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Developments and applications of thermal indices in urban structures by RayMan and SkyHelios model

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1. Introduction

The human body does not have any selective sensors for the perception of individual climatic parameters. It can therefore only feel the effect of all parameters together. The application of thermal indices gives detailed information on the effect of complex thermal environments on humans, especially in complex environments like urban areas. Based on the human energy balance, thermal indices can be derived, which describe the integral effect of climate on humans. All the thermal indices require the same meteorological input parameters: air temperature (T_a), air humidity (*RH*), wind speed (v), as well as the short and long wave radiation fluxes summarized as the mean radiant temperature (T_{mrt}). These input parameters show a temporal and spatial variability. Wind speed and mean radiant temperature show the highest variability and are modified strongly by surroundings and obstacles in complex urban areas (Matzarakis 2010, Ketterer and Matzarakis, 2014).

Data and information about the human biometeorological conditions in terms of frequencies (e.g. number of days or hours per year or season), as well as the quantification of temperature differences between different planning scenarios are relevant for application in urban planning and architecture (Ketterer and Matzarakis, 2014). The quantification of heat stress and its reduction by planning measures is a big challenge, especially in the light of climate change (Matzarakis, 2010, Matzarakis and Endler, 2010). Due to climate change, the mean air temperature is expected to increase and also heat waves are assumed to become more frequent, more intense and longer lasting (Schär et al., 2004). Thus, there is a demand for the assessment and quantification of adaptation measures improving the urban climate, i.e. street morphology or different types of vegetation (Herrmann and Matzarakis, 2011, Fröhlich and Matzarakis, 2013, Ketterer and Matzarakis, 2014). This approach is twofold: the analysis and description of single places for urban planning measures and the construction of maps for the detection of areas with frequent heat stress (Matzarakis, 2013, Matzarakis et al., 2008).

2. Methods and models

2.1 Thermal indices

The application of thermal indices based on the human energy balance gives detailed information on the effect of complex thermal environments on humans (Höppe, 1999). Commonly used thermal indices, based on the human energy balance, are Predicted Mean Vote *PMV* (Fanger 1972), Physiologically Equivalent Temperature *PET* (Mayer and Höppe, 1987, Höppe, 1999, Matzarakis et al., 1999), modified Physiologically Equivalent temperature mPET (Chen and Matzarakis, 2014), Standard Effective Temperature *SET** (Gagge et al.,1986), Perceived Temperature *PT* (Staiger et al., 2012) and Universal Thermal Climate Index *UTCI* (Jendritzky et al., 2012). These thermal indices require the same input parameters. Wind speed and mean radiant temperature have the highest variability as they are modified by surroundings and obstacles in complex urban areas the most.

The two most commonly applied thermal indices are *PET* and *UTCI* are presented here.

The Physiologically Equivalent Temperature is the equivalent temperature at a given place (outdoors or indoors) to the air temperature in a typical indoor setting for a human with core and skin temperatures equal to those under the conditions being assessed. Thereby, the heat balance of the human body with a work metabolism of 80 W (light activity, added to basic metabolism) and a heat resistance by clothing of 0.9 clo is maintained (Höppe, 1999).

The following assumptions are made for the indoor reference climate:

- mean radiant temperature equals air temperature ($T_{mrt} = T_a$).
- air velocity (wind speed) is fixed at $v = 0.1$ m/s.
- water vapor pressure is set to 12 hPa (approximately, equivalent to a relative humidity of 50 % at T_a = 20°C).

The procedure for the calculation of PET contains the following steps:

- calculation of the thermal conditions of the body based on the Munich Energy balance Model for Individuals (MEMI) for a given combination of meteorological parameters.
- insertion of the calculated values for mean skin temperature and core temperature into the model MEMI and computation of the energy balance equation system for T_a (with $v = 0.1$ m/s, $VP = 12$ hPa and $T_{mrt} = T_a$).

- the resulting air temperature is equivalent to *PET*.

PET has the advantage of a widely known unit (degrees Celsius) and the related assessment classes (Matzarakis and Mayer, 1996), which makes results more comprehensible to regional or urban planners, who are not necessarily familiar with modern human-biometeorological methods (Matzarakis et al., 1999).

