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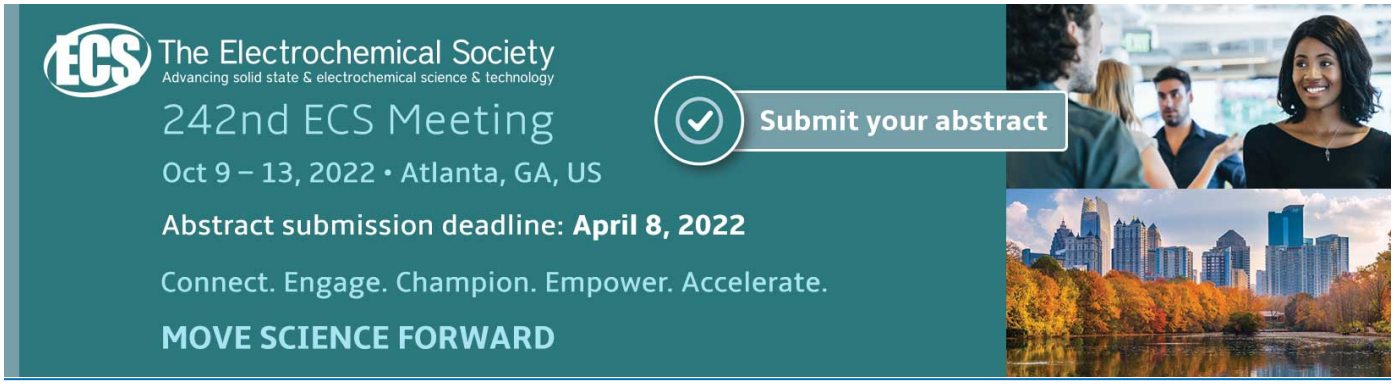

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Modelling mean radiant temperature in outdoor environments: contrasting the approaches of different simulation tools

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Abstract. Global warming and increasing urbanization are expected to threaten public health in cities, by increasing the heat stress perceived by the inhabitants. Outdoor thermal comfort conditions are influenced by the material and the geometric features of the surrounding urban fabric at both the urban and building scales. In built environments, performance-aware design choices related to street paving or building façade can enhance outdoor thermal comfort in their surroundings. Reliable estimations of outdoor thermal comfort conditions are required to evaluate and control the micro-bioclimatic influences of different design choices. The mean radiant temperature is the physical variable that has the greatest influence on outdoor thermal comfort conditions during summertime. Since its calculation is complex, the available simulation tools employ different approaches and assumptions to estimate it, and potential users need to be aware of their capabilities and simplifications. This research compares the calculation procedures and assumptions of different performance simulation tools (i.e. ENVI-met, TRNSYS, Ladybug/Honeybee, CitySim, and SOLENE-microclimat) to predict the mean radiant temperature in outdoor spaces, based on the available information in the scientific literature. Their ability to account for different radiative components in both the longwave and shortwave spectra is summarized, and practical information regarding the degree of interoperability with the modelling environments and the level of geometrical detail of the virtual model supported by the tools is provided. This work aims to help potential users in the selection of the most appropriate performance tool, based on the requirement of their projects.

1. Introduction

Under the challenges of increasing urbanization, population growth, urban heat island and climate change, the interest towards outdoor thermal comfort conditions in cities has increased [1]. The World Health Organization estimates that heat will cause more than 90,000 of additional deaths in 2030 and more than 250,000 in 2050, and that adaptation measures can reduce such impact [2]. The enhancement of outdoor thermal conditions in urban environments (e.g. street canyons, parks and squares) is crucial to promote the wellbeing of the population and increase the attractiveness of open spaces.

Human thermal perception in outdoor environments is influenced by the microclimatic conditions within the urban canopy layer, that are in turn affected by the morphological and material properties of the surrounding urban fabric. Since design decisions at the urban and building scales have long-lasting, cumulative implications on the liveability of outdoor spaces, performance-aware choices can enhance

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outdoor thermal comfort and help protecting public health. Simulation tools allow to test the effect of different geometric and material properties of design proposals on outdoor thermal comfort conditions, thus easing the inclusion of microclimatic criteria in decisions processes. Reliable estimations of outdoor thermal comfort are therefore essential to effectively orient design decisions. The mean radiant temperature (T_{mrt}) is the environmental parameter with the greatest impact over outdoor thermal comfort conditions during summer [3] and is required to calculate outdoor thermal comfort indices that describe human thermal perception. However, its estimation is difficult due to the complexity of urban fabric.

