URock uses the Röckle approach to calculate the 3D wind field of an urban environment. First, the wind field is initialized according to a priori knowledge. Second, the initialized wind flow is numerically balanced in order to make it physically relevant. The initialization is performed everywhere but near obstacles it is done according to empirical laws drawn from wind tunnel experiments. In URock, most of the schemes used for those zones are derived from the ones integrated in QUIC-URB: seven of them are building related (1) while two of them are vegetation related (2).

Table 1: Description of the seven building zones considered in URock

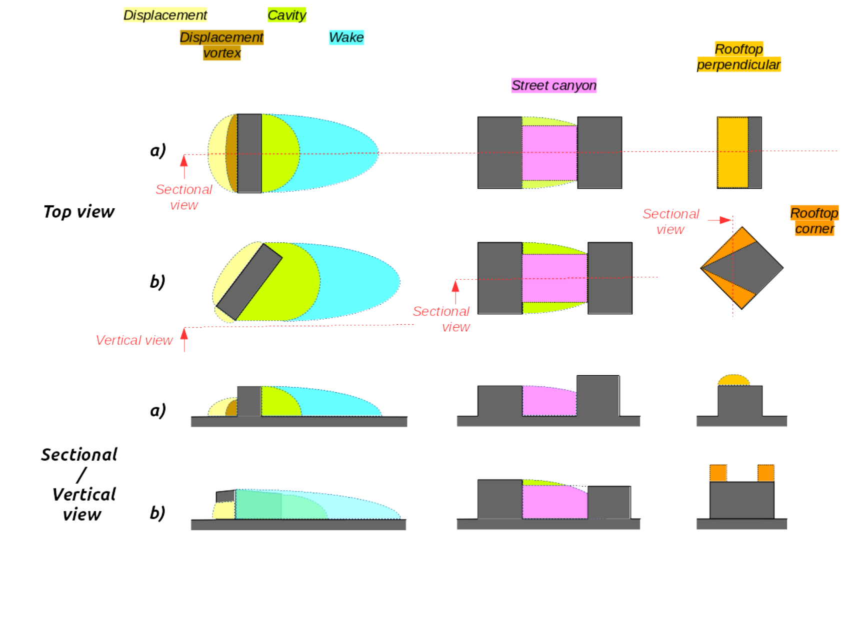
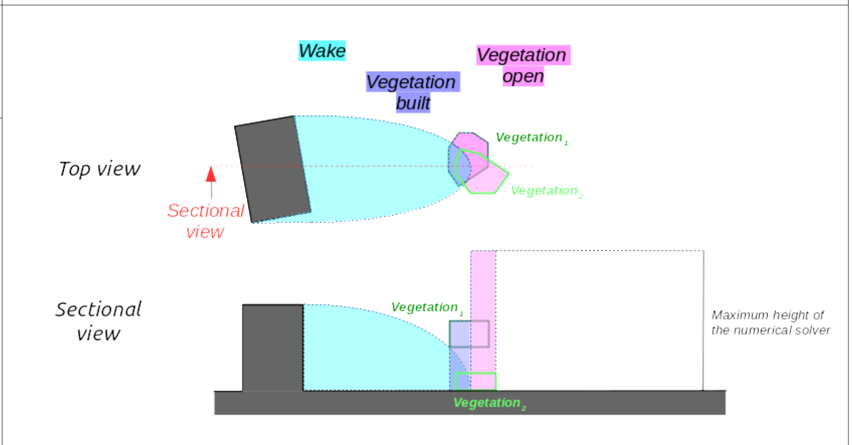
Name	**Location**	**Condition of creation**	**Illustration of the zones (wind coming from left)**
Displacement	Building front	None	
Displacement vortex	Building front	θ C [$-\theta_{perp}$, θ_{perp}]	
Cavity	Behind building	None	
Wake	Behind building	None	
Rooftop perpendicular	Above building	θ C [$-\theta_{perp}$, θ_{perp}] and if the building is not the downstream one of a street canyon with the lowest height	
Rooftop corner	Above building	θ C [$\theta_{corn\ min}$, $\theta_{corn\ min}$]	
Street canyon	Between buildings	Wherever the cavity zone of an upstream building intersects a downstream building	

Table 2: Description of the two vegetation zones considered in URock

Name	**Location**	**Condition of creation**	**Illustration (when wind comes from left)**
Vegetation built	Within and below vegetation	Wherever the vegetation footprint intersects a building wake zone footprint	
Vegetation open	Within, below and above vegetation	Wherever the vegetation footprint is not intersected by a building wake zone footprint	

Calculations are performed for a built zone defined by geographical data (building and vegetation footprint) and for static wind data (a given wind speed and direction at a specified height). The calculation of the 3D wind field is then performed in a four-steps approach (Figure 1):

I. The input geographical data is initialized into the format needed for the URock calculations,
II. All obstacles located within the model domain are considered as a whole to set a common vertical wind profile,
III. Each obstacle is considered individually to set the initial wind factor near buildings and near and within vegetation,
IV. The 3D wind speed components are initialized for each cell of the sketch and then used in the numerical solver to get the final balanced wind field.

