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Short communication

Sharing knowledge via software components: Models on reference evapotranspiration

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Abstract

Evapotranspiration (ET) is a cross-platform software component containing routines to estimate daily and hourly values of reference evapotranspiration (and related variables) according to alternative approaches. A standardized form of the FAO-56 implementation of the Penman–Monteith equation is used to estimate daily and hourly evapotranspiration for two reference surfaces (namely clipped grass and alfalfa). Other methods (implementations of Priestley–Taylor and Hargreaves equations) estimate daily evapotranspiration from limited sets of inputs. A multi-layer canopy, similar to a well-developed tomato crop within standard greenhouse conditions, is taken as a reference to estimate hourly evapotranspiration in greenhouse environment (Stanghellini approach). The component is released as .NET (C#) version, allowing the development of clients under Windows operating systems. The component has an extensive hypertext help file. The component design allows users developing client applications to extend the functionalities by adding further options for estimating reference ET. Illustrative examples of clients developed in C# are provided as source code; the component is made available as compiled version. Also, the component was used to activate a web service and a web application based on such a service; the relevant C# code is provided as example.

Keywords: ET; Evapotranspiration; Modelling; Software component

1. Introduction

Estimation of reference evapotranspiration (ET_0) is needed to support irrigation design and scheduling, watershed hydrology studies, process-based crop growth models, and other models that attempt to simulate the soil water budget. ET_0 refers to the water removed from a unit ground area completely covered with a reference crop, healthy and unstressed and with ample water supply (Allen et al., 1998; Walter et al., 2002). Operational software tools in the domains specified above require the estimate of ET_0, and procedures to do that have been repeatedly implemented in software applications. This is one of the reasons why there is an increasing demand for modular approaches in model development (e.g., Jones et al., 2001; Donatelli et al., 2003a). Such a modular approach leads to the concept of encapsulating the solution of a modelling problem in a discrete, replaceable and interchangeable unit (Troya and Vallecillo, 2001; Jifeng et al., 2003; Donatelli et al., 2004b). However, the demand of modular agro-ecological models has not caused availability of the units mentioned, and there is no real example available to be used as a template.

Component-oriented development is a natural choice for building scalable, robust, large-scale applications, and to maximize the ease of maintenance (e.g., Löwy, 2003). A software component is an executable unit of independent production, acquisition and deployment that can be composed into a functioning system (Szypersky et al., 2002). Modularity and replaceability are typical features of these physical pieces of a system being built, that encapsulate implementation and expose a set of interfaces (e.g., http://www.sparxsystems.com.au). Since the year 2002 (Fila et al., 2002) software components for use in agronomy and agro-meteorology modelling have been developed at the Agriculture Research Council – Reasearch Institute for Industrial Crops (Donatelli et al., 2003b, 2004a; Fila et al., 2003), as a response both to the demand for modular approaches in model development, and to rationalize the internal process of development of software tools for modelling. Whether the appropriateness of the selection of biophysical modelling approaches is of utmost importance for the development of a component, the desired features of robustness, ease of use, transparency

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and extensibility pose some non-trivial problems in software design.

In this context, the objectives of the paper are:

- to present the features of the cross-platform component evapotranspiration (ET), designed to estimate reference evapotranspiration data and related variables for 1-h (mm h^{-1}) or 24-h (mm day^{-1}) time step, according to alternative approaches;
- to propose some software design traits to be used for developing components in agro-ecological modelling.

2. Background

ET_0 is calculated from alternative sets of inputs and for different canopies, conditions and time steps, using one-dimensional equations based on aerodynamic theory and energy balance (Table 1).

A brief description of the different models follows. Basic inputs and constituent equations are given in Tables 2 and 3 , respectively.

2.1. Penman–Monteith equation

The Penman–Monteith equation (Monteith, 1977) in the following form is used to estimate daily or hourly ET_0 for two reference surfaces:

$$ET_0 = \frac{1}{\lambda} \cdot \frac{s \cdot (R_n - G) + K_t \cdot \frac{VPD \cdot \rho \cdot C_p}{r_a}}{s + \gamma \cdot \left(1 + \frac{r_c}{r_a}\right)} \tag{1}$$

The constant K_t is a time unit conversion factor (86,400 s day^{-1} for ET_0 in mm day^{-1}; 3600 s h^{-1} for ET_0 in mm h^{-1}).

