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Wind Load Prediction on Trees in Virtual Urban Landscape for Greenery Management

Dr. POH Hee Joo, IHPC, A*STAR

Mar 2021

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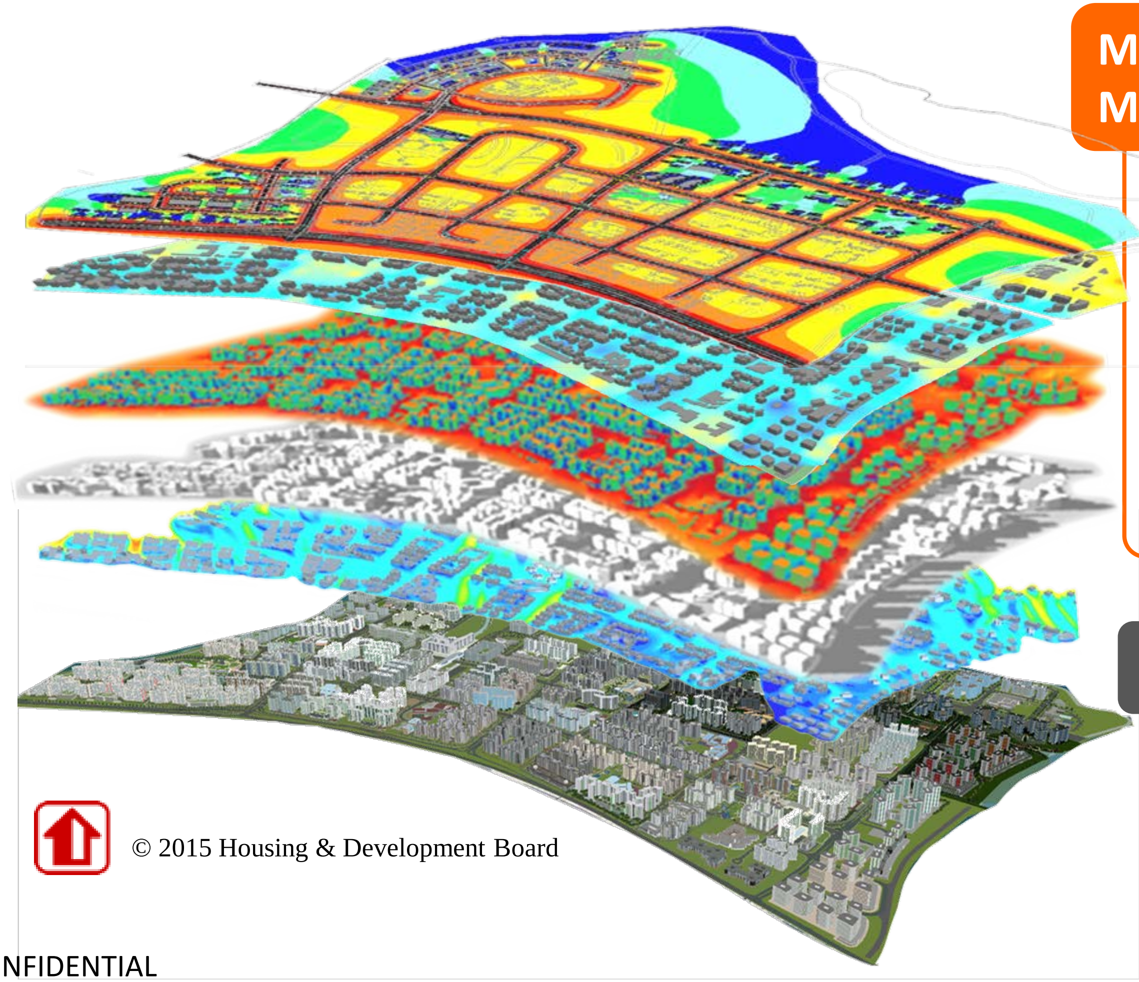
Content

IEM - Integrated Environmental Modeller

Integrate whole process (master planning, urban design & environmental modelling)