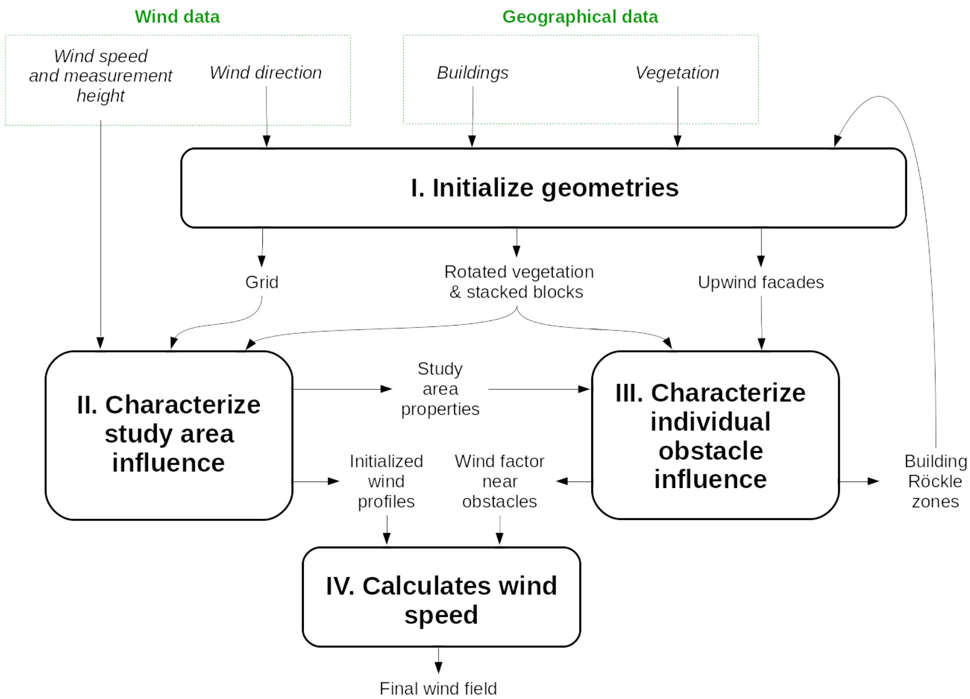


Figure 1: Overall methodology used by URock to calculate the 3D wind speed field

Further detail concerning each of this step can be found in the next subsections.

1 Initialize geometries

This step is dedicated to the transformation of standard input vector geometries into a format that will facilitates the wind speed initialization and also to create the grid used for numerical solving (Figure 2). First, individual buildings are converted to stacked blocks. Then the entire sketch (buildings and vegetation) is rotated to always have the wind coming from North. Last, a 3D grid of rectangular-based cells is created and the facades facing the wind are identified.

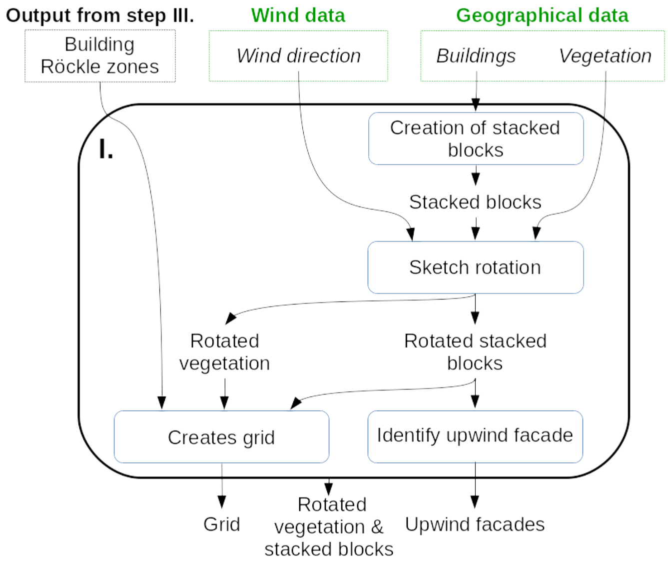
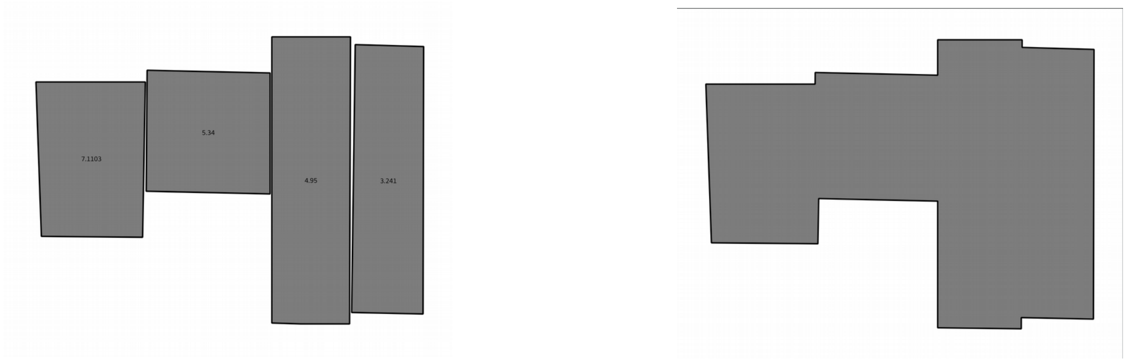


Figure 2: Processes used to initialize the URock geometries

1.1 Creation of stacked blocks

The size of a Röckle zone depends on the size of the obstacle. Thus a preliminary task is to merge buildings touching each other (or being within a *SNAPPING_TOLERANCE* to each other). This is solved by first creating a buffer around each building[1]. Then the footprints touching each other are spatially unioned (Figure 3).



(a) (b)

Figure 3: Top view of the (a) initial buildings and (b) resulting block after unioning

The building height may vary within a block which will also affect the Röckle zone size. Thus we round building height values and we create as many stacked blocks as there are isolated blocks of same height (Figure 4).

1 This is done using using the H2GIS ST_BUFFER function (http://www.h2gis.org/docs/dev/ST_Buffer/) with bufferSize = *SNAPPING_TOLERANCE* and bufferStyle='join=mitre'

Figure 4: Top view and sectional view of the resulting stacked blocks

Buildings may have an oversampled number of points, which could affect the size and the shape of some of the Röckle zones (which are for some of them created for each unique segments). Thus the geometry is simplified using the H2GIS ST_Simplify function[2] with distance = GEOMETRY_SIMPLIFICATION_DISTANCE (Figure 5).

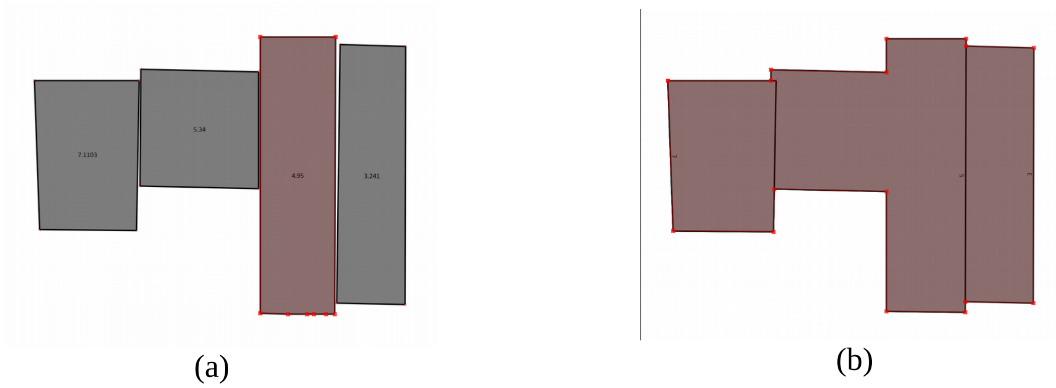


Figure 5: Simplification of the building geometries from (a) initial oversampled buildings to (b) final simplified stacked blocks

1.2 Sketch rotation

To simplify the calculations performed in the initialization step, we rotate all obstacles in order to have the wind coming downward (Figure 6). The rotation center is defined as the top right corner of the smallest bounding box containing all obstacles.