According to FAO Irrigation and Drainage Paper no. 56 (Allen et al., 1998), the reference surface is a 0.12-m height (short crop), cool-season extensive grass such as perennial fescue (*Festuca arundinacea* Schreb.) or ryegrass (*Lolium perenne* L.). A second reference surface, recommended by the American Society of Civil Engineers (Walter et al., 2002), is given by a crop with an approximate height of 0.50 m (tall crop), similar to alfalfa (*Medicago sativa* L.).

2.2. Priestley–Taylor equation

The Priestley–Taylor equation (Priestley and Taylor, 1972) is useful for the calculation of daily ET_0 for conditions where weather inputs for the aerodynamic term (relative humidity, wind speed) are unavailable. The aerodynamic term of Penman–Monteith equation is replaced by a dimensionless empirical multiplier (α: Priestley–Taylor coefficient):

$$ET_0 = \frac{1}{\lambda} \cdot s \cdot \frac{R_n - G}{s + \gamma} \cdot \alpha \tag{2}$$

An implementation of α from Steiner et al. (1991) is given, depending on the value of the vapour pressure deficit for each day.

2.3. Hargreaves equation

As an alternative when solar radiation data are missing, daily ET_0 can be estimated using the Hargreaves equation (Hargreaves and Samani, 1985; Hargreaves and Allen, 2003). An adjusted version of this equation, according to Allen et al. (1998) is given:

$$ET_0 = A + B \cdot \frac{1}{\lambda} \cdot 0.0023 \cdot \left(\frac{T_{max} + T_{min}}{2} + 17.8\right) \cdot \sqrt{T_{max} - T_{min}} \cdot R_a \tag{3}$$

The parameters A (intercept) and B (slope) are calibrated coefficients, to be determined on a monthly or yearly basis by regression analysis or visual fitting.

2.4. Stanghellini equation

Stanghellini (1987) revised the Penman–Monteith model to represent conditions in greenhouse, where air velocities are typically low (<1.0 m s^{-1}). A multi-layer canopy is considered to estimate hourly ET_0, using a well-developed tomato crop (*Lycopersicon esculentum* Mill.), grown in a single glass, Venlo-type greenhouse with hot-water pipe heating. The Stanghellini model includes calculations of the solar radiation heat flux derived from the empirical characteristics of short wave and long wave radiation absorption in a multi-layer canopy (Kirnak and Short, 2001; Prenger et al., 2002). The leaf area index (LAI, $m^2\,m^{-2}$) is used to account for energy exchange from multiple layers of leaves on greenhouse plants. The form of the equation is:

$$ET_0 = 2 \cdot LAI \cdot \frac{1}{\lambda} \cdot \frac{s \cdot (R_n - G) + K_t \cdot \frac{VPD \cdot \rho \cdot C_p}{r_R}}{s + \gamma \cdot \left(1 + \frac{r_c}{r_a}\right)} \tag{4}$$

The time unit conversion factor K_t is equal to 3600 s h^{-1}.

Table 1
Characteristics of alternative evapotranspiration models

Features	Evapotranspiration model			
	Penman–Monteith	Priestley–Taylor	Hargreaves	Stanghellini
Condition	Open field	Open field	Open field	Greenhouse
Reference crop	Clipped grass, alfalfa	–	–	Tomato
Time step	Daily, hourly	Daily	Daily	Hourly
Input	Air temperature, solar radiation, relative humidity, wind speed	Air temperature, solar radiation	Air temperature	Air temperature, solar radiation, relative humidity, wind speed

The constituent equations are in accordance with the standards of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 1993) and the American Society of Agricultural Engineers (ASAE Standards, 1998).

3. Software features and availability

3.1. Documentation

The procedures implemented in the component, the scientific background, and principles of usage are illustrated in a fully documented hypertext help file. Most of the ET_0 models and supporting equations have been extracted from peer-reviewed sources in which the most influential and widely adopted concepts concerning the estimate of evapotranspiration on a reference crop were presented. The relevant information was collected, interlinked and uniformly formatted into a navigable structure to grant easy access to readers. This outline of the literature review makes it possible to use the same sources in either a comprehensive or selective fashion to possibly re-implement the models.