Nowadays several simulation tools can predict T_{mrt} in complex urban settings. These tools often simplify the thermal exchanges between the human body and the surrounding environment to different extents. While the understanding of the model assumptions is required for a correct interpretation of the simulation results, such simplifications are often not clearly stated by the developers [4,5]. This may lead to ineffective design solutions due an improper interpretation of the results, and cause difficulties for potential users in the selection of the most appropriate tool to analyze the specific design scenarios.

This article aims to shed some light on the calculation assumption used to estimate T_{mrt} by some of the most advanced simulation tools available, i.e. ENVI-met, Ladybug/Honeybee, CitySim, TRNSYS and SOLENE-microclimat. It intends to evidence the extent to which the radiative exchanges between the human body and the surrounding environment are simplified by the tools, based on the available information on the T_{mrt} models. The article does not aim to perform a comprehensive comparison of the T_{mrt} models, but to provide practical information on their main model assumptions, on the tool licencing, on the interoperability with modelling programs, and on the supported calculation positions. The study aims to help potential users to select an appropriate tool to perform outdoor thermal comfort analyses in different design scenarios, and to ease the results interpretation in light of the capabilities of the tools.

1.1. Quick overview on the mean radiant temperature

The T_{mrt} is defined as "the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings" [6]. It includes both longwave and shortwave radiation exchanges, that are influenced by the geometric and radiative properties of the surrounding environment and of the human body. Such shortwave and longwave radiative exchanges consist of the components either reflected or emitted by the environmental surfaces and by the sky vault. An illustration of such components is presented in Figure 1.

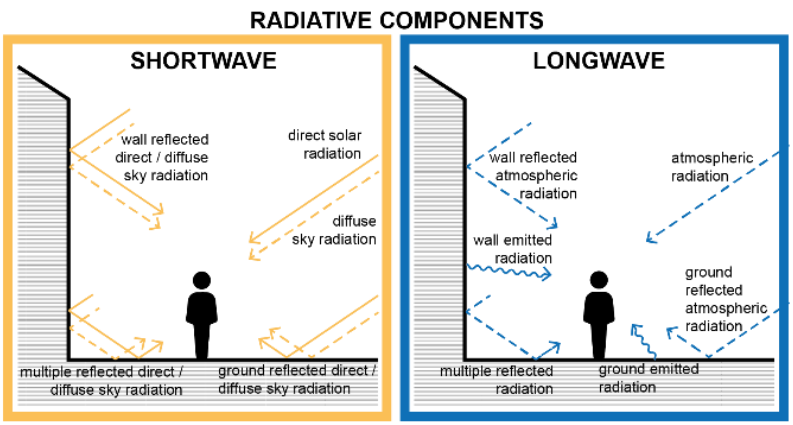

Figure 1. Illustration of the radiative components between the human body and the surrounding environment.

In an urban scenario (in absence of vegetation), the longwave radiative components are composed by the radiation a) emitted by the surfaces of the built environment (walls and ground); b) reflected by the surfaces of the built environment (walls and ground); c) the atmospheric radiation from the sky. The shortwave radiation components are: a) direct solar radiation from the sun; b) diffuse sky radiation, i.e. the radiation scattered by the atmosphere; c) direct and diffuse solar radiation reflected by the surfaces of the built environment (walls and ground). The longwave radiation emitted by the surfaces of the built

environment is estimated using the Stefan-Boltzmann law, based on the elements' emissivity and the surface temperature predicted by the simulation tool. Shortwave and longwave radiation reflected by the surrounding surfaces can be estimated from the incident radiation and the reflection coefficients of the surfaces. Direct and diffuse sky radiation, and atmospheric longwave radiation can be derived from weather data or calculated using different formulations [7]. The simulation scenario is detailed by the virtual model of the built environment, which often requires a certain degree of geometric simplification to be fed to the simulation tool. The view factors can be used to calculate the radiation exchanges between the human body and the surrounding surfaces; they quantify the fraction of radiation leaving a given surface (by emission or reflection) that strikes the human body; more information about view factors calculation can be found in [1,7,8]. The human body geometry is normally simplified to ease the view factors calculation [8]. A seated person can be approximated to a cube or a sphere, while a standing one by a cylinder, an oval cylinder or an octagonal prism [8]. To account for direct solar radiation, the projected area factors are often introduced to quantify the fraction of human body that is exposed to direct solar radiation based on solar azimuth and altitude, and human body posture (standing/seated).