2 http://www.h2gis.org/docs/dev/ST_Simplify/

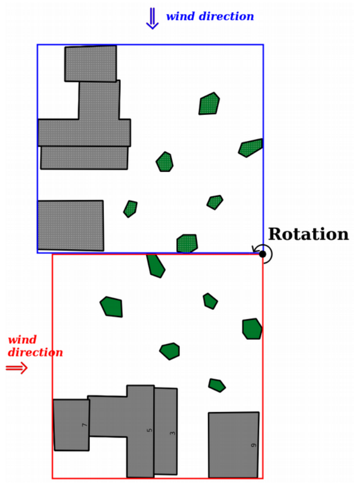


Figure 6: Rotation of the obstacles (in red bounding box) in order to have the wind coming downward (in blue bounding box)

1.3 Identify upwind facades

Each facade (segment) facing the wind is identified in order to apply the displacement zone scheme. This scheme affects the wind up to 60% of the facade height. Thus first we need to merge facades belonging to a same vertical plan in order to avoid unexpected displacement zone scheme (Figure 7a). Thus a facade from an upper stacked block is snapped to the facade of the lowest stacked block using the function ST_SNAP[3] with a snapTolerance = SNAPPING_TOLERANCE (Figure 7b). The facade base height H_{FBi+1} is then set to the base height of the facade used for the snapping (the lowest one).

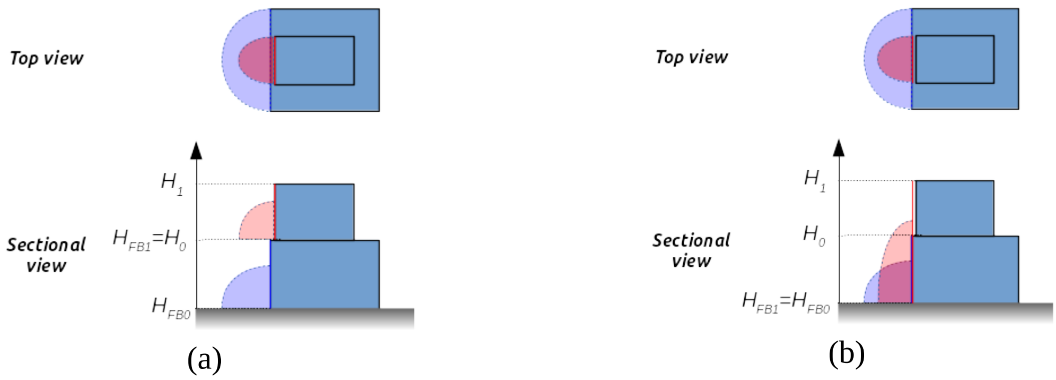


Figure 7: Facade base height and displacement zone of an upper stacked block if the facade is (a) outside or (b) within the snapping tolerance

1.4 Creates grid

The grid of rectangular-based cells is created according to a horizontal and a vertical resolution set by the user. The size of the grid is defined as an extend distance beyond built Röckle zones and vegetation boundaries. The user can define two horizontal extends (cross-wind zone extend and the along-wind zone extend) and a vertical extend (Figure 8).

3 http://www.h2gis.org/docs/dev/ST_Snap/

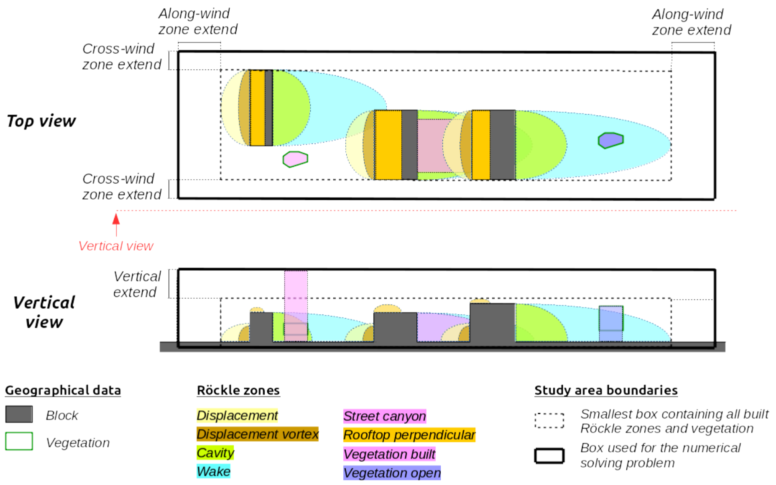


Figure 8: Vertical and horizontal extend of the grid away from Röckle zones boundaries when the wind comes from left

2 Characterize study area influence

The vertical wind profile is first initialized considering mean roughness properties of the study area (Figure 9). Thus the individual effect of each obstacles is not considered in this first approach but in the next section. This section is rather dedicated to characterize a mean global effect of several obstacles.

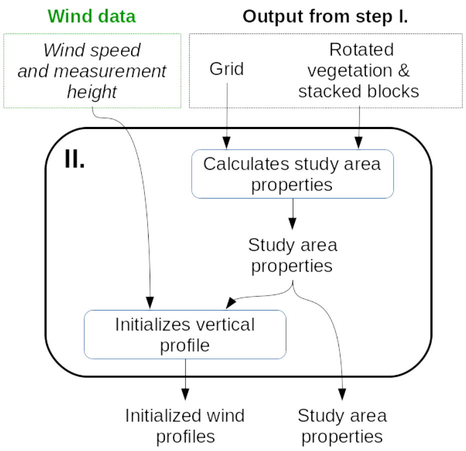


Figure 9: Processes used to characterize the study area influence

2.1 Calculates study area properties

The roughness height (z_0) and displacement length (d) are both calculated as a unique value characterizing the entire study area. The method described by Hanna et Britter (2002) is used. First the normalized frontal area (λ_f) is calculated as the ratio between the projected frontal area of obstacle facing the wind (A_f) and the area of the smallest rectangle containing all buildings and vegetation (A_T). Then z_0 and d are calculating based on the geometric mean obstacle height (H_r) and the λ_f value. Note that the equations differ upon λ_f values (3).