3.2. Sample applications

An interface allows using the component via its public methods. Sample client–server applications are provided with the accompanying documentation as examples of possible use of the component. The examples are meant to illustrate the use of the component in C# (WinForm sample application). The component was also used to activate a sample web service (http://www.sipeaa.it/wset) for use in a sample web application (http://www.sipeaa.it/wfet), in order to show further options for the ET component use.

3.3. Extending ET models

The developer of a software application which uses the component ET may wish to make available to end users also one

Table 2
Input and output variables

Variable	Unit	ET_0 model[a]	Output
Input			
R_a, extra-terrestrial solar radiation	$MJ\,m^{-2}\,day^{-1}$, $MJ\,m^{-2}\,h^{-1}$	PM, PT, H, S	1, 2, 3, 4
R_s, ground-level solar radiation	$MJ\,m^{-2}\,day^{-1}$, $MJ\,m^{-2}\,h^{-1}$	PM, PT, S	1, 2, 3, 4
τ, clear-sky transmissivity	–	PM, PT	1, 2, 3, 4
z, elevation above see level	m	PM, S	1, 13
h, elevation above ground level	m	PM, S	1, 12
U_z, hourly or daily mean wind speed	$m\,s^{-1}$	PM, S	1, 12
T_{max}, daily maximum air temperature	°C	PM, PT, H, S	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 13
T_{min}, daily minimum air temperature	°C	PM, PT, H, S	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 13
T, hourly or daily mean air temperature	°C	PM, S	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 13
RH_{max}, daily maximum relative air humidity[b]	%	PM, S	1, 5, 8, 9
RH_{min}, daily minimum relative air humidity[b]	%	PM, S	1, 5, 8, 9
RH, hourly or daily mean relative air humidity	%	PM, S	1, 5, 8, 9
T_d, daily dew-point air temperature[c]	°C	PM, S	1, 5, 8, 9
PT_c, Priestley–Taylor constant	–	PT	1
a, aridity factor	kPa^{-1}	PT	1, 10
LAI, leaf area index	$m^2\,m^{-2}$	S	1
A, intercept of the Hargreaves equation	–	H	1
B, slope of the Hargreaves equation	–	H	1
Output			
ET_0, daily or hourly reference evapotranspiration	$mm\,day^{-1}$, $mm\,h^{-1}$	PM, PT, H, S	1
R_n, daily or hourly net radiation	$MJ\,m^{-2}\,day^{-1}$, $MJ\,m^{-2}\,h^{-1}$	PM, PT, S	2
R_{nl}, daily or hourly net long wave radiation	$MJ\,m^{-2}\,day^{-1}$, $MJ\,m^{-2}\,h^{-1}$	PM, PT	3
f_c, cloudiness factor	–	PM, PT	4
f_h, air humidity factor	–	PM, PT	5
λ, latent heat of vapourization	$MJ\,kg^{-1}$	PM, PT, H, S	6
$e_s(T)$, saturation vapour pressure	kPa	PM, S	7
e_a, actual vapour pressure	kPa	PM, S	8
VPD, daily or hourly vapour pressure deficit	kPa	PM, S	9
VPD_{max}, maximum vapour pressure deficit	kPa	PT	10
s, slope of the saturation vapour pressure curve	$kPa\,°C^{-1}$	PM, PT, S	11
r_a, aerodynamic resistance	$S\,m^{-1}$	PM, S	12
C_h, volumetric heat capacity[d]	$MJ\,m^{-3}\,°C^{-1}$	PM, S	13

For each input, the outputs calculated using that specific input are listed as ID outputs. Explanation of the outputs in Table 3.

[a] PM, Penman–Monteith (model); PT, Priestley–Taylor (model); H, Hargreaves (model); S, Stanghellini (model).

[b] If relative humidity values are null, daily dew-point temperature is used to estimate vapour pressure values with Penman–Monteith model.

[c] If T_d is null, then (Penman–Monteith model) $T_d = 0.38 \cdot T_{max} - 0.018 \cdot T_{max}^2 + 1.4 \cdot T_{min} - 5$ (Linacre, 1992).