T_{mrt} can be calculated from the mean radiative flux density absorbed by the human body S_{Str} [W/m^2] estimated from the shortwave and longwave flux densities and direct solar radiation, as follows [3]:

$$S_{Str} = a_l \cdot \sum_{i=1}^{n} F_i \cdot E_i + a_k \cdot \sum_{i=1}^{n} F_i \cdot D_i + a_k \cdot f_p \cdot I^* \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{1}$$

Where a_l and a_k are the absorption coefficients of the human body for longwave and shortwave radiation, respectively; F_i are the view factor between the i-th surface of the surrounding environment and the human body, E_i and D_i are respectively the longwave and shortwave flux density from the i-th surface; I* is the direct solar irradiance and f_p is the projected area factor of the human body.

T_{mrt} is defined as the temperature of fictive isothermal enclosure that behaves as a perfect black body emitter (ε=1) and cause the same amount of radiative exchange with the human body as the actual environment where it is located. Therefore, T_{mrt} [K] can be calculated as:

$$T_{mrt} = \sqrt[4]{\frac{S_{Str}}{\varepsilon_p \cdot \sigma}} \quad [\mathrm{K}] \tag{2}$$

where ε_p is the emissivity of the human body ($\varepsilon_p = a_l$ according to Kirchhoff's law) and σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \cdot 10^{-8}$ W/m^{2}K^4).

Several simulation tools can predict T_{mrt} in complex urban settings, that is often used to calculate outdoor thermal comfort indices (e.g. UTCI, PET). As T_{mrt} plays an essential role in the assessment of outdoor thermal comfort, its accurate estimation is crucial to run reliable analyses. The T_{mrt} models of by the different simulation tools apply various degrees of simplification to the radiative exchanges considered in the calculations, the geometric and radiative properties of the urban environment, and the geometry of the human body. As these diverse approaches may result in differences in the T_{mrt} predicted by the tools, the awareness of the calculation assumptions can ease a proper interpretation of the results.

This work briefly compares the T_{mrt} models of ENVI-met, Ladybug/Honeybee, CitySim, TRNSYS and SOLENE-microclimat. After a short presentation of the tools, where information on the licensing and level of integration with modelling programs is provided, this work details the approximations applied to the model of the built environment and the main assumptions of the T_{mrt} models, with a focus on the simplifications applied to the considered radiative components. Previous works have analysed some of the selected tools through validation studies with respect to measured data [4,9,10], or software inter-comparisons [5,11], often reporting noticeable differences among the predicted T_{mrt} values.

2. Method

The selected simulation tools are some of the most advanced programs currently available to estimate T_{mrt}; their main features have been summarized in Table 1.

Table 1. Summary of the main features of the selected tools.

	ENVI-met (no IVS)	Ladybug/ Honeybee	CitySim	TRNSYS	SOLENE-microclimat
License	commercial	free	commercial/ free	commercial	commercial
Tool type	Stand-alone	Complete integration	Stand-alone	Stand-alone	Stand-alone
Plug-ins to ease interoperability	Grasshopper plug-in	-	SketchUp + Grasshopper plug-ins	SketchUp plug-in	SketchUp plug-in