The Universal Thermal Climate Index *UTCI* (Jendritzky et al., 2012) is defined as the air temperature of the reference condition causing the same model response as the actual condition. Thus, *UTCI* represents the air temperature, which would lead to the same thermal strain under reference conditions, as in the actual thermal environment. Both meteorological and non-meteorological (metabolic rate and thermal resistance of clothing) reference conditions were defined:

- wind speed of 0.5 m/s at 10 m above ground (approximately 0.3 m/s in 1.1 m),
- mean radiant temperature equal to air temperature,
- vapor pressure (*VP*) that represents a relative humidity of 50 %, at high air temperatures (> 29 ºC) the reference air humidity is defined as 20 hPa.
- representative activity to be that of a person walking with a speed of 4 km/h (1.1 m/s).

The adjustment of clothing insulation is a powerful behavioral response to changing atmospheric conditions. The conception behind *UTCI* was to consider seasonal clothing adaptation habits of Europeans based on available data from field surveys in order to obtain a realistic representation of this behavioral action.

The categorization of *UTCI* is based on physiological response of an organism at actual environmental conditions depending on the response for the reference conditions and thermal load (i.e. heat or cold stress). UTCI values between 18 and 26 °C may comply closely with the definition of the “thermal comfort zone” supplied in the Glossary of Terms for Thermal Physiology (2003) as: “The range of ambient temperatures, associated with specified mean radiant temperature, humidity, and air movement, within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period”.

The meteorological input parameters have to be measured or transferred to the average height of a standing person’s gravity center, 1.1 m above ground (VDI, 1998). These meteorological parameters can be measured or calculated by numerical models.

2.2 Point models - RayMan

The RayMan model is developed to calculate short wave and long wave radiation fluxes affecting the human body (Fig. 1). The model considers complex building structures and is suitable for the analysis of the effect of various planning scenarios in different micro to regional scales. The model calculates the mean radiant temperature, which is required for the human energy balance model and thus, for the assessment of human thermal bioclimate (Matzarakis et al., 2007, 2010). The thermal indices Predicted Mean Vote, Standard Effective Temperature, Physiologically Equivalent Temperature, Universal Thermal Climate Index and Perceived Temperature can be calculated.

In order to assess the influence of the surrounding environment, urban morphological information (topography, fish eye pictures and geometrical dimensions of obstacles (buildings and trees) (Fig. 3)) can be imported. In addition, information about urban structures (buildings, deciduous and coniferous trees) can be generated or imported (Fig. 2, right). For the estimation of the Sky View Factor (*SVF*), free drawing possibilities (natural or artificial) are included. Fish-eye photographs for the calculation of the *SVF* can be imported and processed (Fig. 2 left).

Based on the input possibilities, sunshine duration with or without *SVF*, estimation of the daily mean, max or sum of global radiation or shadows for existing or future complex environments can be calculated. For the estimation of thermal indices, meteorological data can be entered through manual input or by loading data files. The output is provided as graphs and text files. RayMan offers the possibility of importing long-term data sets of meteorological parameters long term analysis.

The most important question regarding radiation properties on the micro scale in the field of applied climatology and human-biometeorology, is whether or not an object of interest is shaded (Fig. 3 right). Hence, in the presented model, shading by artificial and natural obstacles is included. Horizon information (in particular the sky view factor) is required to obtain sun paths (Fig. 2 left). Additional features, which can be used for the evaluation of climate in a region or for diverse other applications are the calculation of sunshine duration with or without sky view factor, estimation of the daily mean, max or sum of global radiation and calculation of shadows for existing or future complex environments (Matzarakis et al., 2007, 2010). These can be also used for the assessment of questions in the field of renewable energy.