Table 3: Displacement length and roughness height equations depending on the normalized frontal area value

Condition	**Displacement length d (m)**	**Roughness height z_0 (m)**
$\lambda_f <= 0.05$	$d = 3 \cdot \lambda_f \cdot H_r$	$z_0 = \lambda_f \cdot H_r$
$0.05 <= \lambda_f < 0.15$	$d = 0.15 + 5.5 \cdot (\lambda_f - 0.05)$	$z_0 = \lambda_f \cdot H_r$
$0.15 <= \lambda_f < 1$	$d = 0.7 + 0.35 \cdot (\lambda_f - 0.15)$	$z_0 = 0.15 \cdot H_r$
$1 <= \lambda_f$	$d = 1$	$z_0 = 0.15 \cdot H_r$

Note that Hanna et Britter specified that these relations are valid for an upper H_r limit of about 20 m, thus it may lead to higher error if applied to neighborhoods such as skyscrapers.

2.2 Initializes vertical profile

The vertical wind speed profile ($V_p(z)$) is set according to the power-law equation proposed by Kuttler (2000) and used in QUIC-URB (Pardyjak et Brown, 2003) where the exponent equation comes from Matzarakis et al. (2009):

$$V_p(z) = V_{ref} \cdot (\frac{z}{z_{ref}})^{0.12 \cdot z_0 + 0.18}$$

where
$V_p(z)$ the wind speed profile along the y axis
z the height from ground
V_{ref} the reference wind speed along the y axis observed at the reference height z_{ref}
z_{ref} the reference height of V_{ref}
z_0 the roughness height

Note that z_0 being homogeneous over the entire study area, the vertical profile is also homogeneous.

3 Characterize individual obstacle influence

Obstacles locally altered the wind field: wind direction or / and wind speed may be modified within vegetation and around buildings. The Röckle approach is applied to set an initial wind factor to those locations using seven building schemes and two vegetation ones (Figure 10). First, stacked block properties are calculated. Then building and vegetation Röckle zones boundaries are identified and the wind factor corresponding to each zone is calculated. Last, some rules are set to keep only one wind factor value when two (or more) Röckle zones are superimposed.

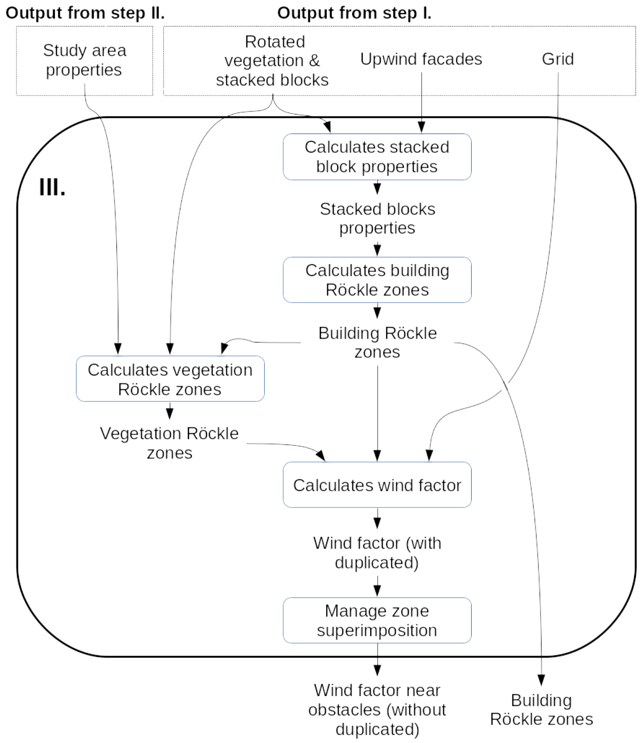


Figure 10: Processes used to characterize individual obstacle influence

3.1 Calculates stacked block properties

A vertical property: the cavity block base height

To each stacked block *i* is attributed the height of the roof (H_i) and also the height of its base (H_{Bi}). The cavity zone of a stacked block *i* may be erased by the cavity zone of the stacked block *i+1* located above (Figure 11). The base height of the cavity zone H_{CBi+1} of a stacked block *i+1* is calculated according to Equation XX (according to Brown et al. (2009)).

$$H_{CBi+1} = H_{Bi+1} - \frac{L_{i+1}}{L_i} \cdot (H_i - H_{Bi})$$

where

L_i and L_{i+1} the cross wind width of respectively stacked blocks *i* and *i+1*

H_{Bi} and H_{Bi+1} the base height of respectively stacked blocks *i* and *i+1*

H_i the top height of stacked block *i*

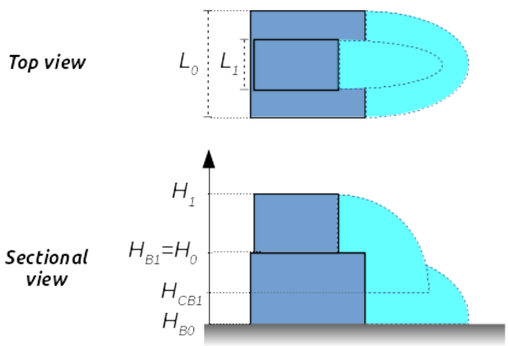


Figure 11: Cavity base zone extension for upper stacked blocks

Horizontal properties: the effective width and length

The effective width (cross-wind width - W_{eff}) and effective length (along wind length - L_{eff}) are of major importance to calculate the size of the "Röckle" zones. In the QUIC-URB software, Nelson et al. (2008) have modified the original algorithm to improve the accuracy of their estimated wind field (Figure 12).

