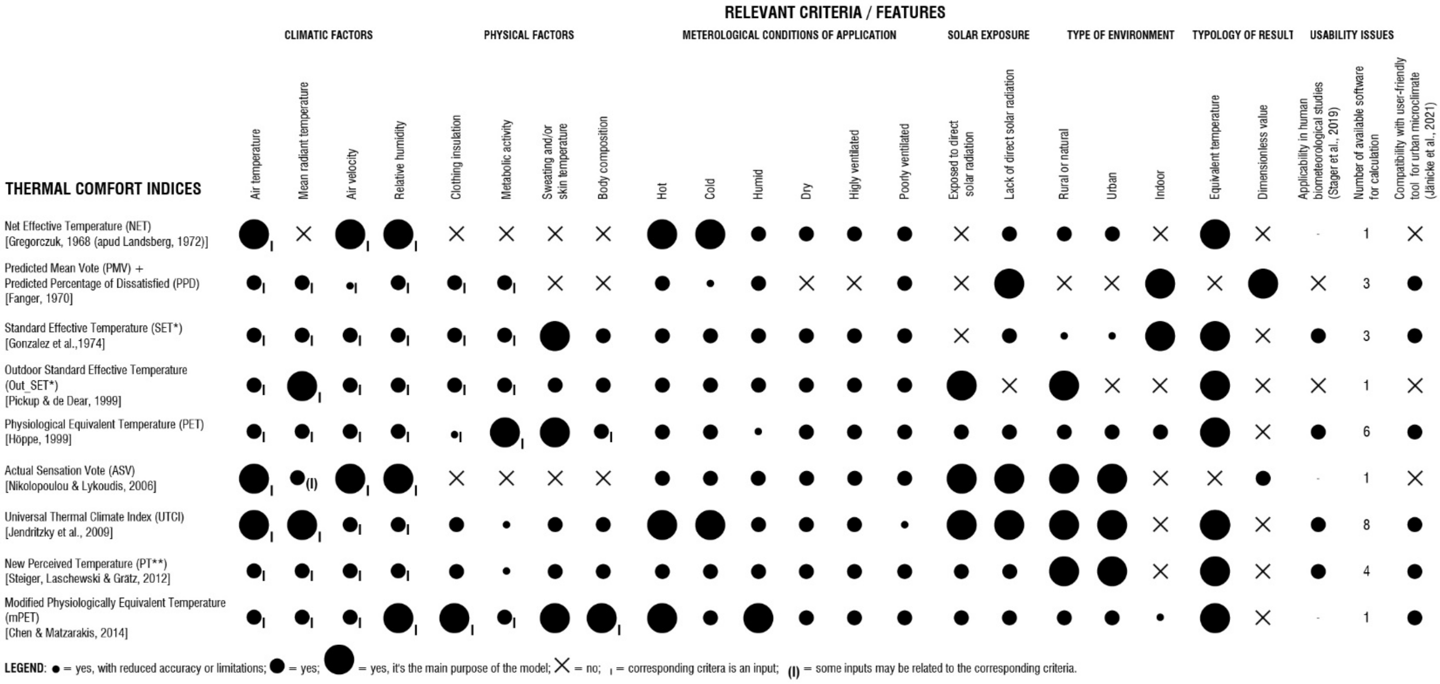

figure 1. Operational Metamatrix of Thermal Comfort for European areas.

For its application, it’s recommended to define the domains of interest at first, including only the key features that are needed for a project, to retain the indices that has no cross (✕), or at least the lesser number of them, in the identified domain. Nevertheless, a cross (✕) isn’t a necessarily a demerit: in fact, for conducting studies where few data are available (for example at the macro-scale), it is preferable to find an index that doesn’t consider the unknown variables in the thermal comfort assessment. If multiple indices will be retained after this operation, a further selection can be made by the user, consulting the original literature.

3. Study-case and discussion

3.1. Description of the requirements of the selected study-case

To better understand the application process of the Metamatrix, a study-case with the objective to analyse the link between human thermal perception and the configuration of the urban environment in Europe, both in summer and in winter, is provided. These conditions reflect the operational needs of the ongoing ADEME’s MODEVAL-URBA 2019 research project “MESH 2C” by Franck Boutté Consultants. The following selection criteria were considered:

- all the environmental factors must be integrated in the calculation methodology: air temperature, mean radiant temperature, wind speed and relative humidity;
- applicability of the index at any time of the day and of the year, which implies different seasons and situations with and without direct solar radiation;
- employability in urban areas;
- the index must be appropriate for applications in human biometeorological studies and computable with at least 3 Software.