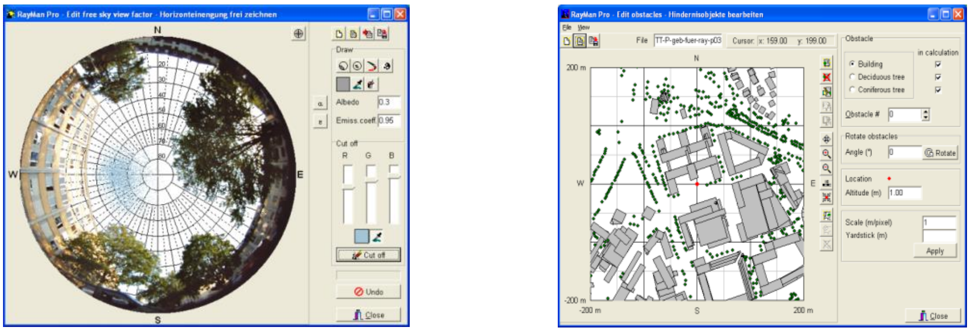

Fig. 1 Input possibilities in RayMan (left: fish-eye, right: geometrical obstacles.

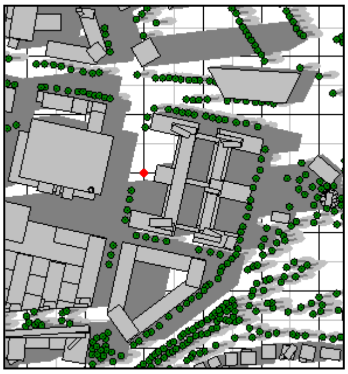

Fig. 2 Output possibilities of RayMan (left: polar diagram with sun path, right: shade based on obstacles)

Calculation of hourly, daily and monthly averages of sunshine duration, short wave and long wave radiation fluxes with and without topography or obstacles in urban structures can be carried out with RayMan. The output is given in form of graphs and text. RayMan provides the possibility of importing long term data sets of meteorological parameters and the calculation of thermal indices with or without considering urban morphology. A specific input window gives the opportunity to select the required and demanded parameters for the calculation. In addition, if radiation data is available from a nearby station or measurements which are not affected by any surroundings (very high sky view factor), RayMan provides the opportunity to transfer this data into complex environments. In addition, for detailed thermo-physiological approaches, the energy balance fluxes of the human body and body parameters, i.e. core and skin temperature, can be provided.
An advantage of RayMan is the user friendly environment and short running time. A disadvantage is the limitation to single points in space.

2.3 Spatial modeling - SkyHelios

For consideration of the spatial dimension of micro climate the SkyHelios model (Fig. 3) has been developed. SkyHelios can be applied for modeling climate conditions or climate-relevant parameters on the micro-scale with respect to complex morphologies (Matzarakis and Matuschek, 2011).

The following benefits are provided by SkyHelios: (a) short computing time and (b) low costs due to the use of open source frameworks (MOGRE, GDAL, spatialite, SQLite). Short computing time is reached by utilizing 3D graphics hardware to solve the complex calculations needed for 3D modeling. The main focus lies on providing a 3D model of the environment to the graphics engine, and making the engine visualize factors like SVF.

In order to run simulations of the continuous sky view factor, the calculation of the SVF for each point of a complex area has to be included. Therefore digital elevation models (*DEM*), data representing urban obstacles (OBS) or other file types can serve as input data in order to quantify relevant climatic conditions such as sunshine duration in urban and complex areas (Fig. 3). The newly developed annual sunshine duration diagram allows a estimation of the influence of topography and buildings on sunshine duration (Fig. 3) both on a yearly and diurnal scale in the spatial context (Fig. 3, top right). In addition, estimations of maximum global radiation for solar energy devices and other background information in micro-climatology are possible. A three-dimensional visualization of structures (input data) and states of the model area, e.g. shade, is provided. The simulations can be performed for different single points but also for the whole area. Fig. 4 shows the calculation of *SVF* for a specific place in the northern part of Freiburg. In this specific area the Meteorological Urban Station of the Albert-Ludwigs-University of Freiburg is located. In Fig. 4 the *SVF* for planar and spheric calculation (see Matzarakis and Matuschek, 2011) are illustrated. In addition, Fig. 5 shows the estimation of roughness length based on the approach by Bottema (1997) for different wind directions (a: 90°, b: 225°, c: 360°). It can be seen that the roughness is not the same for all wind directions. The calculation of roughness can be performed also with other morphological and geometrical approaches.