Multi Disciplinary Modelling Platform

- Noise
- Thermal
- Solar Irradiance
- Shadow
- Wind

Integrated process

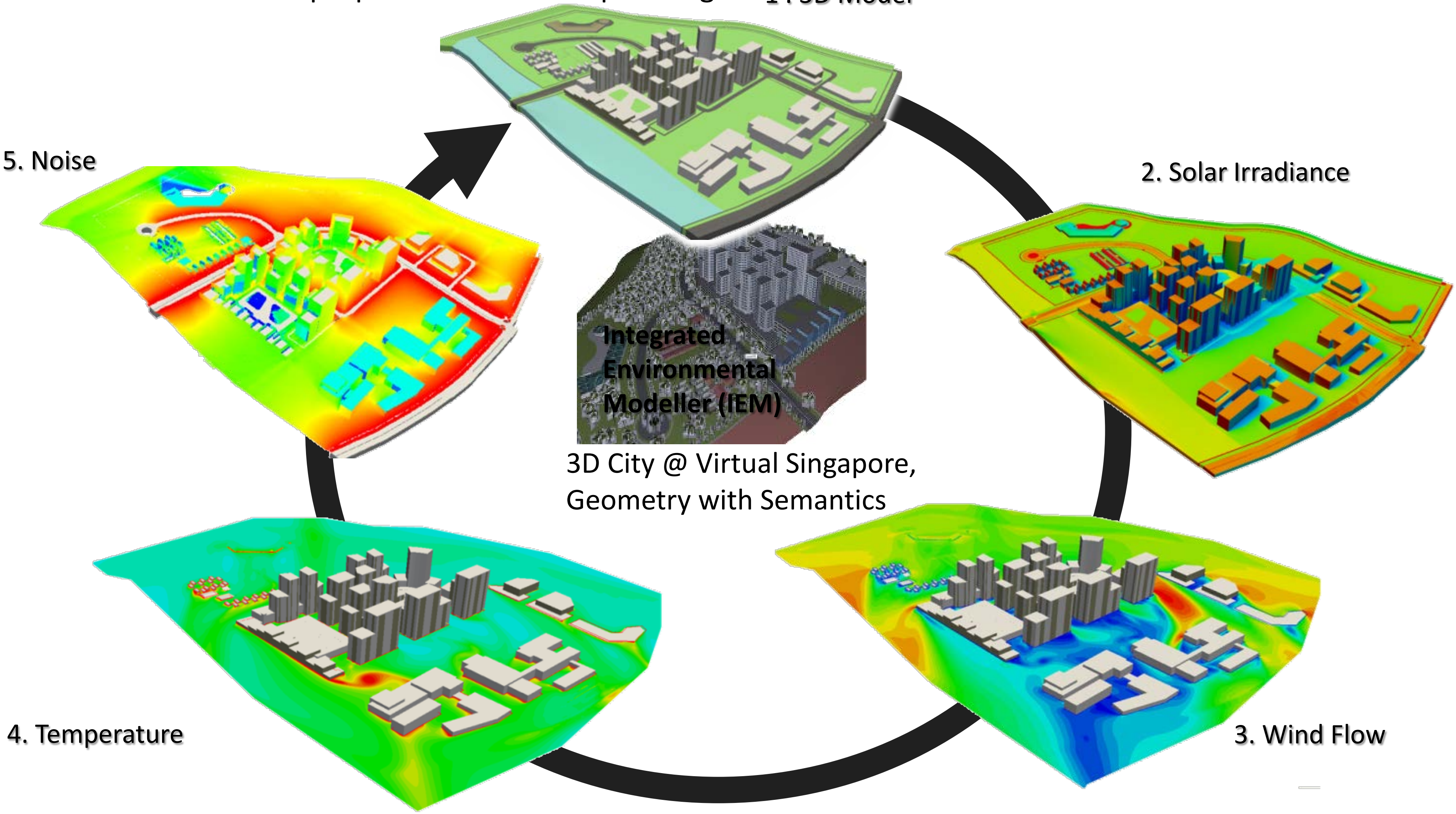
Urban Digital Model

Planning & Urban Visualisation

Integrating Modelling and Simulation Applications (IEM) into Virtual Singapore

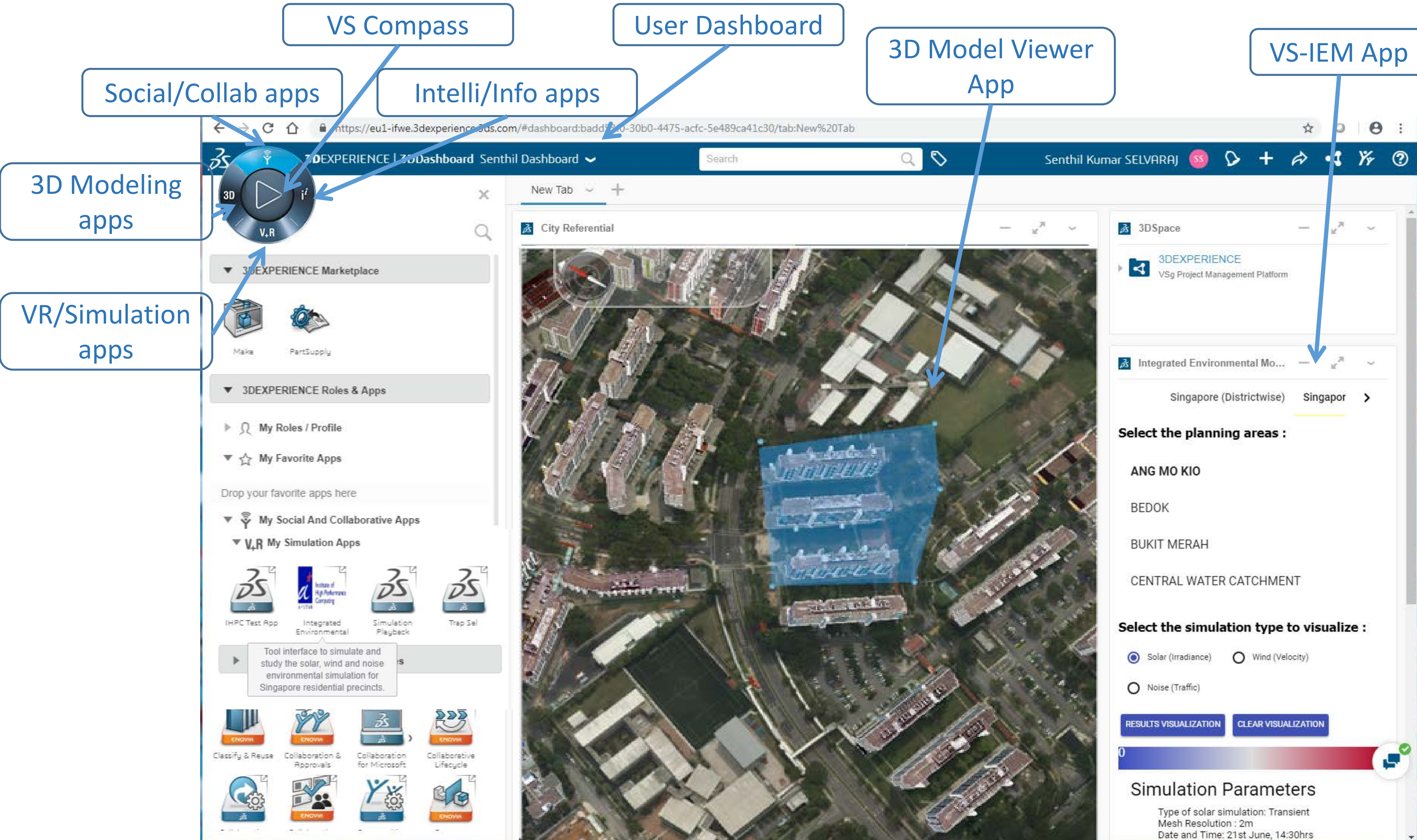
Objective

Integration of stand alone IEM work flow into Virtual Singapore platform. IEM captures interrelationships between wind flow, temperature, solar irradiance, day lighting and noise propagation in a 3D urban environment for the purpose of new town planning.

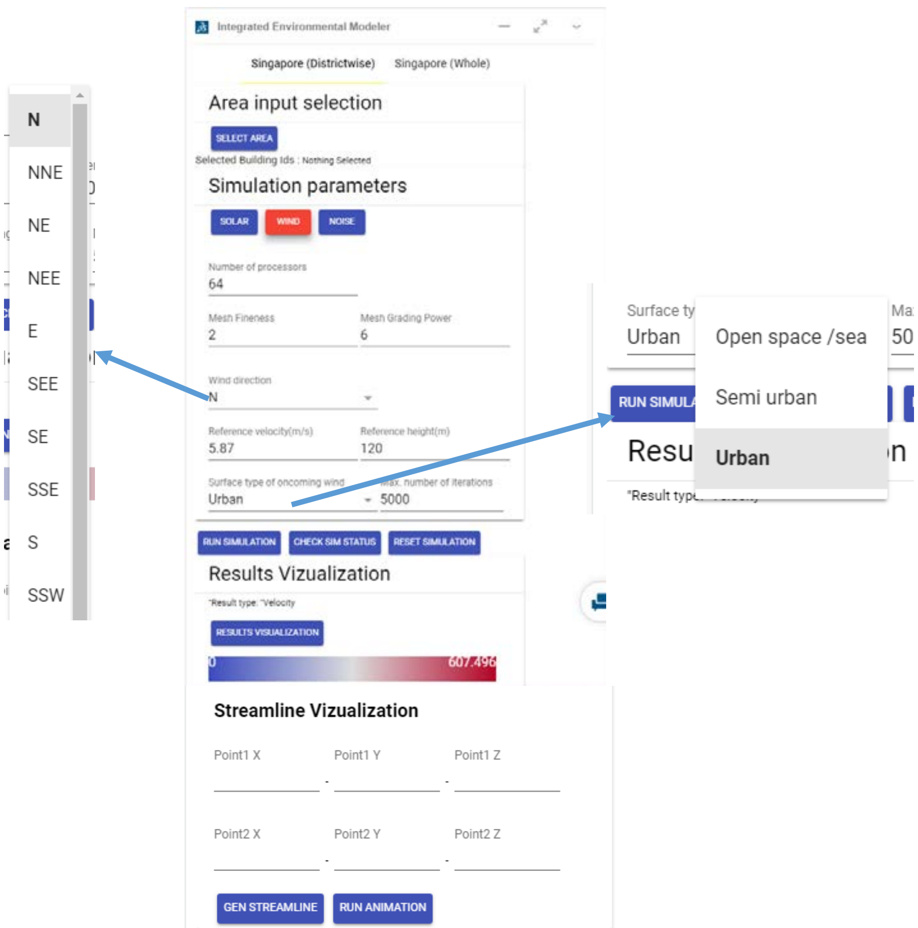


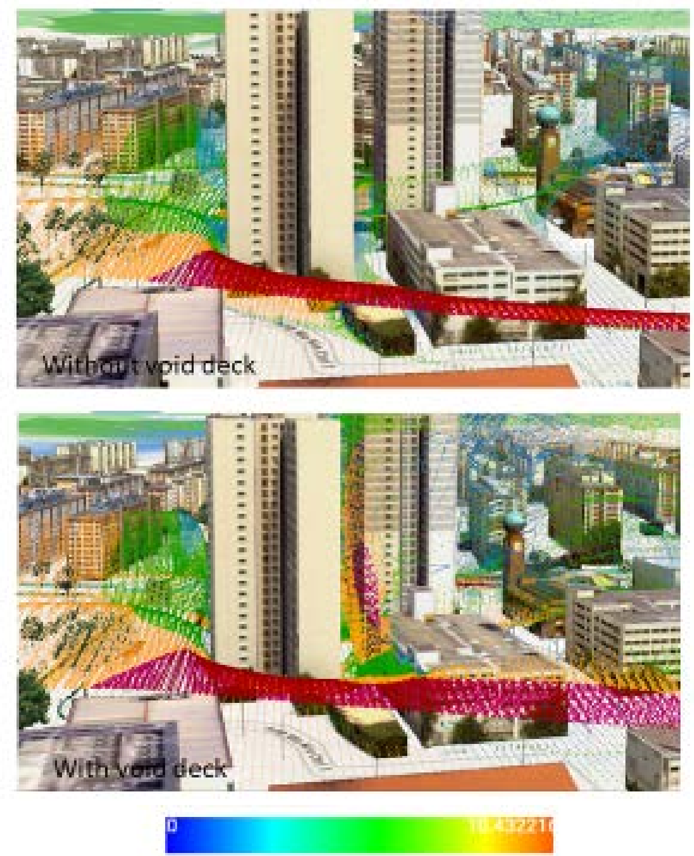
Virtual Singapore Platform

https://eu1-ds-iam.3dexperience.3ds.com/



VS-IEM User Interface – Wind Simulation





Trees Failure & Management Scenario

Tree Failure Events

Despite the trees' good condition, extreme winds caused numerous branch failures along Dunearn Road during a thunderstorm in 2014

Tree Management Scenario

Before Pruning
August 25, 2010

After Pruning
March 12, 2013

Difference in tree structure (e.g. crown size, shape and Leaf Area Density) due to pruning

It is important to reduce maintenance costs associated with the upkeep and mitigate the risks to both people and property **when trees uproot or branches break**

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Challenges in Urban Tree Modelling

In urban modeling, e.g., Google Earth & Virtual Singapore, millions of trees are represented with generic, static 3D tree models

- For visual/viewing only
- Lack of biology & physical semantic accuracy – shape, species, age, leaf density, etc.. – needed for meaningful, high precision simulation results
- Need effective approach to automate the tree semantic modelling for scalability to a city level

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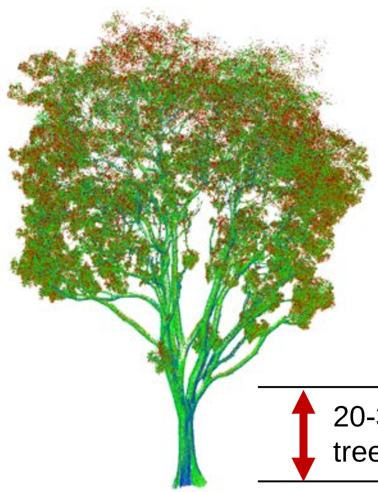
VS 1 – Tree Model Generation – From Point Cloud to Simulation-ready Mesh

BRANCH CLASSIFICATION

Separating the leaves from the branches

Unorganized & Unconnected Point Cloud



Point clouds of tree are captured under many different conditions, affected by the **amount of sunlight**, **distance from scanner**, etc.

20-30% from base of tree used for estimation

Intensity Scale

Leaves

- Lower Intensity values
- Sparse Neighbourhood

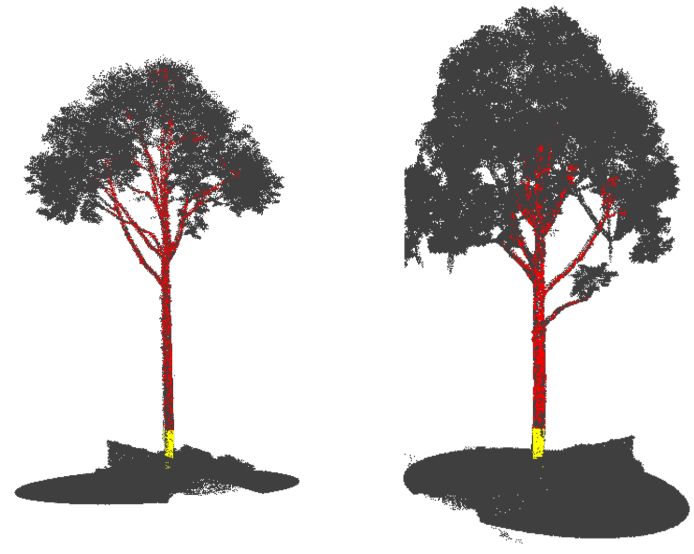
Branches

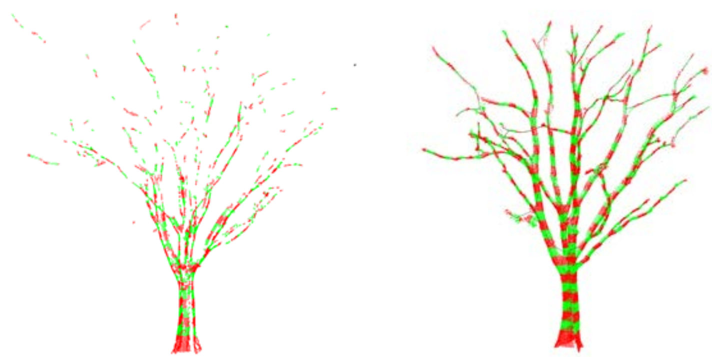
- Higher Intensity values
- Dense Neighbourhood

VS 1 – Tree Model Generation – From Point Cloud to Simulation-ready Mesh

BRANCH CLASSIFICATION

Results of Auto-Classification





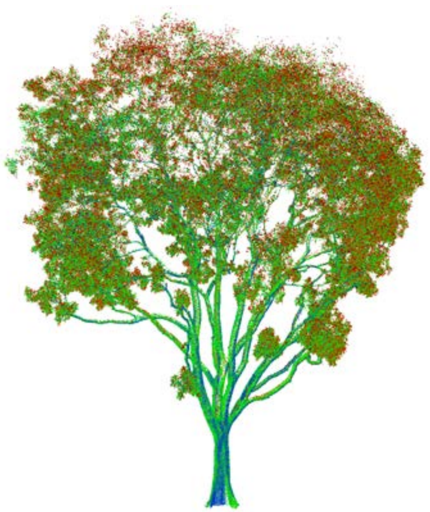
After classification, only **pockets of points** are selected as branch points. They are usually **disjoint**.