[d] $C_h = \rho \cdot C_p$.

Table 3
Components of the ET_0 equations (inputs are specified in Table 2)

Variable	Unit	Reference evapotranspiration equation			
		Penman–Monteith	Priestley–Taylor	Hargreaves	Stanghellini
λ, latent heat of vapourization[a]	$\mathrm{MJ\,kg^{-1}}$	$\lambda = 2.501 - 0.002361 \cdot T$	$\lambda = 2.501 - 0.002361 \cdot T$	$\lambda = 2.501 - 0.002361 \cdot T$	$\lambda = 2.501 - 0.002361 \cdot T$
G, soil heat flux	$\mathrm{MJ\,m^2\,day^{-1}}$, $\mathrm{MJ\,m^2\,h^{-1}}$	Daily, $G = 0$ Daytime, $G = 0.1 \cdot R_n$ (short), $0.5 \cdot R_n$ (tall) Nighttime, $G = 0.04 \cdot R_n$ (short), $0.2 \cdot R_n$ (tall)	$G = 0$	–	$G = 0$
R_n, net radiation	$\mathrm{MJ\,m^2\,day^{-1}}$, $\mathrm{MJ\,m^2\,h^{-1}}$	$R_n = R_{ns} - R_{nl}$	$R_n = R_{ns} - R_{nl}$	–	$R_n = 0.07 \cdot R_{ns} - \dfrac{252 \cdot \rho \cdot C_p \cdot (T - T_0)}{r_R}$
R_{ns}, net short wave radiation	$\mathrm{MJ\,m^2\,day^{-1}}$, $\mathrm{MJ\,m^2\,h^{-1}}$	$R_{ns} = 0.77 \cdot R_s$	$R_{ns} = 0.77 \cdot R_s$	–	$R_{ns} = 0.77 \cdot R_s$
R_{nl}, net isothermal long wave radiation	$\mathrm{MJ\,m^2\,day^{-1}}$, $\mathrm{MJ\,m^2\,h^{-1}}$	$R_{nl} = f_c \cdot f_h \cdot \sigma \cdot f(T_K)$	$R_{nl} = f_c \cdot f_h \cdot \sigma \cdot f(T_K)$	–	–
σ, Stefan–Boltzmann constant	$\mathrm{MJ\,m^{-2}\,K^{-4}\,day^{-1}}$, $\mathrm{MJ\,m^{-2}\,K^{-4}\,h^{-1}}$	Daily, $\sigma = 4.903 \times 10^{-9}$ Hourly, $\sigma = 2.043 \times 10^{-10}$	$\sigma = 4.903 \times 10^{-9}$	–	–
$f(T_K)$, function of the absolute air temperature[a]	$\mathrm{K^4}$	$f(T_K) = (T + 273.16)^4$	$f(T_K) = (T + 273.16)^4$	–	–
C_p, specific heat of the air	$\mathrm{MJ\,kg^{-1}\,{}^\circ C^{-1}}$	$C_p = 0.001013$	$C_p = 0.001013$	–	$C_p = 0.001013$
ρ, mean atmospheric density[a]	$\mathrm{kg\,m^{-3}}$	$\rho = \dfrac{1000 \cdot P}{1.01 \cdot R \cdot (T + 273.16)}$	$\rho = \dfrac{1000 \cdot P}{1.01 \cdot R \cdot (T + 273.16)}$	–	$\rho = \dfrac{100000}{R \cdot (T + 273.16)}$
P, atmospheric pressure	kPa	$P = P_0 \cdot \left(\dfrac{T_{K0} - \eta \cdot z}{T_{K0}}\right)^{\frac{g}{\eta \cdot R}}$	$P = P_0 \cdot \left(\dfrac{T_{K0} - \eta \cdot z}{T_{K0}}\right)^{\frac{g}{\eta \cdot R}}$	–	–
R, specific gas constant	$\mathrm{J\,kg^{-1}\,K^{-1}}$	$R = 287$	$R = 287$	–	$R = 287$
P_0, atmospheric pressure at sea level	kPa	$P_0 = 103.1$	$P_0 = 103.1$	–	–
T_{K0}, reference absolute air temperature at sea level	K	$T_{K0} = 293.16$	$T_{K0} = 293.16$	–	–
η, lapse rate	$\mathrm{K\,m^{-1}}$	$\eta = 0.0065$	$\eta = 0.0065$	–	–
g, gravitational acceleration at sea level	$\mathrm{m\,s^{-2}}$	$g = 9.807$	$g = 9.807$	–	–
f_c, cloudiness factor	–	$f_c = 1.35 \cdot \dfrac{R_s}{R_{so}} - 0.35$	$f_c = 1.35 \cdot \dfrac{R_s}{R_{so}} - 0.35$	–	–
R_{so}, clear-sky solar radiation	$\mathrm{MJ\,m^{-2}\,day^{-1}}$, $\mathrm{MJ\,m^{-2}\,h^{-1}}$	$R_{so} = \max(R_s, \tau \cdot R_a)$	$R_{so} = \max(R_s, \tau \cdot R_a)$	–	–
f_h, air humidity factor	–	$f_h = 0.34 - 0.14 \cdot \sqrt{e_a}$	$f_h = 0.34 - 0.14 \cdot \sqrt{e_a}$	–	–