ENVI-met is a 3D microclimate model and is widely used to assess outdoor thermal comfort. It is a stand-alone program released under a commercial license. The virtual model needs to be created directly within the simulation environment; however, a recently released plug-in for Rhinoceros named Dragonfly can ease such step. Ladybug/Honeybee is a free and open-source plug-in for Grasshopper for Rhinoceros, built on top of several validated engines, (i.e. Radiance, EnergyPlus, OpenStudio, Therm and OpenFOAM). Its complete integration in Rhinoceros allows to couple modelling and simulation, and to visualize the results directly in the modelling environment, thus easing design optimization processes based on performance criteria. Moreover, the codes are available to the users, allowing for a certain degree of customization [12]. CitySim is free simulation model developer by the École Polytechnique Fédérale de Lausanne; CitySim Pro is its graphical user interface and is released under a commercial license. It is a stand-alone program with an extension for SketchUp and Grasshopper to ease the preparation of the virtual model. TRNSYS is a transient systems simulation program with a modular structure to calculate energy and climatic conditions of building environments, thermal and energy systems. It is a commercial stand-alone tool, with a SketchUp plugin named TRNSYS3D to ease the preparation and importation of the virtual model, and a Rhinoceros plugin named TRNLizard that enables to run the simulation and visualize the results in Rhinoceros. SOLENE-microclimat is a commercial tool for urban microclimate simulations developed at CERMA laboratory at the School of Architecture of Nantes. A SketchUp plugin eases the coupling with the modeling tools.

3. Analysis

In ENVI-met, the virtual model geometries are set according to a regular 3D grid, with the maximum resolution of 0.5 m. The calculation is performed for all the grid cells in the model domain and allows to collect results in different positions. Despite the widespread use of ENVI-met, no up-to-date information on the calculation model has been officially released by the developers: according to [4], the most recent description of the T_{mrt} model is given in the PhD dissertation by Huttner in 2012 [13]. The work in [4] has attempted to understand the calculation assumptions of the T_{mrt} model of ENVI-met v4.4.2 with respect to previous descriptions. It must be highlighted that the model description refers to the standard radiation model, i.e. without Indexed View Sphere (IVS), that is an optional and more advanced radiation model. According to [4,13], the model subdivides the 3D environment into an upper and a lower hemisphere, each accounting for 50% of the emitted or reflected radiation. As noted in [4], for the lower hemisphere only the ground emitted longwave radiation and ground reflected shortwave radiation are considered, while the upper one accounts for wall reflected longwave and shortwave radiation, diffuse sky and direct solar radiation, and atmospheric longwave radiation. As regards shortwave radiation, the model neglects the diffuse sky radiation reflected by walls and multiple reflections among urban surfaces, while it considers direct and diffuse sky radiation, ground reflected direct and diffuse radiation and wall reflected direct radiation [4]. Moreover, separate domain-wide mean albedo values are used to characterize walls and ground. As concerns longwave radiation, that emitted by the built environment is calculated considering domain-wide mean values of surface temperature and emissivity for ground and walls, separately [4]. Reflections of atmospheric longwave radiations are calculated for walls, while ground reflected and multiple reflected longwave radiation are neglected [4]. The use of domain-wide mean values hampers the ability of the tool to run site-specific evaluations with the standard radiation settings (i.e. without IVS), since the model neglects the distinct

properties of the surfaces surrounding the human body are not considered. Moreover, while the assumption applied to radiative fluxes accounted by the two hemispheres is considered reasonable for pedestrians' positions, it may result in errors at greater heights from the ground (e.g. in balconies).

Ladybug/Honeybee (legacy plug-ins) supports complex geometries and the calculation points are set according to a user-defined horizontal grid. T_{mrt} analyses can be performed through the Honeybee component named "Microclimatic Map Analysis" [12]. The radiation model used to calculated T_{mrt}, described in [12,14–17], is based on a solar adjusted T_{mrt}, where the longwave T_{mrt} is corrected with the contribution of solar radiation obtained from SolarCal model. Considering longwave radiation, the T_{mrt} model includes atmospheric longwave radiation and the radiation emitted by the built environment. Reflections of longwave radiation are neglected, and the surrounding surfaces are assumed as black-body emitters (ε=1). These assumptions may lead to errors when considering low emissivity materials, such as glazing and metal surfaces, that reflect longwave radiation. The SolarCal model [6,15] accounts for direct solar radiation, diffuse sky radiation and ground-reflected global radiation. Wall-reflected shortwave radiation is neglected, limiting the reliability of the predictions in urban scenarios where solar reflections by walls play a major role (e.g. high-albedo façade). Diffuse sky radiation and ground reflected solar radiation are assumed to be distributed respectively on the upper and lower halves of the radiatively exposed portion of human body. As noted for ENVI-met, this may reduce accuracy for calculation positions at greater heights from the ground. Moreover, the ground albedo is set by default at 0.2, but the value can be easily manipulated by the user in the script of the Grasshopper component.