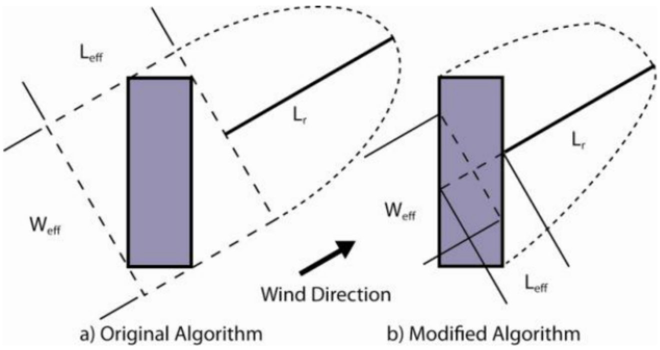


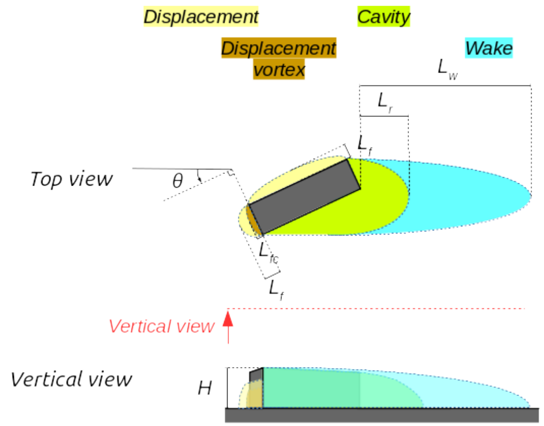
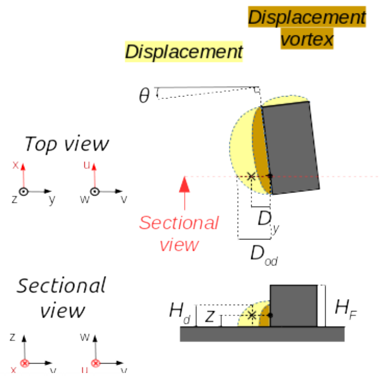
Figure 12: QUIC-URB algorithm to calculate the effective width and length before and after modification by Nelson et al. (2008) (Source: Nelson et al., 2008)

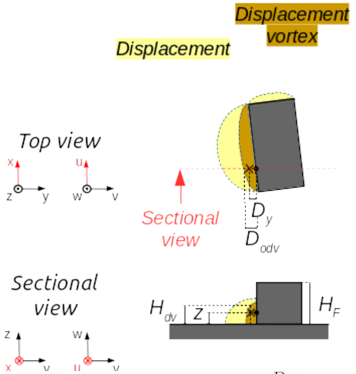
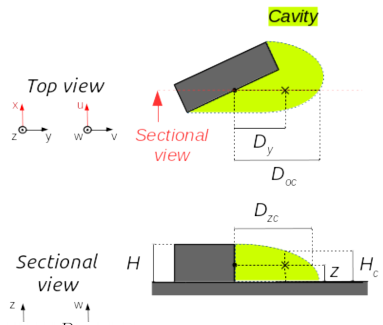
However, their modified algorithm only works for rectangular shape whereas our stacked blocks may have any shape. Thus the effective width and length are calculated using the original QUIC-URB algorithm (Figure 12a - bounding box width and length) but they are weighted by the ratio of stacked block area to bounding box area.

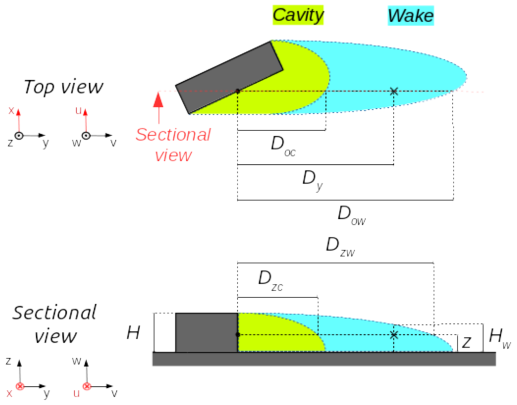
3.2 Identify Röckle zones and calculates corresponding wind factors

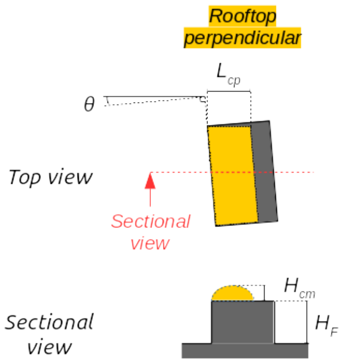
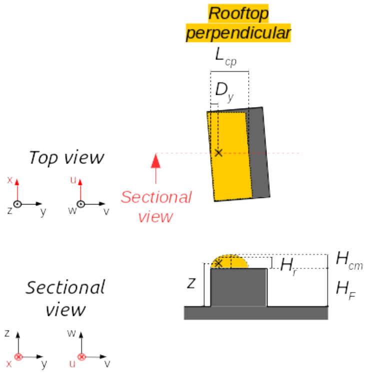
4 summarizes informations about each Röckle zone size (height, width, length) and the calculation of their initial wind speed factor. The wind speed factor is defined as the ratio between the wind speed after initialization (U_0, V_0, W_0) and the wind speed V_p calculated by the wind profile method (section 2.2). Note that the height of V_p taken as reference for calculation depends on the Röckle zone. More detail can be found about wind speed factor calculation in Annex XX.

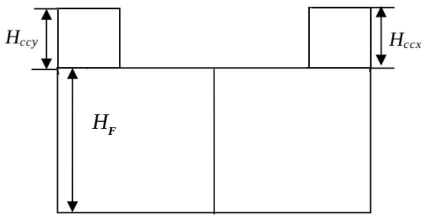
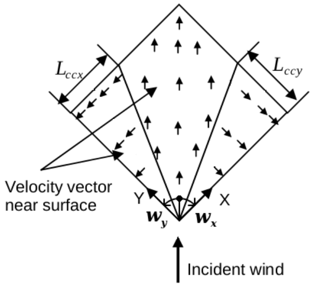
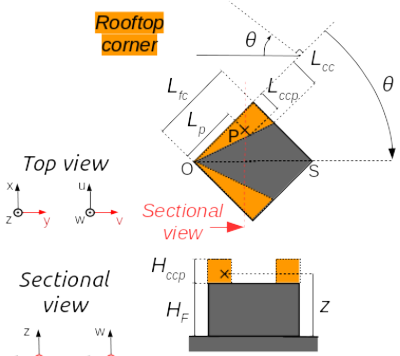
Table 4: Röckle zone sizes and wind speed Equations