e_a, actual vapour pressure[a]	kPa	From relative air humidity Daily, $e_a = 0.5 \cdot \left[e_s(T_{\min}) \cdot \frac{\mathrm{RH}_{\max}}{100} + e_s(T_{\max}) \cdot \frac{\mathrm{RH}_{\min}}{100}\right]$ Hourly, $e_a = e_s \cdot \frac{\mathrm{RH}}{100}$ from dew-point air temperature, $e_a = 0.6108\,\mathrm{e}^{\frac{17.27 \cdot T_d}{T_d + 273.3}}$	–	–	$e_a = e_s \cdot \frac{\mathrm{RH}}{100}$
e_s, saturation vapour pressure[a]	kPa	Daily, $e_s = 0.5 \cdot [e_s(T_{\min}) + e_s(T_{\max})]$ Hourly, $e_s = 0.6108\,\mathrm{e}^{\frac{17.27 \cdot T}{T + 273.3}}$	–	–	$e_s = 6.894757\,\mathrm{e}^{f(R)}$
$f(R)$, function of air temperature	–	–	–	–	$f(R) = \frac{-10440}{T_R} - 11.29 - 0.02702 \cdot T_R + 1.289 \cdot 10^{-5} \cdot T_R^2 - 2.478 \cdot 10^{-9} \cdot T_R^3 + 6.546\,\ln(T_R)$
T_R, air temperature	°R	–	–	–	$T_R = 491.67 + 1.8 \cdot T$
T_0, leaf temperature	°C	–	–	–	Daytime, $T_0 = T + 1.67 \cdot R_s - 0.25 \cdot \frac{\mathrm{VPD}}{\gamma}$ Nighttime, $T_0 = T - 0.1 \cdot \frac{\mathrm{VPD}}{\gamma}$
s, slope of the saturation vapour pressure curve[a]	kPa $°\mathrm{C}^{-1}$	$s = 4098 \cdot \frac{0.6108\,\mathrm{e}^{\frac{17.27 \cdot T}{T + 237.3}}}{(T + 237.3)^2}$	$s = 4098 \cdot \frac{0.6108\,\mathrm{e}^{\frac{17.27 \cdot T}{T + 237.3}}}{(T + 237.3)^2}$	–	$s = 0.04145\,\mathrm{e}^{0.06088 \cdot T}$
VPD, vapour pressure deficit	kPa	$\mathrm{VPD} = e_s - e_a$	$\mathrm{VPD} = 0.475 \cdot \mathrm{VPD}_{\max}$	–	$\mathrm{VPD} = e_s - e_a$
$\mathrm{VPD}_{\max}$, daily maximum vapour pressure deficit	kPa	–	$\mathrm{VPD}_{\max} = \frac{e_s(T_{\max}) - e_s(T_{\max})}{1 - a \cdot (e_s(T_{\max}) - e_s(T_{\max}))}$	–	–
γ, psychrometric constant	kPa $°\mathrm{C}^{-1}$	$\gamma = \frac{C_p \cdot P}{\varepsilon \cdot \lambda}$	$\gamma = \frac{C_p \cdot P}{\varepsilon \cdot \lambda}$	–	$\gamma = \frac{C_p \cdot P}{\varepsilon \cdot \lambda}$
ε, water to dry molecular weight ratio	–	$\varepsilon = 0.622$	$\varepsilon = 0.622$	–	$\varepsilon = 0.622$
r_a, aerodynamic resistance	$\mathrm{s\,m^{-1}}$	$r_a = \frac{208}{U_2}$	–	–	$r_a = \frac{665}{1 + 0.54 \cdot U_2}$
r_c, canopy resistance	$\mathrm{s\,m^{-1}}$	Daily, $r_c = 70$ (short), 45 (tall) Daytime, $r_c = 50$ (short), 30 (tall) Nighttime, $r_c = 200$	–	–	Daytime, $r_c = 70$ Nighttime, $r_c = 200$
r_R, radiative resistance	$\mathrm{s\,m^{-1}}$	–	–	–	$r_R = \frac{\rho \cdot C_p}{4 \cdot \sigma \cdot (T + 273.15)^3}$
U_2, wind speed at 2-m height	$\mathrm{m\,s^{-1}}$	$U_2 = U_z \cdot \frac{4.87}{\ln(67.8 \cdot h - 5.42)}$	–	–	$U_2 = U_z \cdot \frac{4.87}{\ln(67.8 \cdot h - 5.42)}$
α, Priestley–Taylor coefficient	–	–	$\alpha = 1 + (PT_c - 1) \cdot \mathrm{VPD}$	–	–