The further development includes the integration of a diagnostic wind field driven by measurements of wind speed and wind direction as well as estimation of the mean radiant temperature based on different approaches. Finally the calculation of thermal indices (*PET*, *UTCI*) based on all required parameters will be implemented. This implies that for future human thermal comfort studies the initial wind direction has to be available. It is also planned to provide the possibility of importing results from specific measurements or output from other models, which provide similar specific data and information.

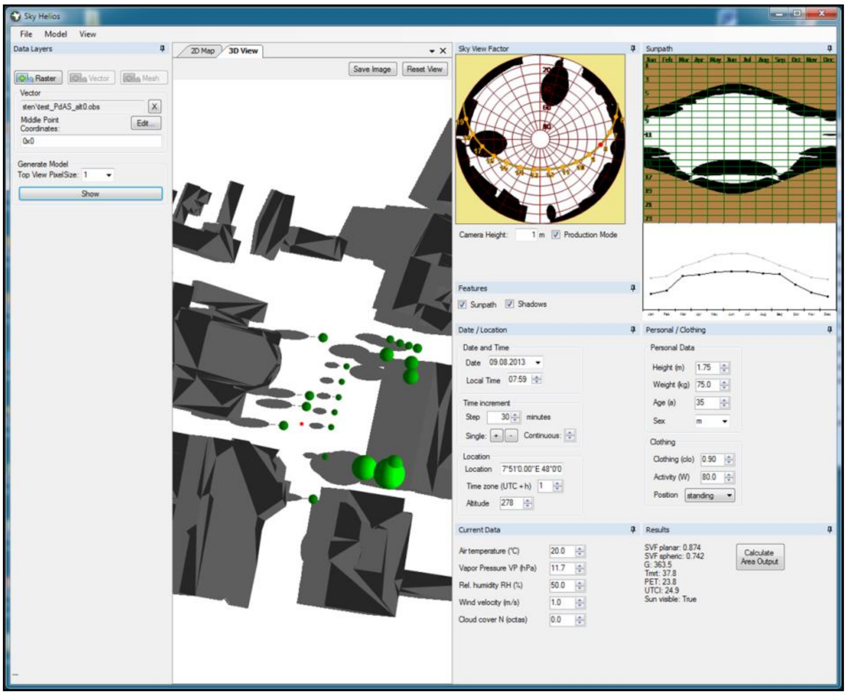

Fig. 3 Screenshot of the SkyHelios main window

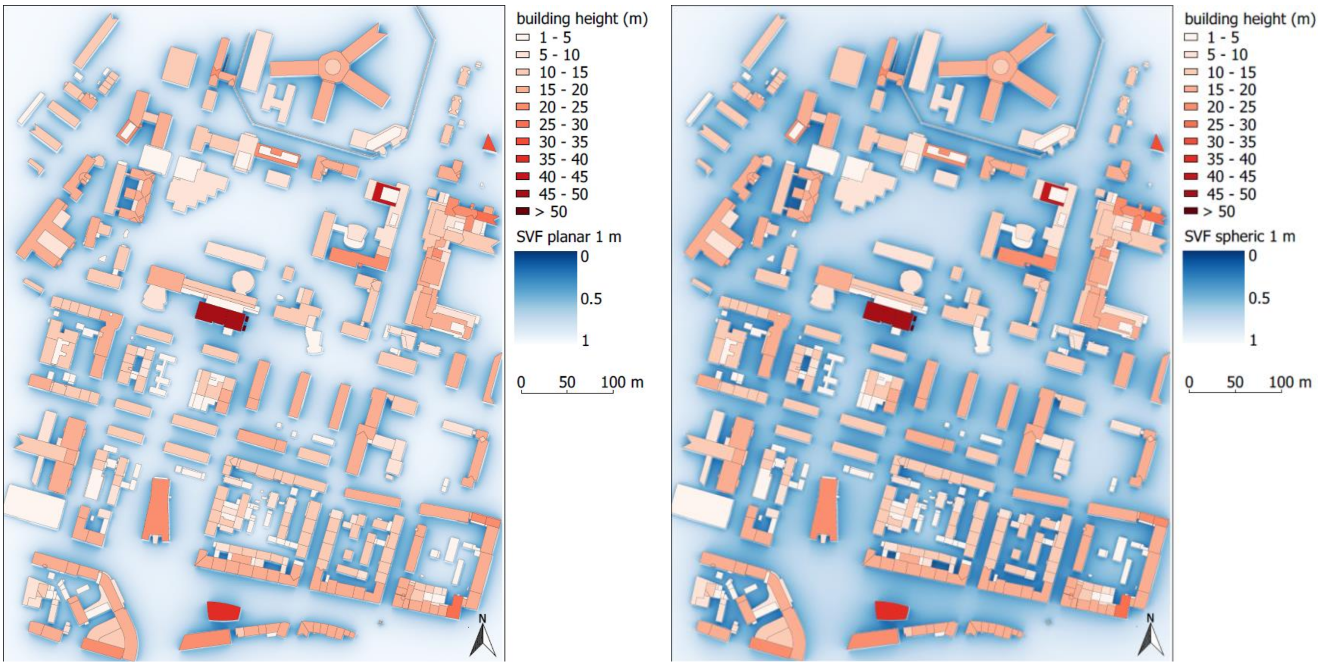

Fig. 4 Sky View factor for a part of Freiburg (Meteorological Urban Climate Station Freiburg is located on highest building, left: planar SVF, right: spheric SVF) with resolution 1x1 m at height of 1 m

2.4. Data exchange between micro scale models and data formats

One of the challenges in quantifying urban micro climate is the availability of data in an appropriate format. Frequently-used data formats (i.e. laser- or satellite based Digital Terrain Models (*DTM*)) are supported. Calculated data can be displayed with the Climate Mapping Tool (Matuschek and Matzarakis, 2011). The RayMan obs file format is implemented (Matzarakis et al., 2007), what is a further advantage and allows for a combination of the two models. SketchUp files provided by Google Earth can also be imported. The visualization of morphological factors (especially in urban areas) helps to understand micrometeorological processes. Both models include several options for the import and processing of data. Files generated for the use with one of the models can be also used in the other one. Fish-eye pictures of single points calculated by SkyHelios can be saved and imported into RayMan in order to calculate sunshine duration, radiation fluxes or thermal indices.