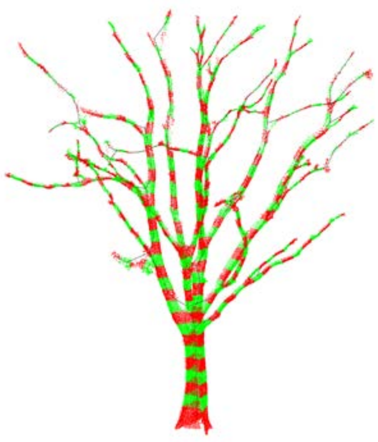
Using a **flow concept**, where every point "flows" to the root using the shortest path, we can strengthen the classification and **form a full connectivity**.

VS 1 – Tree Model Generation – From Point Cloud to Simulation-ready Mesh

BRANCH CONNECTIVITY

Establishing connectivity between classified points





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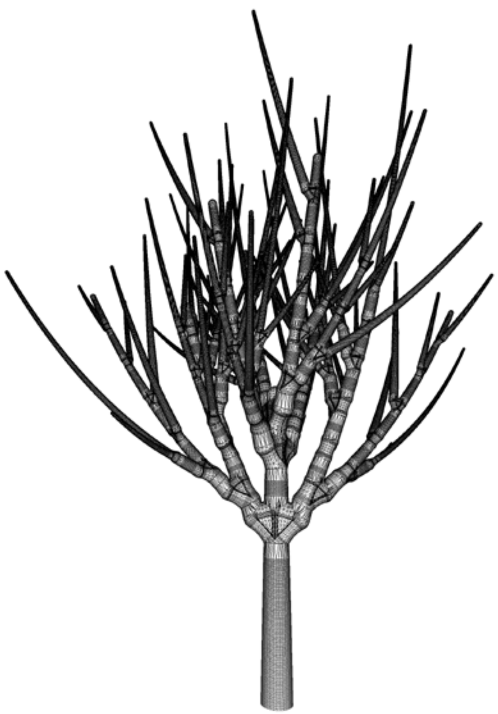
VS 1 – Tree Model Generation – From Point Cloud to Simulation-ready Mesh

TREE MODEL

Meshing a L-System Generated Fractal Tree in MTG format



Full Tree Model (Fractal)

- Generated from an L-System fractal tree model.
- Consisted of 50 joints components
- 300k vertices, 700k faces.

VS2 - Wind Load Prediction on Trees in Urban Landscape

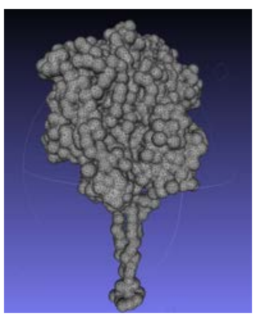
Overview

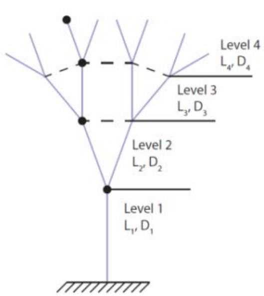
It is important to understand the complex and dynamic wind-tree interaction phenomena, in order to estimate the aerodynamic force that tree can endure in given locations; and assess the tree management scenario & risk of tree failure.

Proposed Work Scopes:

WP1 – Fractal Modelling

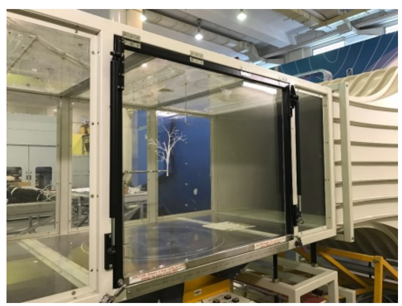
Point-based Urban Tree Modelling

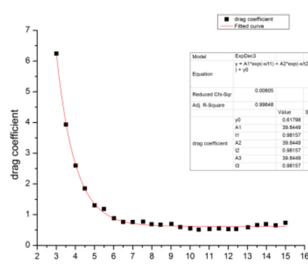




WP2 – Lab Testing

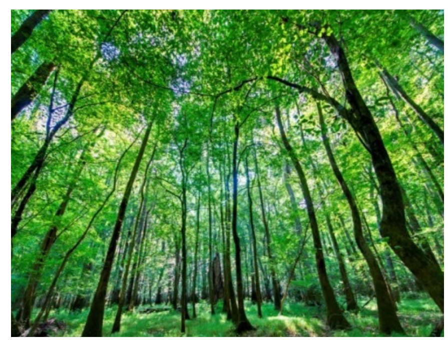
Wind tunnel analysis on fractal-Tree model

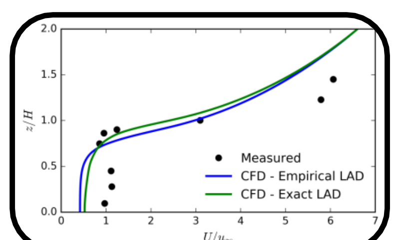




WP3 – IEM Simulation

CFD Wind Load Prediction at Urban landscape



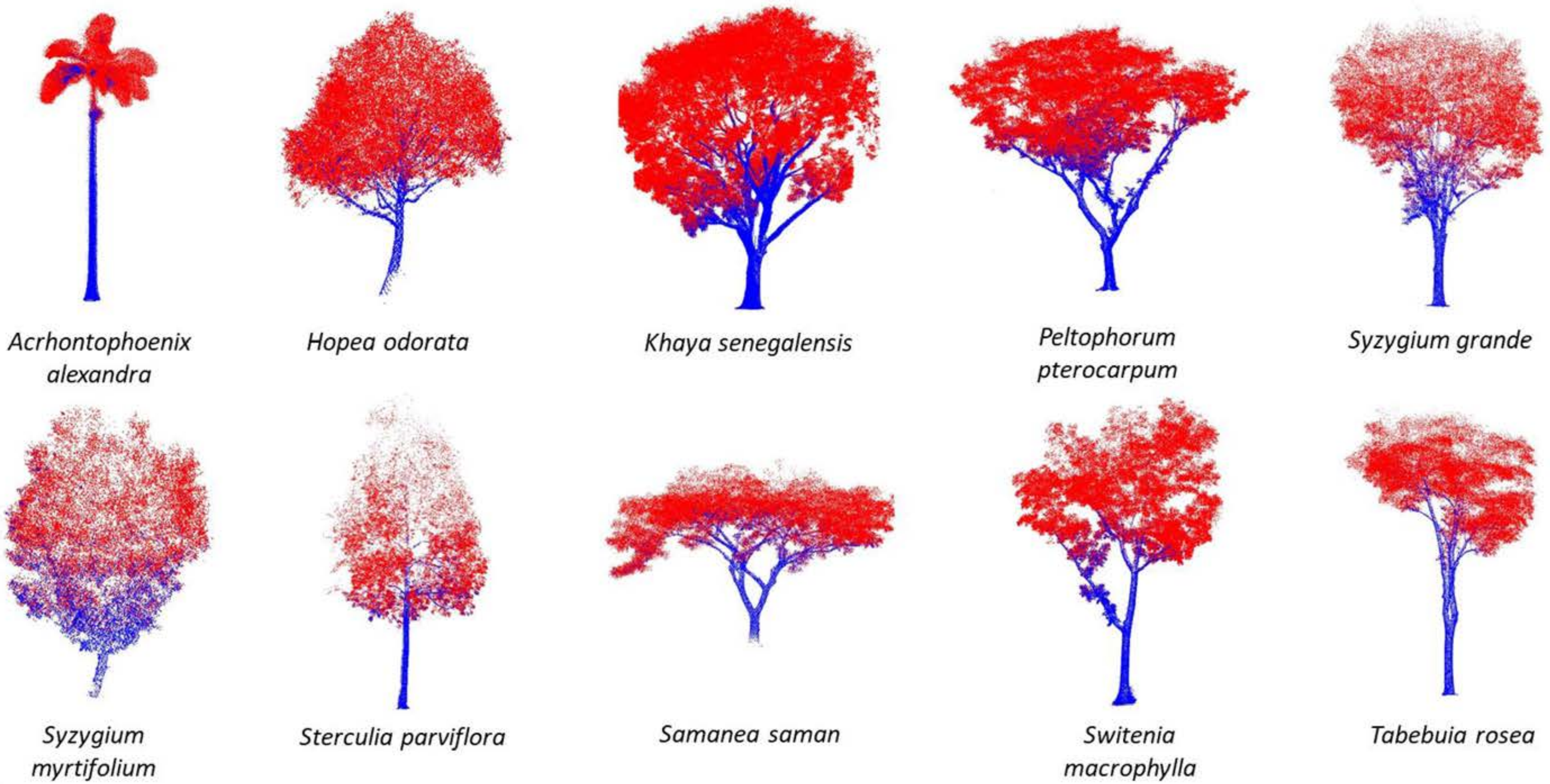


WP4 - Tree Management

Application in Virtual City (Example) – Tree Pruning

WP1 - *Tree Semantics and 3D Fractal Modelling*

Actual Point Cloud laser-scanned Data – typical tree species in Singapore



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Fractal tree model

Point cloud data

Filtering process removes the bulk of the leaves regions

Using a distance to base root computation. A distance clustering process to identify the branches and removes the leaf regions

Estimate the species-specific tree parameters, such as the height, trunk diameters, crown box dimensions, etc.