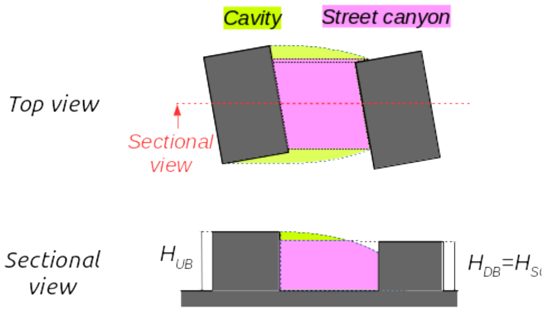
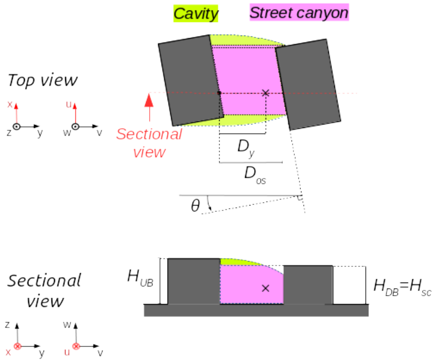
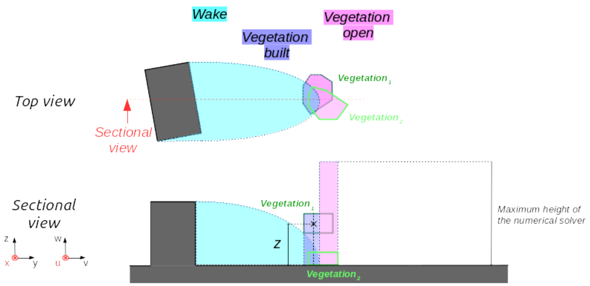
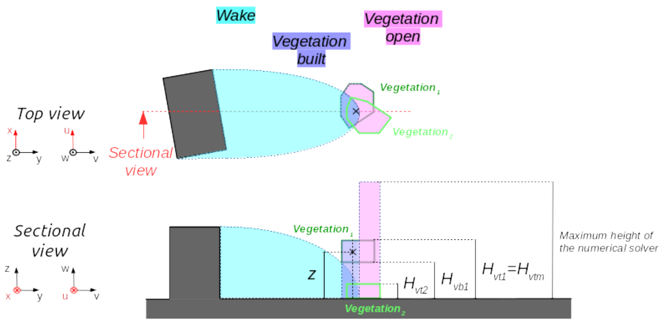
Zone name	**Zone size**	**3D wind speed equations**	**Example of wind field**
Displacement (adapted from Bagal et al., 2004)	 $L_f = 1.5 \cdot \frac{W_{eff}}{1 + 0.8 \cdot \frac{W_{eff}}{H_F})}$ where L_f displacement vortex length W_{eff} stacked block effective length H_F facade height	 $\frac{V_0(z)}{V_p(H_F)} = C_{dz} \cdot (\frac{z}{H_F})^p \cdot sin^2\Theta$ $\frac{U_0(z)}{V_p(H_F)} = C_{dz} \cdot (\frac{z}{H_F})^p \cdot \frac{sin(2 \cdot \Theta)}{2}$ if $z < H_d = 0.6 \cdot H_F \cdot \sqrt{(1 - \frac{D_y^2}{D_{od}^2})}$ where D_y distance to wall along y axis H_d ellipsoid height at the distance D_y $C_{dz} = 0.4$ p = 0.16 z level of the cell D_{od} length of ellipsoid along y axis at z = 0 m θ angle between wind direction and perpendicular to the building wall H_F building facade height	

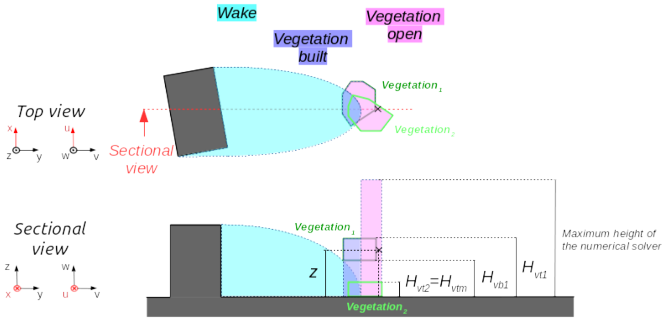
Zone name	**Zone size**	**3D wind speed equations**	**Example of wind field**
Displacement vortex (Bagal et al., 2004)	$L_{fv} = 0.6 \cdot \frac{W_{eff}}{1 + 0.8 \cdot \frac{W_{eff}}{H_F})}$ where L_{fv} displacement vortex length W_{eff} stacked block effective length H_F facade height	 $\frac{V_0(z)}{V_p(H_F)} = -[0.6 \cdot cos(\frac{\pi \cdot z}{0.5 \cdot H_F}) + 0.05] \cdot 0.6 \cdot sin(\frac{\pi \cdot D_y}{D_{odv}})$ $\frac{W_0(z)}{V_p(H_F)} = -[0.1 \cdot cos(\frac{\pi \cdot D_y}{D_{odv}}) + 0.05]$ if $z < H_{dv} = 0.5 \cdot H_F \cdot \sqrt{(1 - \frac{D_y^2}{D_{odv}^2})}$ where D_y distance to wall along y axis H_{dv} ellipsoid height at the distance D_y $C_{dz} = 0.4$ p = 0.16 z level of the cell D_{od} length of ellipsoid along y axis at z = 0 m θ angle between wind direction and perpendicular to the building wall H_F building facade height	
Cavity (Kaplan et al., 1996)	$L_r = 1.8 \cdot \frac{W_{eff}}{(\frac{L_{eff}}{H})^{0.3} \cdot (1 + 0.24 \cdot \frac{L_{eff}}{H}))}$ where L_r cavity length W_{eff} stacked block effective length H stacked block height	 $\frac{V_0(D_y, z)}{V_p(H)} = -(1 - \frac{D_y}{D_{oc}\sqrt{1 - \frac{z^2}{H^2}}})^2$ if $z < H_c = H \cdot \sqrt{1 - \frac{D_y^2}{D_{oc}^2}}$ where D_y distance to wall along y axis H_c ellipsoid height at the distance D_y z level of the cell D_{oc} length of ellipsoid along y axis at z = 0 m H stacked block height	