CitySim, although primary developed to predict energy consumption of urban settlements at a district scale, has been used to calculate T_{mrt} in outdoor conditions in [5,18,19]. The tool can deal with complex geometries, although it can only recognize facade, roof, shading, surface, ground and floor elements; consequently, glazing cannot be modeled [20]. The calculation position can be defined by the user [19]. The radiation model included in CitySim is described in [21,22] and the T_{mrt} calculation is presented in the PhD thesis by Coccolo [19]. The longwave radiation considers the emissions from the built environment and atmospheric longwave radiation; reflections of longwave radiation are neglected by the model, which may result in errors when dealing with low-emissivity surfaces. The calculation of the shortwave radiation is based on the Simplified Radiosity Algorithm (SRA) [21,22], in which the surrounding environment is considered by modeling an upper and lower hemisphere, each discretized into patches of similar solid angles. The SRA accounts for direct, diffuse and reflected shortwave radiation, including multiple reflections among urban facets. Based on the calculation of the mean radiant flux densities S_{Str}, the T_{mrt} is determined according to Equation 2.

TRNSYS supports virtual models with complex geometries and allows users to freely set the position of the calculation points. The T_{mrt} model, described in [23,24], has been used to estimate T_{mrt} in outdoor settings in [11,24] by modelling a fictive enclosure where the sky is represented by the enclosure's roof, that is modeled as a window completely transparent to shortwave radiation whose surface temperature equals sky temperature. The T_{mrt} model includes direct, diffuse and multiple reflected shortwave radiation, as well as emitted and multiple reflected longwave radiation. The calculation of multiple reflections is performed using the Gebhart factors, that are calculated based on the view factors, the absorption coefficient of the receiving surfaces and the reflection coefficients of the surrounding ones. While not primarily developed for outdoor conditions, the radiative model includes all the shortwave and longwave radiation components from the surrounding environment, including multiple reflections.

The thermo-radiative model of SOLENE-microclimat enables the calculation of outdoor comfort conditions and can be used to estimate outdoor T_{mrt} [25]. The model is presented in [26] and an early description of the T_{mrt} calculation is detailed in [27], while no more recent descriptions of the T_{mrt} model were found in literature. The tool support virtual models with complex geometries and the calculation point positions can be defined by the user. As reported in [25,26], the model accounts for emitted and single reflections of longwave radiation from the surrounding surfaces; solar radiation accounts for direct radiation and diffuse sky radiation, and multiple reflections of solar radiation using radiosity method. The T_{mrt} is calculated from the shortwave and longwave radiation impinging on the surfaces of a cylinder-like prism representing the human body [25].

4. Results

While most of the selected tools are commercial stand-alone programs, they often offer a plug-in for common modeling environments, such as SketchUp and Rhinoceros, to ease the creation of the virtual model to be imported for simulation. A notable exception is Ladybug/Honeybee, that is a free and open-source program entirely integrated in Rhinoceros and allows to run the simulation and visualize the results directly in the modeling environment, thus greatly facilitating design optimization processes.

While all the tools support user-defined calculation positions, some of them, such as ENVI-met and Ladybug/Honeybee, are mainly intended to estimate T_{mrt} at the street level as they apply assumptions to radiation exchanges which are likely to lead to reasonably accurate results only at the street level.

The shortwave and longwave radiative components considered in the calculation procedure to estimate the T_{mrt} vary among the selected tools. Table 2 summarizes the radiative components considered by the selected tools based on the categorization of components illustrated in Figure 1. As it can be noticed, reflections of radiation are often simplified, either by using average or standard values, or only partially modeled (e.g. considering only radiation reflected by specific surfaces), or entirely neglected. These simplifications reduce the complexity of the radiative exchanges occurring in actual environments and can cut the computation time. However, they may lead to result inaccuracies, especially in scenarios where the neglected or simplified radiative exchanges play a relevant role. For instance, the application of high-albedo materials in dense urban settings would cause multiple reflections of solar radiation, which may or may not be accounted for depending on the tool's simplification. Similarly, low-emissivity materials, such as glazing and metal surfaces, result in reflections of longwave radiation, which are often simplified or neglected by the programs. Other simplifications are applied to the radiative properties of the surfaces of the environments, that may be simplified using average or standard values, or applying the black body assumption. These simplifications may result in significant errors depending on the characteristic of the scenario under analysis and limit the ability of the tools to reliably predict local T_{mrt}.