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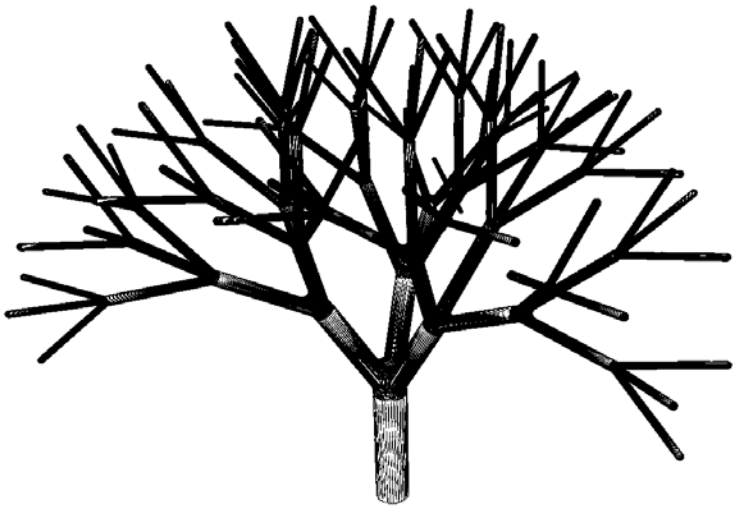
Fractal tree model



Scaled down fractal tree model of the Yellow Flame Tree (*Peltophorum pterocarpum*)

The fractal tree is formed by branches which are each recursively split into 3 child branches for 3 iterations

Total cross sectional area of the three child branches is equal to the parent branch's.

Each level of child branch's length is reduced by a fixed ratio.

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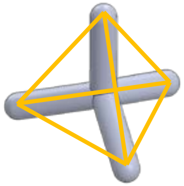
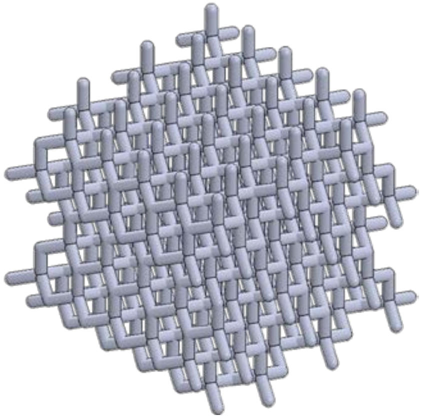
Tree crown generator

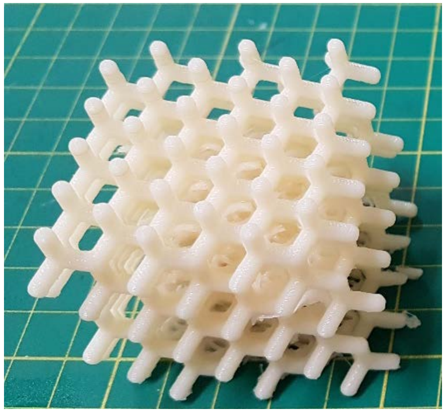
Impossible to construct/fabricate the leaves



Use porous volume to represent the crown



Porous volume is constructed by stacking tetrahedral elements repeatedly



A tree crown generator is designed to construct the porous volume

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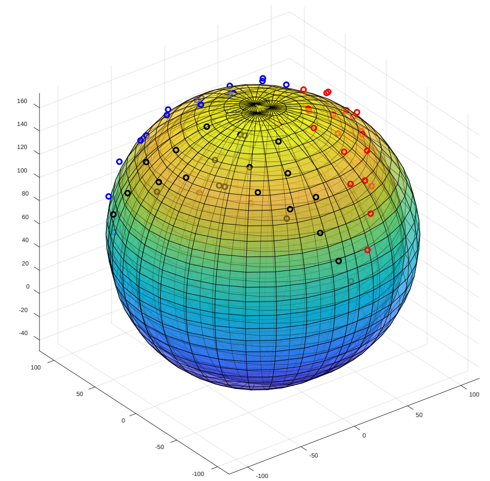
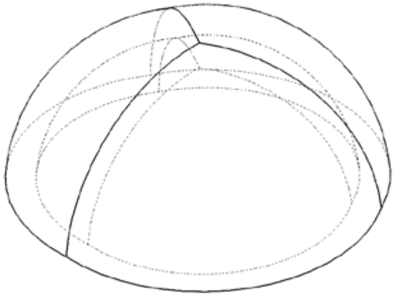
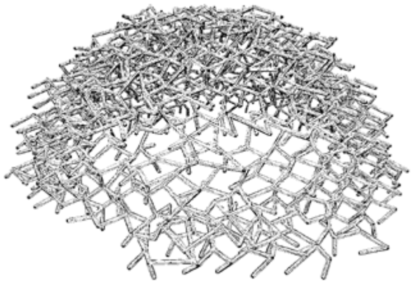
Tree crown generator

The coordinates of the nodes and centroid of the tetrahedral elements are randomized to avoid aligned channels in the volume

Crown volume of the Yellow Flame is defined using three spheres which are least squared fitted to the tip of branches, and a flat plane







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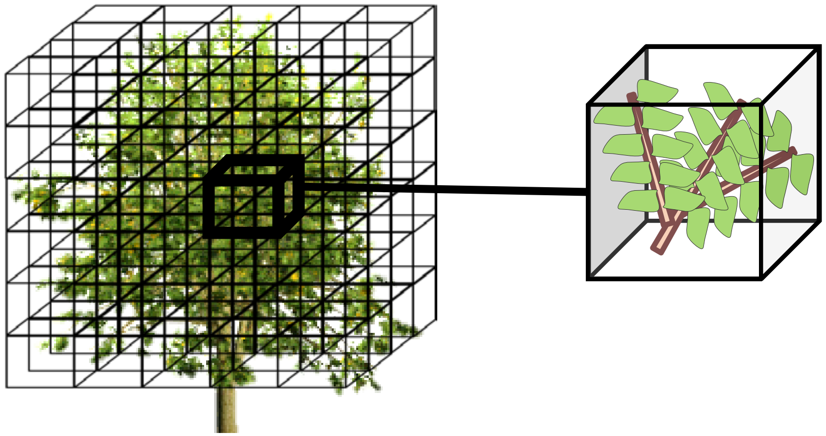
Wind Load on Tree analysis – Which Structural Information is Important?

Leaf area density (LAD) distribution



LAD: Total one-sided leaf area per unit volume [m^2/m^3]

Importance of LAD distribution

For elucidating radiation balance
Sinoquet et al. (2007), Iio et al. (2011)

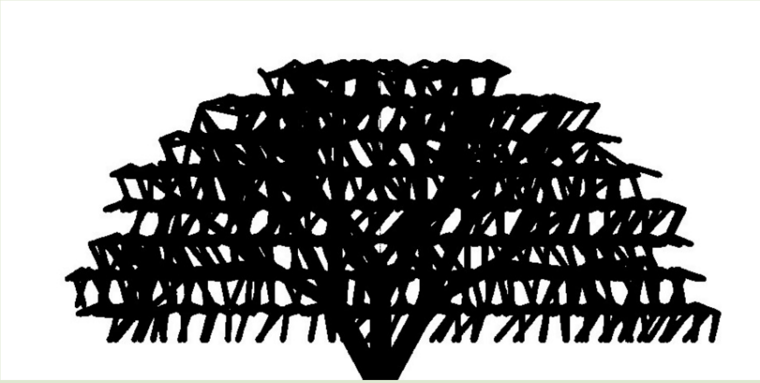
For elucidating drag force
Narita et al. (2004)

It is difficult to acquire LAD distribution for many trees

Leaf Area Density measurement

1. Stratified clipping of biomass samples

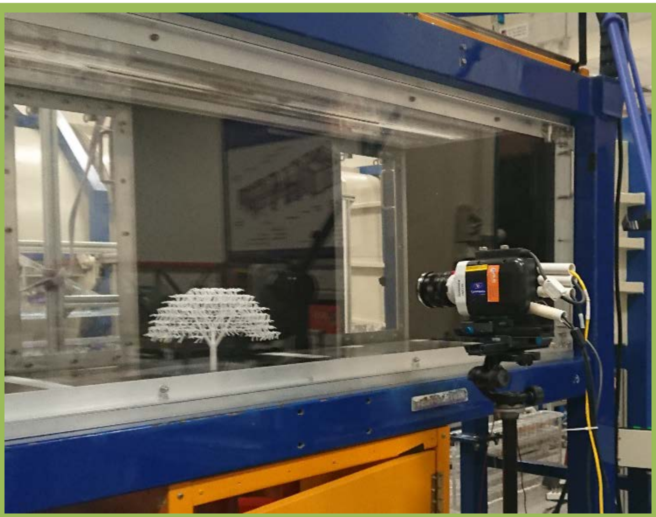
2. Point-quadrat method[22]



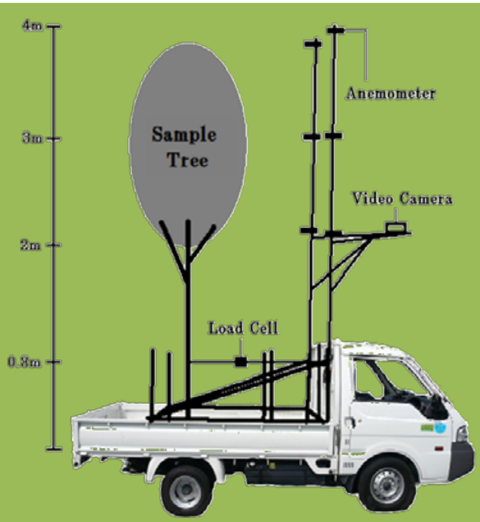
3. Gap-fraction method[23-24]