Zone name	**Zone size**	**3D wind speed equations**	**Example of wind field**
Wake (Kaplan et Dinar, 1996)	$L_w = 3 \cdot L_r$ where L_w cavity length L_r cavity length	 $\frac{V_0(D_y, z)}{V_p(z)} = -[1 - (\frac{D_{oc}}{D_y})^{1.5} \sqrt{1 - \frac{z^2}{H^2}}^{1.5}]$ if $z < H_w = H \cdot \sqrt{1 - \frac{D_y^2}{D_{ow}^2}}$ where D_y distance to wall along y axis H_w ellipsoid height at the distance D_y z level of the cell D_{ow} length of ellipsoid along y axis at z = 0 m H stacked block height	

Zone name	Zone size	3D wind speed equations	Example of wind field
Rooftop perpendicular (Pol et al., 2006)	 $L_c = 0.9 \cdot (0.67 * MIN(H_F, W_{eff}) + 0.33 \cdot MAX(H_F, W_{eff}))$ $H_{cm} = 0.22 \cdot (0.67 * MIN(H_F, W_{eff}) + 0.33 \cdot MAX(H_F, W_{eff}))$ where L_{cp} rooftop perpendicular length H_{cm} rooftop perpendicular height H_F facade height W_{eff} stacked block effective length	 $\frac{V_0(D_y, z)}{V_p(z_{ref})} = -(\frac{H + H_r - z}{z_{ref}})^p \cdot \lvert\frac{H + H_r - z}{H_r}\rvert$ if z > H and z < H + H_r where $H_r = H_{cm} \cdot \sqrt{1 - (\frac{D_y - \frac{L_{cp}}{2}}{L_{cp}})^2}$ p = 0.16 $V(z_{ref})$ wind speed at measurement height z_{ref} D_y distance to wall along y axis H_r ellipsoid height at the distance D_y H_{cm} maximum ellipsoid height L_{cp} rooftop perpendicular length z level of the cell H facade height	

Zone name	Zone size	3D wind speed equations	Example of wind field
Rooftop corner (adapted from Bagal et al., 2004 for the zone size calculation and from Pol et al., 2006 for the equations)	 Front View  Top View *Source: Adapted from Bagal et al. (2004)* $L_{ccx} = H_{ccx} = 2 \cdot X \cdot tan(2.94 \cdot e^{0.0297 \cdot w_X})$ where L_{ccx} (or L_{ccy}) rooftop zone length at a given distance X (or Y) of the incident facade corner (Figure XX) H_{ccx} (or H_{ccy}) rooftop zone height at a given distance X (or Y) of the incident facade corner (Figure XX)	 $\frac{U_0(D_y,z)}{V_p(z_{ref})} = -C1 \cdot (\frac{H+H_{ccp}-z}{z_{ref}})^p \cdot \lvert\frac{H+H_{ccp}-z}{H_{ccp}}\rvert \cdot sin(2 \cdot \Theta)$ $\frac{V_0(D_y,z)}{V_p(z_{ref})} = -C1 \cdot (\frac{H+H_{ccp}-z}{z_{ref}})^p \cdot \lvert\frac{H+H_{ccp}-z}{H_{ccp}}\rvert \cdot sin^2\Theta$ if $z > H$ and $z < H + H_{ccp}$ where $H_{ccp} = L_{ccp} = \frac{L_{cc} \cdot \sqrt{x_{L_p}^2 + y_{L_p}^2}}{L_{fc} \cdot cos(\Theta - \widehat{SOP})}$ $C1 = \frac{1 + 0.05 * W_{eff}}{H_F}$ *C1* wind speed factor H_F facade height W_{eff} stacked block effective length $V(z_{ref})$ wind speed at measurement height z_{ref} H_r ellipsoid height at the distance D_y H_{ccp} the H_{ccx} value for point p L_{ccp} the L_{ccx} value for point p L_{fc} the facade length L_{cc} the Lccx value at the end of the facade length x_{Lcp} and y_{Lcp} absolute coordinates of vector L_{ccp} z level of the cell θ angle between wind direction and perpendicular to the building wall SÔP the angle between points S, O and P	

Zone name	Zone size	3D wind speed equations	Example of wind field
Street canyon	 The street canyon zone is defined within two buildings wherever the upstream building cavity zone intersects the downstream building. The street canyon zone height (H_c) is defined by the lowest of the upstream building height (H_{UB}) and downstream building height (H_{DB}): $H_c = MIN(H_{DB}, H_{UB})$ *Singh et al. (2008)*	 $\frac{U_0(D_y)}{V_p(H_{UB})} = sin(2\cdot\Theta)\cdot[0.5+\frac{D_y\cdot(D_{os}-D_y)}{0.5\cdot D_{os}^2}]$ $\frac{V_0(D_y)}{V_p(H_{UB})} = sin^2\Theta - cos^2\Theta\cdot\frac{D_y\cdot(D_{os}-D_y)}{0.25\cdot D_{os}^2}]$ $\frac{W_0(D_y)}{V_p(H_{UB})} = -\vert 0.5\cdot(1-\frac{D_y}{0.5\cdot D_{os}})\vert\cdot(1-\frac{D_{os}}{0.5\cdot D_{os}})$ if $z < H_{sc}$ where θ angle between wind direction and perpendicular to the downwind building wall D_y distance along y axis from the upstream building wall D_{os} distance between the upstream and the downwind buildings of the canyon H_{UB} the upwind building height (Adapted from Kaplan et Dinar (1996) and Singh et al. (2008))	
Vegetation built	 The vegetation built zone is defined wherever the wake zone of a building intersects the footprint of a vegetation patch. Only the column of air below the vegetation canopy is impacted by the vegetation,	 $\frac{V_0(z)}{V_p(z)} = \frac{ln(\frac{H_{vtm}}{z_0})}{ln(\frac{z}{z_0})}\cdot exp(\alpha_i\cdot(\frac{z}{H_{vtm}}-1))$ if $z < H_{vtm}$ where H_{vtm} the maximum canopy height above the cell of interest z_0 the roughness length of the surface z level of the cell α_i the attenuation factor of vegetation i (=0 if there is no vegetation at height z)	