[a] T (air temperature) and RH (air relative humidity) identify hourly or daily mean values, depending on the time step used; daily means are given as the average of daily maximum and minimum input values.

or more further approaches for estimating ET_0. This can be done easily taking advantage of the ET component architecture. Different ET_0 models can be implemented using the design pattern "strategy" (Mesketer, 2004). This software design allows encapsulating new models in the application using the ET component, without recompiling the component. A sample application is provided to show how to extend the ET component capabilities. "Design patterns" is a draft of a book chapter published online (http://www.sipeaa.it/tools/biophysical-components-chapter7.pdf), available both as an introduction to the design pattern "strategy" and as a tutorial about strategy-based implementations similar to the one used in this component.

3.4. The design-by-contract approach

The design-by-contract approach (Meyer, 1997) requires pre-conditions (in this case input values within a given range, and concurrent conditions, e.g., maximum air temperature > minimum air temperature) to be respected in order to obtain results complying with post-conditions (output values within a given range). Although respecting pre-conditions is a responsibility of the client application, the ET component implements some options to deal with input data violating pre-conditions, and to check post-conditions. If pre-conditions are violated, exceptions (i.e., errors) may occur. The ET component includes exception handling, both preventing the application from crashing, and providing the user with information about the type and location of the exception. Implementing the test of pre- and post-condition is not only a good programming practice, but in case of biophysical models forces developers to clearly state what are the numerical conditions which need to be respected in order to use the model correctly.

3.5. Availability

The component is freely distributed to non-profit users through the web site http://www.sipeaa.it/tools. The installation includes the compiled component, and the source code of sample applications.

4. Conclusive remarks

With the acceptance of the object oriented programming (OOP) paradigm, the development of reusable software has taken on a whole new dimension. OOP allows a more intuitive separation among data, models and interfaces. Learning the basics of OOP via the .NET platform now makes the development of high quality components easily accessible to modellers. Languages like C# associate a rigorous approach to ease of use, facilitating the development of reusable components. Although the level of reuse is still very low, this ability holds promise for modellers to increase quality through specialization and improved focus on problem solving by avoiding duplication of efforts. The component for the computation of reference evapotranspiration serves as a convenient means to support collaborative projects among scientists involved in creating applications for agronomy and agro-meteorology by assembling and customizing reusable components to develop an application. The documentation supplied, beyond its specific use in this component, has a value per se and can be considered as a way to share knowledge. Regardless the specific implementation presented, the software design adopted here contains what we consider key features (lack of dependencies, use of design patterns and implementation of the design-by-contract approach) for developing reliable software components encapsulating agro-ecological models.

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