Table 2. Summary of the radiative components included in the Tmrt model of the selected tools. The symbol * evidences that a certain degree of simplification (detailed in the section 3) is applied to the component.

				ENVI-met (no IVS)	Ladybug/ Honeybee	CitySim	TRNSYS	SOLENE-microclimat
Shortwave	direct			✓	✓	✓	✓	✓
	diffuse sky			✓	✓	✓	✓	✓
	reflected	ground	direct	✓ *	✓ *	✓	✓	✓
			diffuse	✓ *	✓ *	✓	✓	✓
		building walls	direct	✓ *	×	✓	✓	✓
			diffuse	×	×	✓	✓	✓
	multiple reflections	direct		×	×	✓	✓	✓
		diffuse		×	×	✓	✓	✓
Longwave	atmospheric			✓	✓	✓	✓	✓
	emitted	ground		✓ *	✓	✓	✓	✓
		building walls		✓ *	✓	✓	✓	✓
	reflected	ground		×	×	×	✓	✓
		building walls		✓ *	×	×	✓	✓
	multiple reflections			×	×	×	✓	×

Some previous works have analyzed the differences in T_{mrt} simulated by the tools, by comparing the values among each other or with respect to measurements [4,5,9–11]. For instance, the study in [4] validates ENVI-met results (without IVS) against measurements with integral radiation measurement technique in Hungary, finding a Root Mean Square Errors (RMSE) of 6.92 °C. The same measurements were used in [9] to validate ENVI-met (with IVS) and Ladybug/Honeybee results, obtaining RMSE equal to 7.11 °C and 6.2 °C, respectively. In the attempt to improve the accuracy of the prediction of outdoor thermal comfort, T_{mrt} results obtained from TRNSYS are combined with the results of ENVI-met (without IVS) in [11]; the study also compares the T_{mrt} calculated by two tools, finding differences

up to 7°C and up to 26°C during daytime, depending on the presence of trees. The software intercomparison in [5] contrasts T_{mrt} results from CitySim, ENVI-met and Ladybug/Honeybee, finding marked discrepancies, especially during summer. However, it must be evidenced that conclusions on the accuracy of the T_{mrt} models can hardly be drawn as the mentioned studies analyze different urban and climatic scenarios, feature different simulation settings and tool versions, and field measurements exhibit different degrees of accuracy. Moreover, if T_{mrt} values are used to estimate outdoor thermal comfort indices, the sensitivity of the latter to T_{mrt} variation need to be considered to balance results accuracy with calculation time.

5. Conclusions and further development

This paper presents a brief overview of the T_{mrt} models implemented in ENVI-met, Ladybug/Honeybee, CitySim, TRNSYS and SOLENE-microclimat, evidencing the different degrees of simplification of the radiation exchanges included in the models and suggesting scenarios where they may potentially lead to incorrect estimations. Moreover, information on the level of interoperability between the simulation and modeling programs and on the support of user-defined calculation position is reported. The study aims to provide guidance to potential users in the selection of the most appropriate simulation tool and in the interpretation of the results in light of the calculation assumptions.

Most tools are commercial stand-alone programs with plug-ins to ease the interoperability with modeling environments. Some of the tools are mainly meant to assess T_{mrt} at the street level, as the applied calculation assumptions are only valid for pedestrians. The most common simplifications of the radiation exchanges in the T_{mrt} models are applied to reflected shortwave and longwave radiative exchanges, which are either simplified or neglected. Other simplifications relate to the use of mean or standard values to describe the radiative properties of the materials of the built environment. It should be noted that any information of the accuracy of predicted T_{mrt} cannot be directly inferred from the proposed comparison, nor by contrasting different validation or software-intercomparison studies. A greater understanding of the impact of the calculation assumptions on the accuracy of T_{mrt} models can be achieved by validating the simulated results against field measurements in different urban and climatic scenarios. To conclude, the present analysis can be extended by contrasting the calculation of view factors and the geometrical and radiative properties used by the tools to model human body. In addition, a more detailed description of the practical procedure according to which the proposed tools can be used to predict T_{mrt} may be presented.

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