Zone name	Zone size	3D wind speed equations	Example of wind field
Vegetation open	The vegetation open zone is defined wherever the vegetation is not intersected by any building wake zone. The entire column of air (above and below the vegetation) is impacted, although it gets negligible far from the vegetation.	 $\frac{V_0(z)}{V_p(z)} = \frac{ln(\frac{H_{vtm}-d}{z_0})}{ln(\frac{z}{z_0})} \cdot exp(\alpha_i \cdot (\frac{z}{H_{vtm}} - 1))$ if $z < H_{vtm}$ $\frac{V_0(z)}{V_p(z)} = \frac{ln(\frac{z-d}{z_0})}{ln(\frac{z}{z_0})}$ if $z > H_{vtm}$ where H_{vtm} the maximum canopy height above the cell of interest d the displacement length z_0 the roughness length of the surface z level of the cell α_i the attenuation factor of vegetation i (=0 if there is no vegetation at height z)	

3.3 Manage superimposition

It is frequent that the Röckle zones from two (or more) obstacles intersect each other. In this case, we may decide either if we keep a single wind factor for this intersected zone (thus we need to set priorities between zones) or if we consider several of the wind factors to calculate a new one as a result of the superimposition. In QUIC-URB, Brown et al. (2009) decided to apply both of these possibilities depending on which Röckle zones intersect each other. In URock, the same philosophy is adopted. Three types of zones are considered:

- zone type 1 (upstream weighting zones): if the obstacle creating such zone is upstream to the obstacle creating any zone of type 2, their corresponding wind factors are multiplied. If it is at the same y position, the same is applied only if the obstacle of zone type 1 is higher than the one of the zone type 2. If two zone type 1 intersect each other, only the wind factor from the zone corresponding to the more upstream obstacle (and the highest if they are located at the same y position) is conserved. Only Wake zone is considered as a zone type 1.
- zone type 2 (upstream priority zones): only one wind factor is conserved if two (or more) zone type 2 intersect each other. As previously, we conserve the one belonging to the more upstream obstacle. If they are located at the same y position, we conserve the wind factor corresponding to the highest building and if they have the same height (for example cavity and street canyon zones from a same building), the following priorities are set between zones: street canyon, cavity, rooftop perpendicular, rooftop corner, displacement vortex, displacement.
- Zone type 3 (downstream weighting zones): wherever a zone type 1 or 2 intersects a zone type 3, their wind factors are multiplied. Only vegetation open and built zones are considered as a zone type 3.

Note that in 4, the wind factor for the wake and the vegetation zones are only presented for V (y direction) since the initial wind profile is along the y-axis. Actually the reduction factor is applied to each 3 dimensions wherever the superimposition with a wake or a vegetation zone leads to wind speed in an other axis than y.

Brown et al. (2009) also considered interactions between zones not covering a same space. In their approach, a street canyon would annihilate the rooftop recirculation above the downstream building of the canyon. In URock, the recirculation is removed only if upstream building is higher or equal height than the downstream one. Otherwise, the facade height considered for the rooftop recirculation scheme is reduced to the difference of height between the upstream and downstream buildings.

4 Calculates wind speed

The initial wind field U_0, V_0, W_0 is initialized according to wind profiles and wind factors and then numerical solving methods are used to get a balanced final wind field (Figure 13).

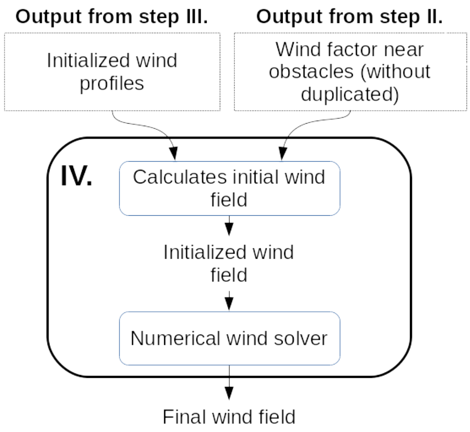


Figure 13: Processes used to calculates the final wind field

The initial wind speed for a given point is obtained multiplying the wind factor and the wind speed coming from wind profile. The latter is taken either at the height of the point or at a specific height such as the height of the building which has created the Röckle zone (see wind factor denominator in the Equations in 4).

The volume flow of the initialized wind speed is then balanced using the numerical method described by Pardyjak et Brown (2003)[4]. Before applying the solver, we interpolate the initialized wind speed that we have at the center of the cells (in black arrows Figure 14) to their faces (in blue arrows Figure 14) according to Equations XX.

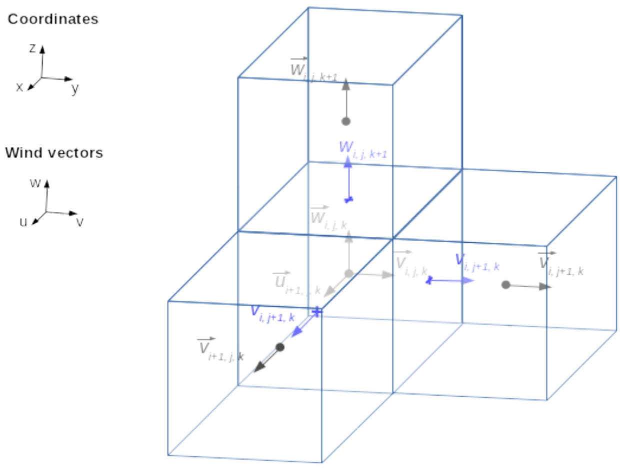


Figure 14: Wind speed at cell faces (blue arrows) and cell center (black arrows)

$$u_{i+1,j,k} = \frac{u_{i,j,k} + u_{i+1,j,k}}{2}$$

$$v_{i,j+1,k} = \frac{v_{i,j,k} + v_{i,j+1,k}}{2}$$

$$w_{i,j,k+1} = \frac{w_{i,j,k} + w_{i,j,k+1}}{2}$$

4 Note that we have modified some of the values in their Table 1: G5 is now 1, H5 is 0, G6 is 0 and H6 is 1. We have also set both α_1 and α_2 to 1 (they were not set in Pardyjak et Brown (2003).

After solving, the wind speed obtained on grid faces is then reinterpolated back to the center of the cells using the same method.