4. LiDar[25-26]

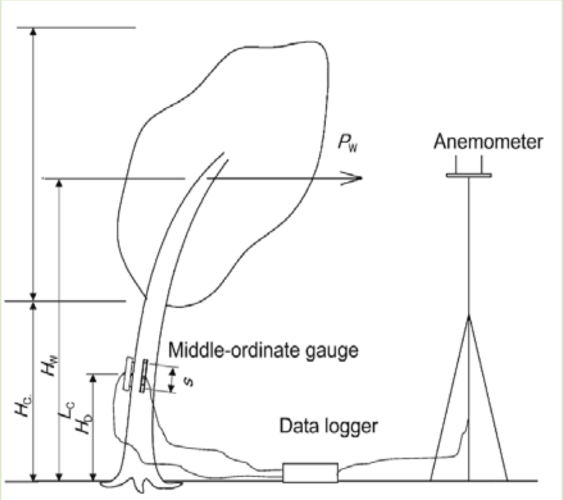
Drag coefficient measurement



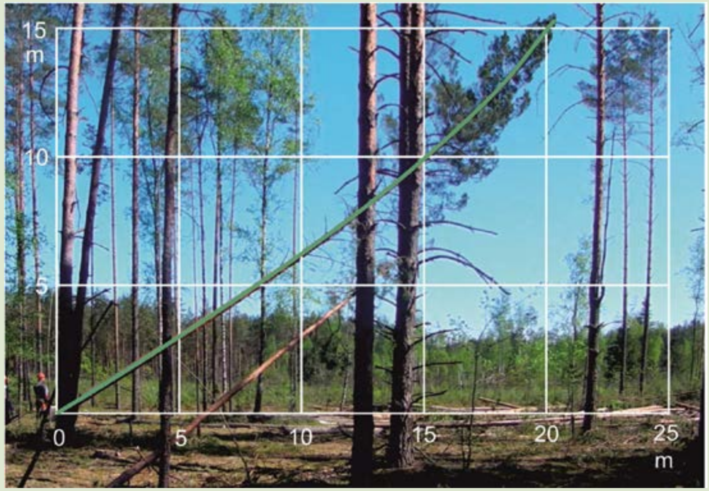
1. Wind tunnel[27]



2. Moving truck[28-29]



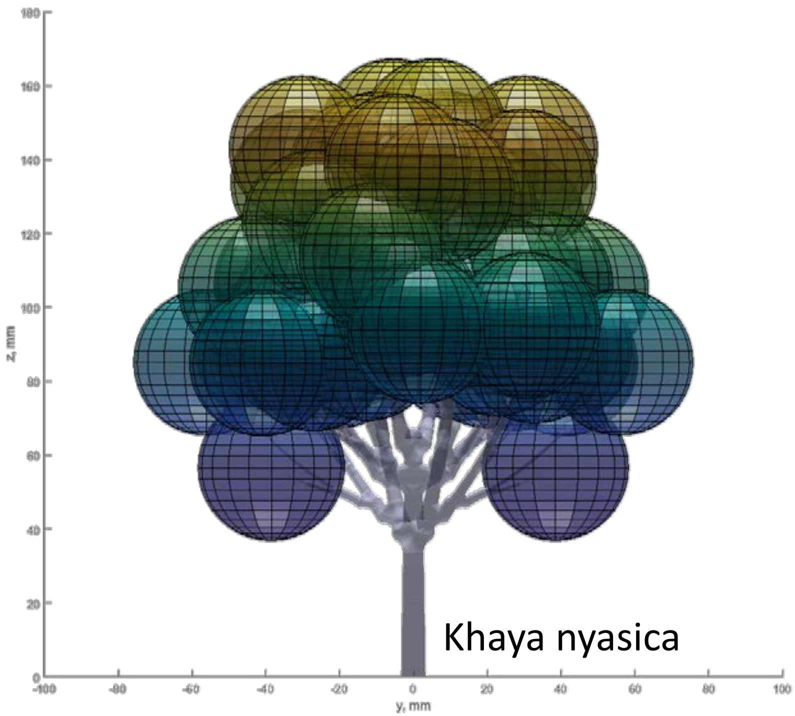
3. Stem deflection gauge[30]

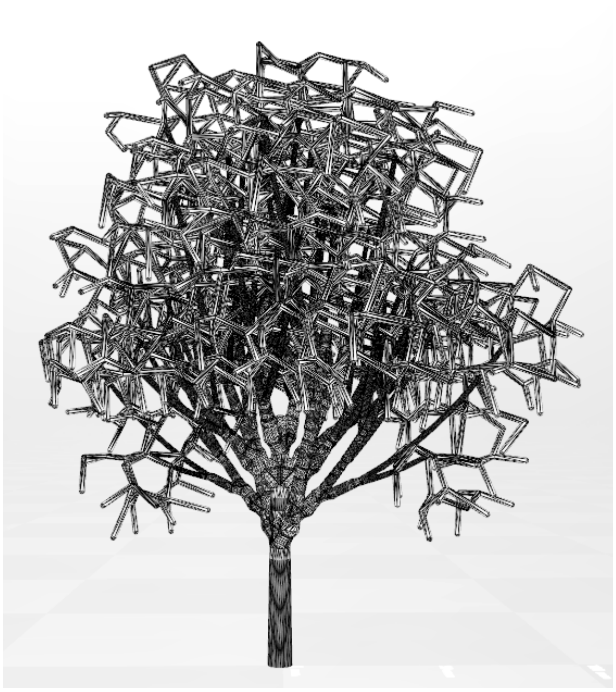


4. Motion in freefall[31]

WP2 - *3D Printing and Parameter Extraction from Fractal Tree Wind Tunnel Model*

Tree Crown of Khaya





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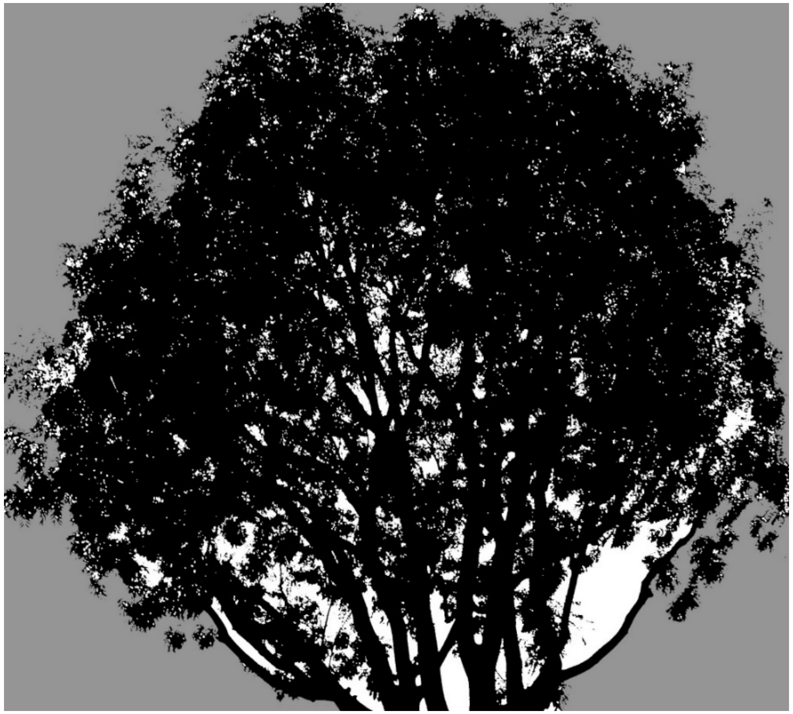
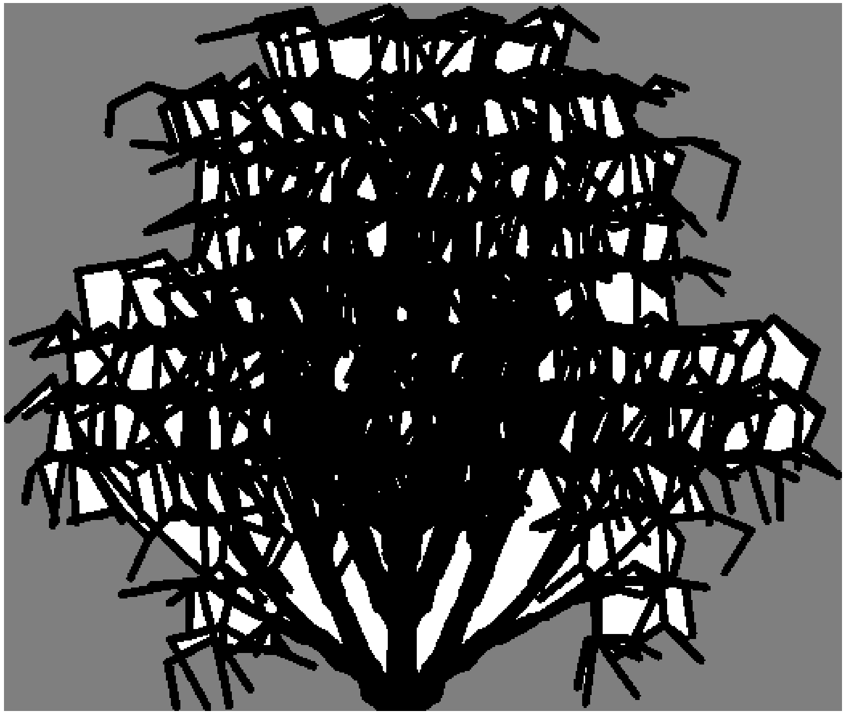
WP2 - *3D Printing and Parameter Extraction from Fractal Tree Wind Tunnel Model*

3D printing for tree fractal model (a number of scenarios) - **nine (9) tree species – Khaya tree**
Matching frontal area ratio of real tree