Since this study-case has the aim is to investigate thermal comfort without focusing on pedestrian physical factors, whose variability can be very high due to the multiplicity of users in urban spaces, no specific conditions were imposed in this category. Other studies that might be interested, for example, in the impact of walking speed or clothing preferences on thermal comfort, will necessarily have to select criteria on personal parameters (which should be editable inputs). Similarly, no specific conditions were imposed on the type of the result, since its form isn't a discriminating factor for obtaining valuable assessments.

3.2. Application of the Metamatrix of Thermal Comfort and discussion

To select consistent comfort indices with the criteria listed in chapter 3.1, several domains of interest have been bordered on the Metamatrix by blue rectangles. The domains include all CLIMATIC FACTORS, all the features related to the METEROLOGICAL CONDITIONS OF APPLICATION and all the possibilities of SOLAR EXPOSURE. For the TYPE OF ENVIRONMENT category, only the urban area assessment is asked to provide a valuable result. Furthermore, a selection criterion in the category USABILITY ISSUES discards indices considered inappropriate to predict the human biometric response in thermal environments and retains only the ones that can be computed by at least 3 Software. An index can be considered applicable for the purposes of the previously described study-case if there are no crosses (✕) in the blue rectangles. Moreover, all climatic factors should be editable inputs in the calculation process.

In accordance with these selection criteria, all the thermal comfort calculation methodologies have been coloured according to the following legend:

- the red indices have been retained unsuitable for the proposed study-case and excluded;
- the green ones represent the final selection operated with the Metamatrix, meaning that they're all potentially applicable in the considered study-case.

The result of the application of the Operational Metamatrix of Thermal Comfort for European areas is showed in Figure 2.