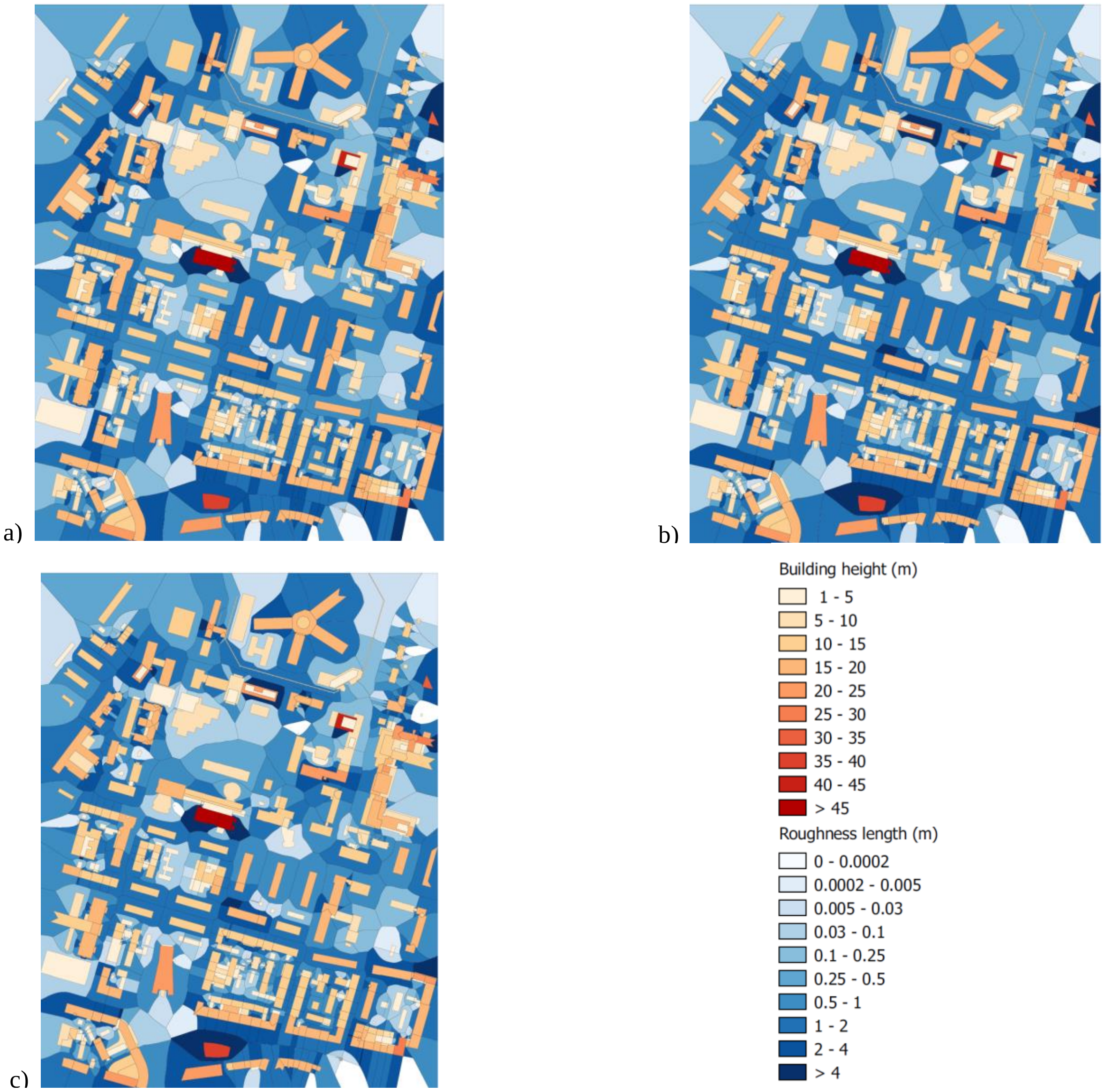

Fig. 5 Estimation of roughness after Bottema (1997) for different wind directions a) 90° b) 225° c) 360° for a specific area in the northern part of Freiburg (Meteorological Urban Climate Station Freiburg is located on highest building)

Micro scale models usually require a long running time, as they have to perform costly numerical approximations. Therefore, a specific area for the simulations can be selected on the screen. Calculations will be run only for this area but with consideration of the effects caused by the full area. In addition, parameters can be selected, which are computed and written in the output files. For visualization of influencing factors, sun paths or shade for the specific locations can displayed dynamically for different times. Time intervals can be defined for different simulations. For some purposes it is of importance to also calculate the vertical change of SVF and to analyze how this can be affected and produces micro scale effects.

The implementation of a micro scale wind field allows for the quantification of local wind conditions. Together with the spatial variability and intensity of short and long wave radiation fluxes they show the greatest influence on the pattern of thermal comfort in complex environments. The graphs and the calculated data can be saved and used for further processing (i.e., in RayMan or other GIS applications) (Hämmerle et al., 2011, Matzarakis et al., 2008, Matuschek and Matzarakis, 2011).

3. Conclusions

Micro-scale models provide diverse opportunities for research and analysis in urban climatological studies. Basic meteorological factors and parameters (wind conditions, radiation fluxes) and the thermal indices for simple and complex environments can be estimated.

Advantage of RayMan are the many possibilities of input data, starting with fish-eye pictures and obstacles file. Other advantages are additional outputs like shade and sunshine duration and the possibility to run long term data sets. Disadvantage is the limitation that the model cannot calculate air temperature, air humidity and calculate or adjust wind speed and also for micro scale is limited to single points. Advantages of SkyHelios are the fast running time for spatial calculations of global radiation, sunshine duration, shade, roughness, wind speed, sky view factors and the interface to RayMan and other models, as well as import possibility of GIS files and formats.

Useful information can be derived in more detail to create open spaces and green areas by urban planning and architectural measures with human thermal comfort in scope. It can also be used for several applications in the field of tourism and recreation. The possibility of combining the models together with the data exchange between the models allows for more detailed and flexible analysis.

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