Average	0.8763081
Standard of Deviation	0.071117513



Model Frontal Area Ratio 0.825695803

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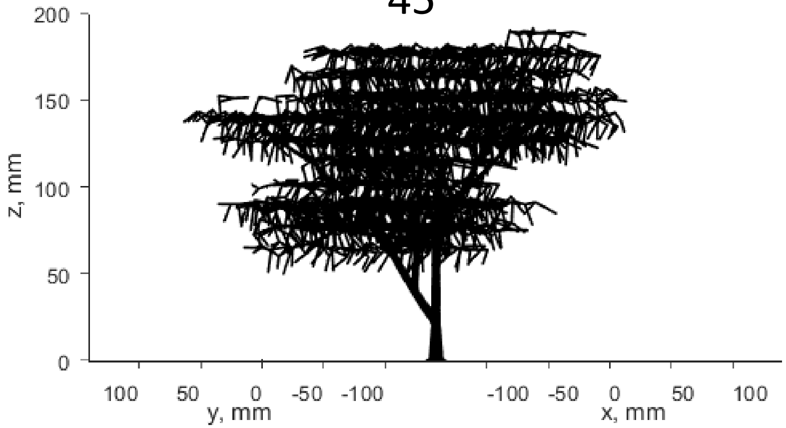
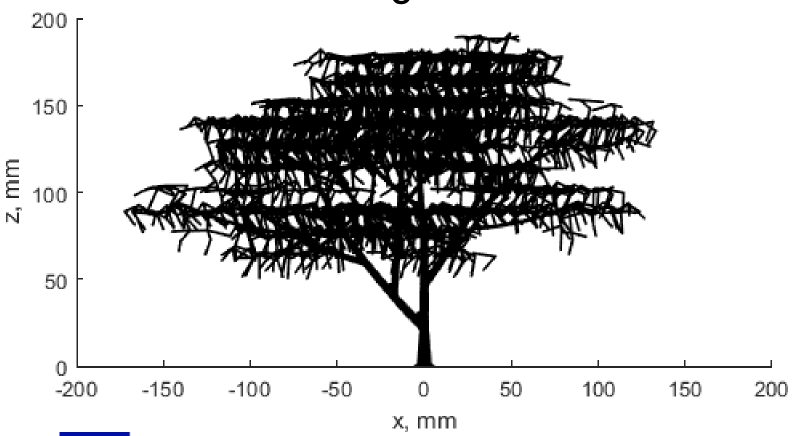
WP2 - *3D Printing and Parameter Extraction from Fractal Tree Wind Tunnel Model*

3D printing for tree fractal model (a number of scenarios) - **nine (9) tree species – Rain tree**

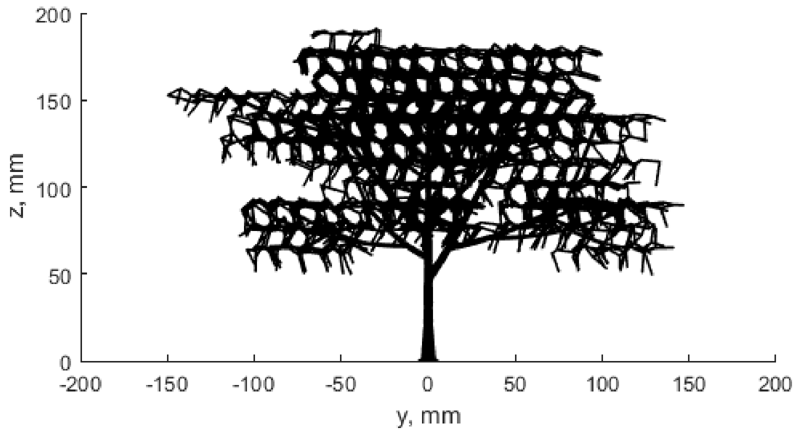
45°



0°



90°



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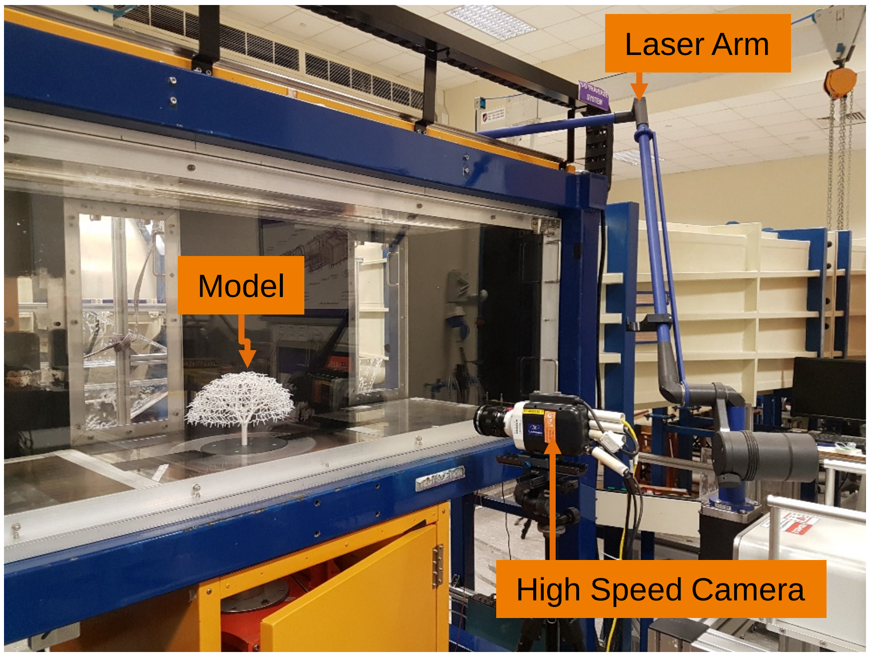
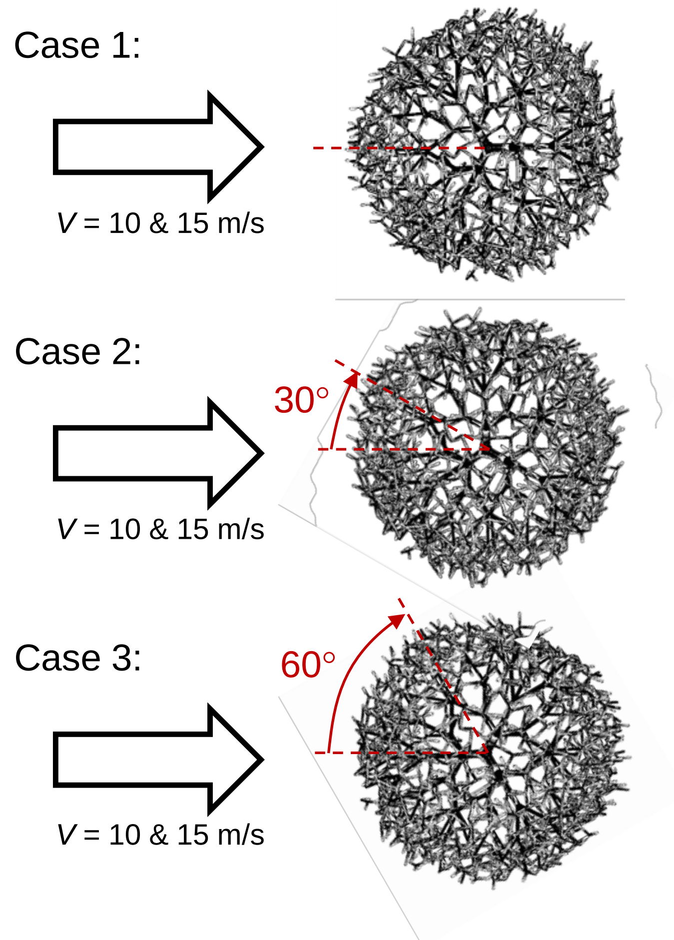
WP2 - *3D Printing and Parameter Extraction from Fractal Tree Wind Tunnel Model*

Wind Tunnel Test - PIV and load cell measurement for Yellow Flame Tree Model.





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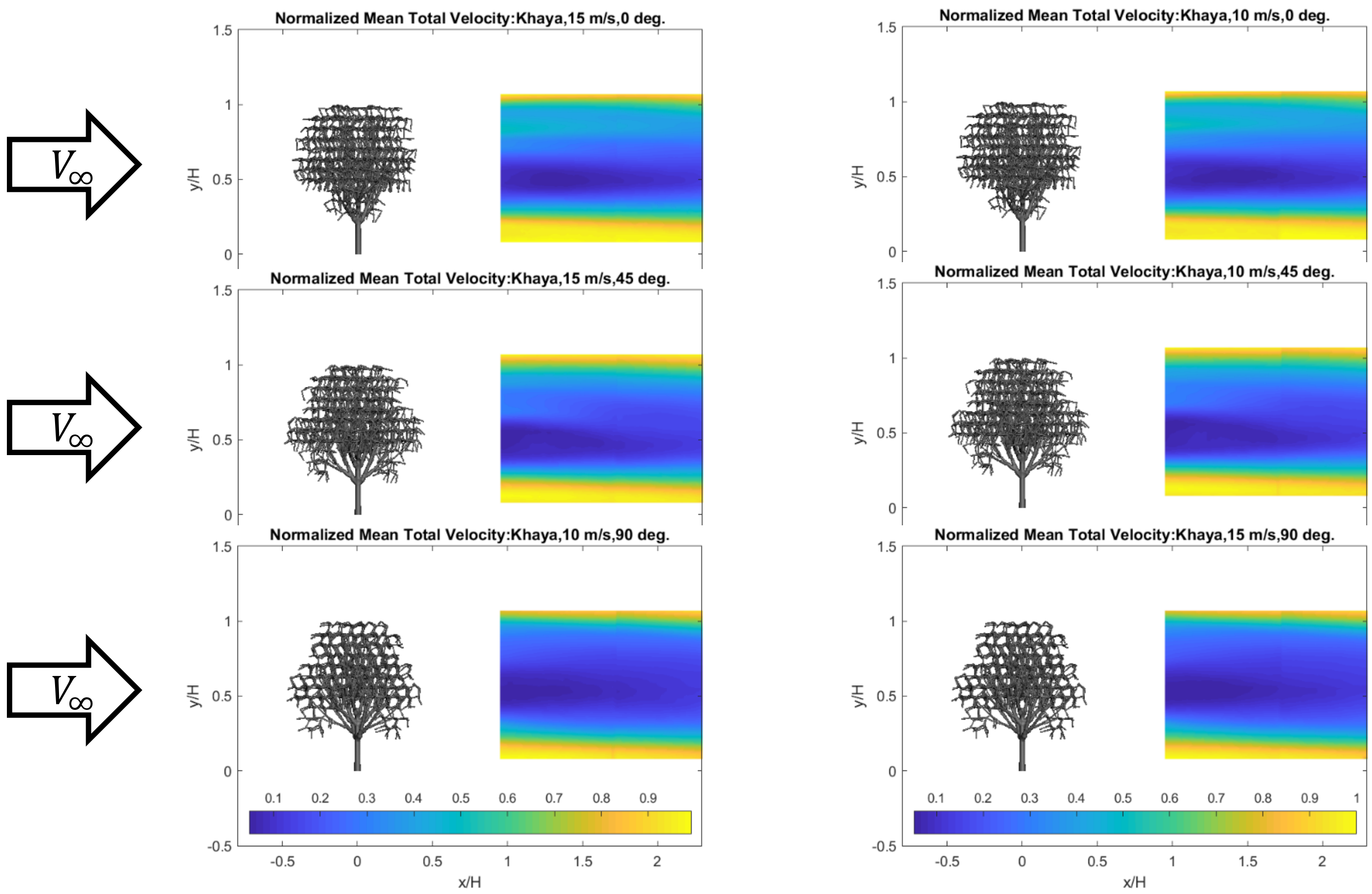
WP2 - *3D Printing and Parameter Extraction from Fractal Tree Wind Tunnel Model*