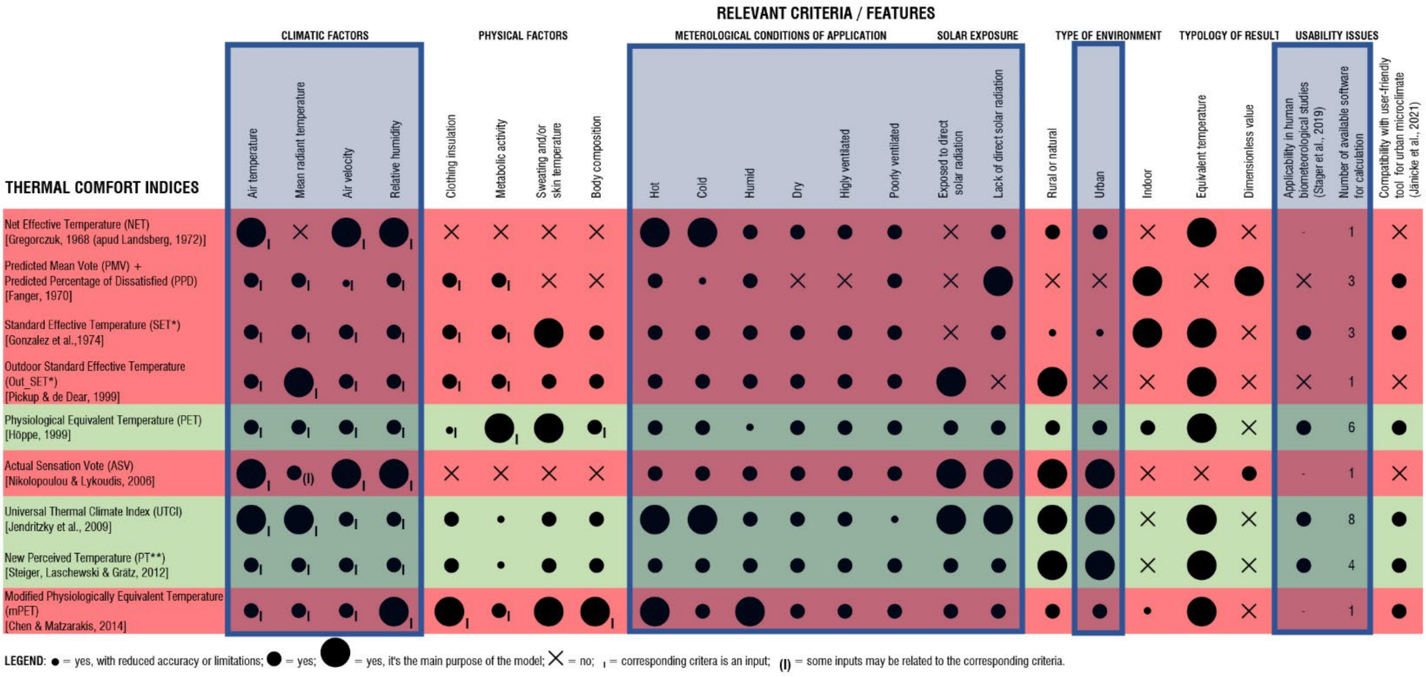

figure 2. Graphical representation of the methodology for indices selection using the Operational Metamatrix of Thermal Comfort for European areas, referring to the described study-case.

Only three indices have been selected in green, as potentially suitable for the study-case: Physiological Equivalent Temperature (PET); Universal Thermal Climate Index (UTCI); New Perceived Temperature (PT**). At present, the combination of these indices would allow to assess thermal comfort in each European urban area, consistently with the arbitrarily selected criteria for the described study-case. However, in future climate scenarios, where microclimatic situations that doesn't exist yet could emerge, the pertinence of these indices should be revalued, and new validity limits could be discovered.

According to Staiger et al., 2019, UTCI is the index that offers the highest level of detail with respect to the human body model, as well as the consideration of clothing insulation as a function of air temperature, to account for seasonal adaptability. In accordance with the current state of the art, UTCI has been selected as the most reliable thermal comfort index to study the variations in the citizens' thermal comfort in different configurations of the European urban space, both in summer and in winter.

Nevertheless, it should be kept in mind that UTCI has several validity limits in terms of air temperature (from -50 to +50 °C), mean radiant temperature (from -30 to +70 °C deviation from the value of air temperature), windspeed (from 0,5 to 17 m/s at 10 m from the reference ground), and water vapour pression (up to 50 hPa maximum vapour pression, within a relative humidity range from 5% to 100%) (Bröde et al., 2012; Jendritzky et al., 2009). For instance, areas with no wind, frequently encountered in case of dense urban fabric, must be investigated with other indices, such as PET or PT**. Given these premises, a range of various thermal comfort indices might be necessary to precisely assess the complexity of all the microclimatic ambiences within an operational project, to better respond to factors' local variability. This implies the evolution of most of existing software, that focus on few specific methodologies for thermal comfort assessment, by implementing the simulation of multiple indices in the same work session.

Conclusion

Outdoor thermal comfort is an essential aspect for sustainable urban development and citizen's safety in the ongoing climate change scenario. Studies to quantify thermal satisfaction produced more than 200 thermal comfort calculation procedures over the past 100 years. Although comprehensive reviews are provided, the existing literature lacks comparative criteria to choose appropriate ones. As resolution, the Operational Metamatrix of Thermal Comfort for European areas has been developed. This graphic chart compares 10 renowned thermal comfort indices, adapted for European climate, that can be computed by available software, capable to simulate the urban climate. Each index is qualitatively evaluated by more than 20 criteria (including physical and climatic factors, types of environments, solar exposures, meteorological conditions and so on), allowing to rapidly detect the thermal comfort calculation methods compatible to customized needs. A study-case has been described through the definition of several domains, for questioning the thermal comfort calculation procedures according to the selected features. The Metamatrix converged on the indices PET, UTCI and PT**. UTCI has been selected as the more appropriate index to respond to the described study-case, jointly with the application of PET or PT** for the microclimatic ambiances outside the UTCI validity domain. For a rigorous assessment of the various microclimatic ambiences coexisting in outdoor spaces, it's advisable to retain a pool of indices among the ones pre-selected by the Metamatrix. Their simultaneous application requires the evolution of most of available software, by implementing multiple simulations in the same work session.

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