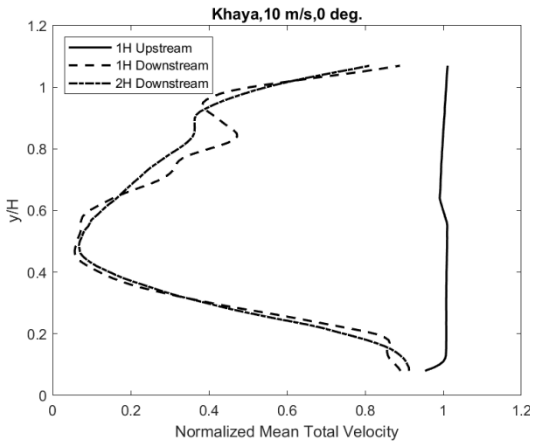
Wind Tunnel Test – PIV Results of Khaya Tree

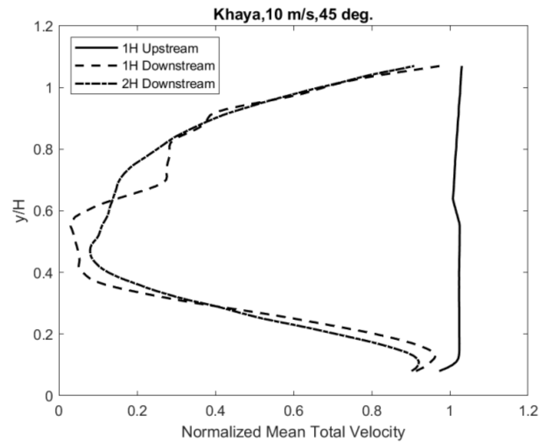


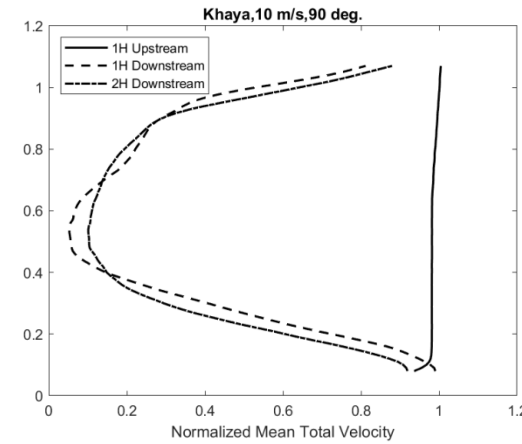
WP2 - *3D Printing and Parameter Extraction from Fractal Tree Wind Tunnel Model*

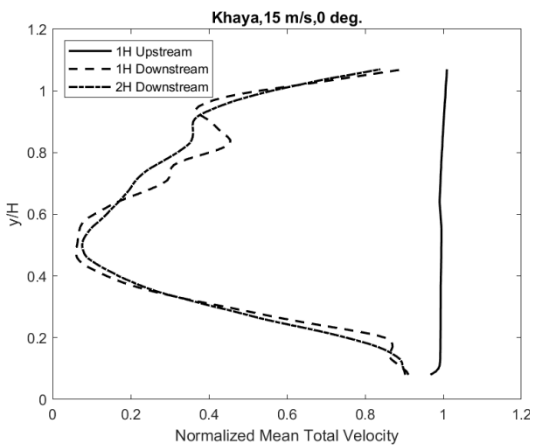
Wind Tunnel Test - Wake Profile of Khaya Tree

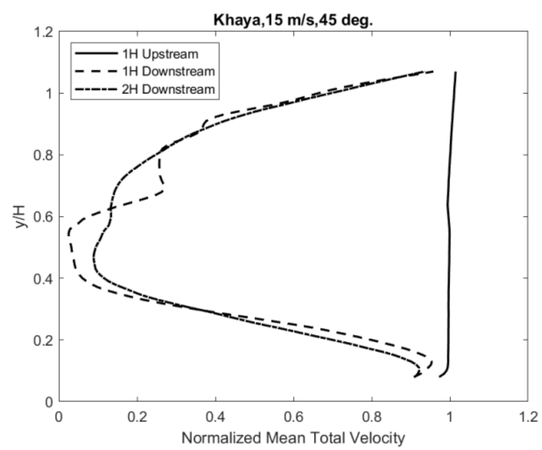
Normalized Velocity, $\hat{V} = \dfrac{V}{V_\infty}$

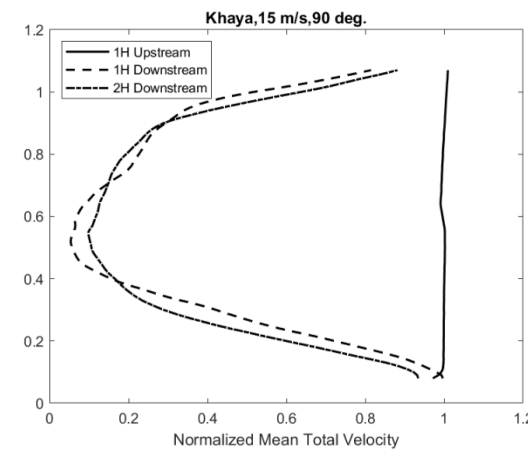








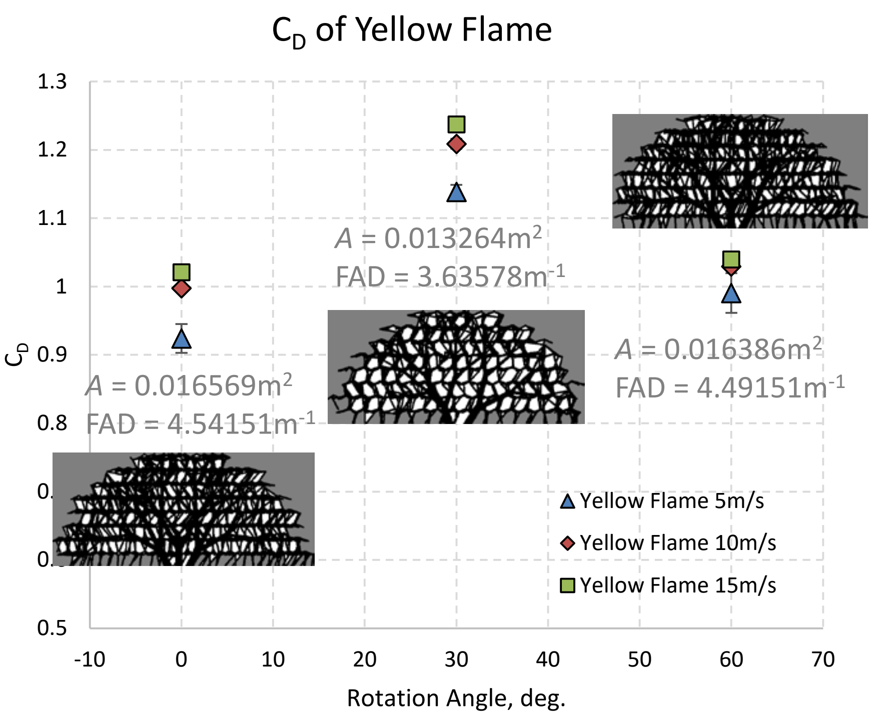


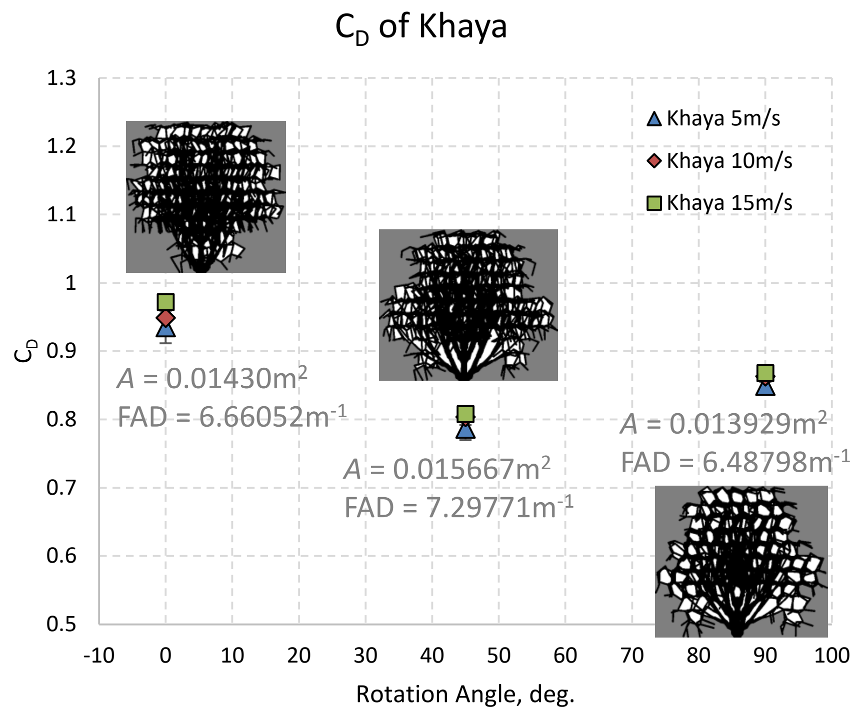


WP2 - *3D Printing and Parameter Extraction from Fractal Tree Wind Tunnel Model*

Derivation of fractal porous media models based on wind tunnel results (a number of scenarios) - **20 case studies**

Wind Tunnel Test – Drag Coefficient





$$C_D = \frac{2F_D}{\rho V^2 A}$$

A = Frontal Projected Area of Tree Crown

F_D = Drag Force

V = Free Stream Velocity

ρ = Air Density

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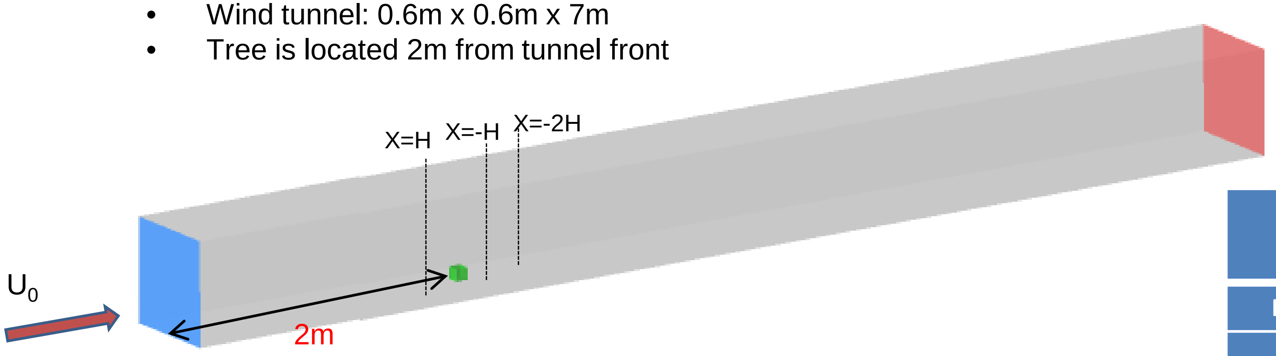
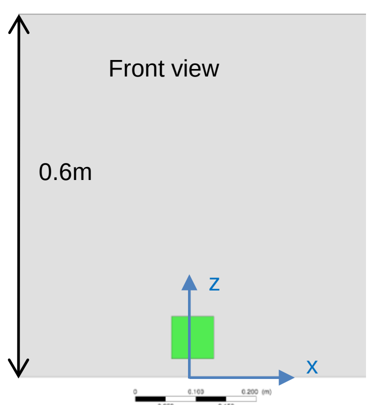
WP3 - *CFD Wind Tree modelling at Urban Landscape*

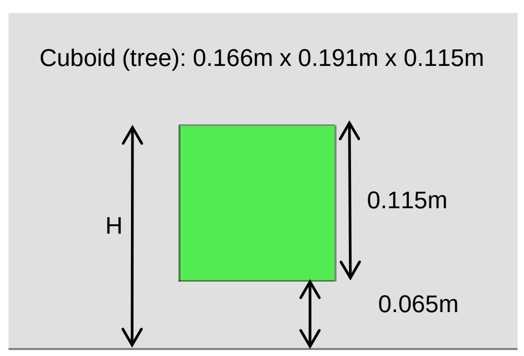
CFD simulation for scaled tree in wind tunnel with Full Closure Model

- Wind tunnel: 0.6m x 0.6m x 7m
- Tree is located 2m from tunnel front



	Angle
	0 degree
Frontal Silhouette Area [m^2]	0.018
Crown Volume [m^3]	0.0036
Frontal Area Density [m^-1]	5.039





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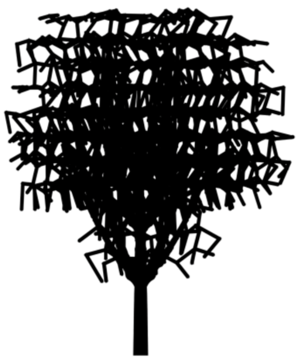
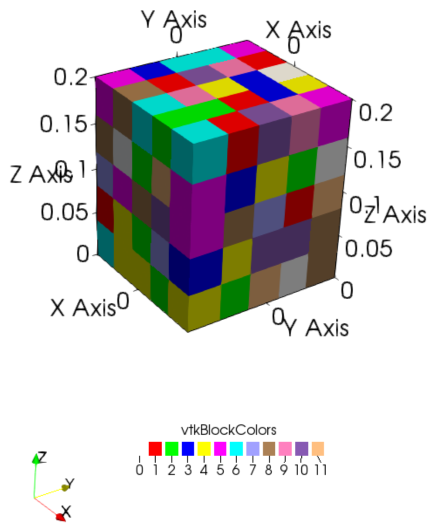
WP3 - *CFD Wind Tree modelling at Urban Landscape*

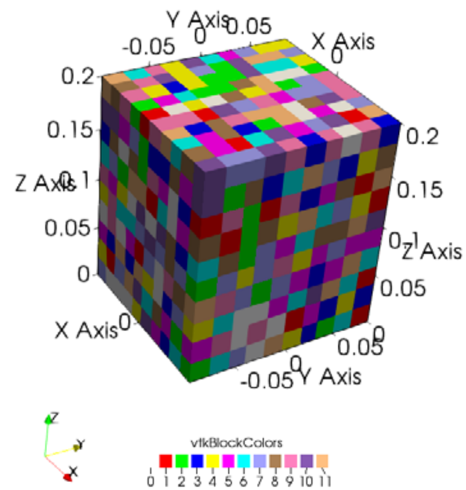
- Discretized Frontal Silhouette Area Density



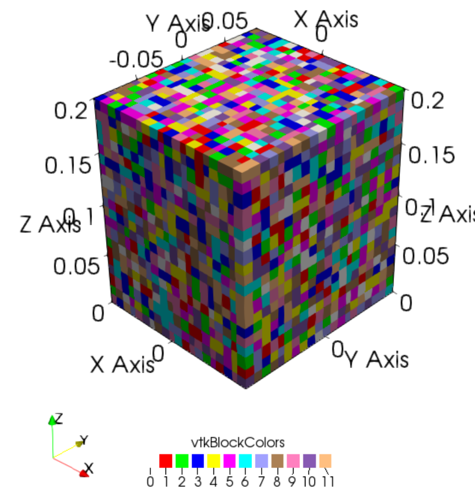
Khaya_0 degree



Split number =5



Split number =10



Split number =20

- $S_u = -aC_D\ \rho u_i\ U$
- Frontal silhouette area density (FSAD): $a = A_{FSA}/V$
- $C_D = \frac{2F_D}{\rho V^2 A}$

	Frontal Silhouette Area (FSA)	Discretized Frontal Silhouette Area		
		split no = 5	split no = 10	split no = 20
Area (m2)	0.0143	0.0305	0.0377	0.0436
C_D	0.9720	0.4564	0.3686	0.3187

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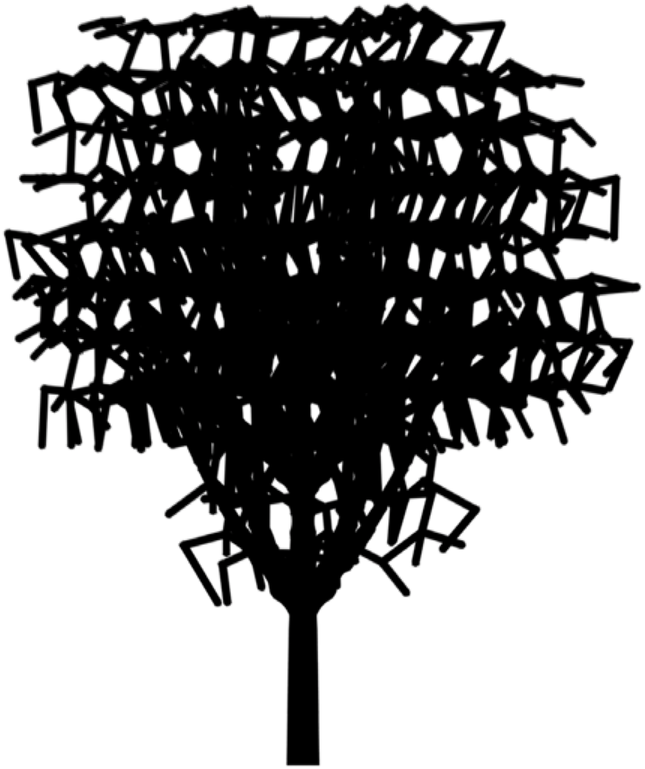
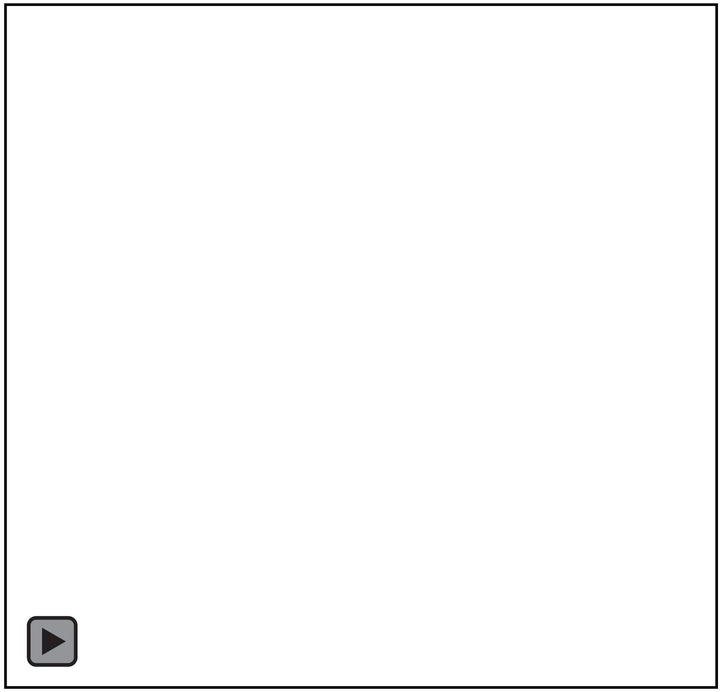
Obtaining discretized A_{FSAD}



Khaya_0degree



Discretized frontal silhouette area
(Split number =20)

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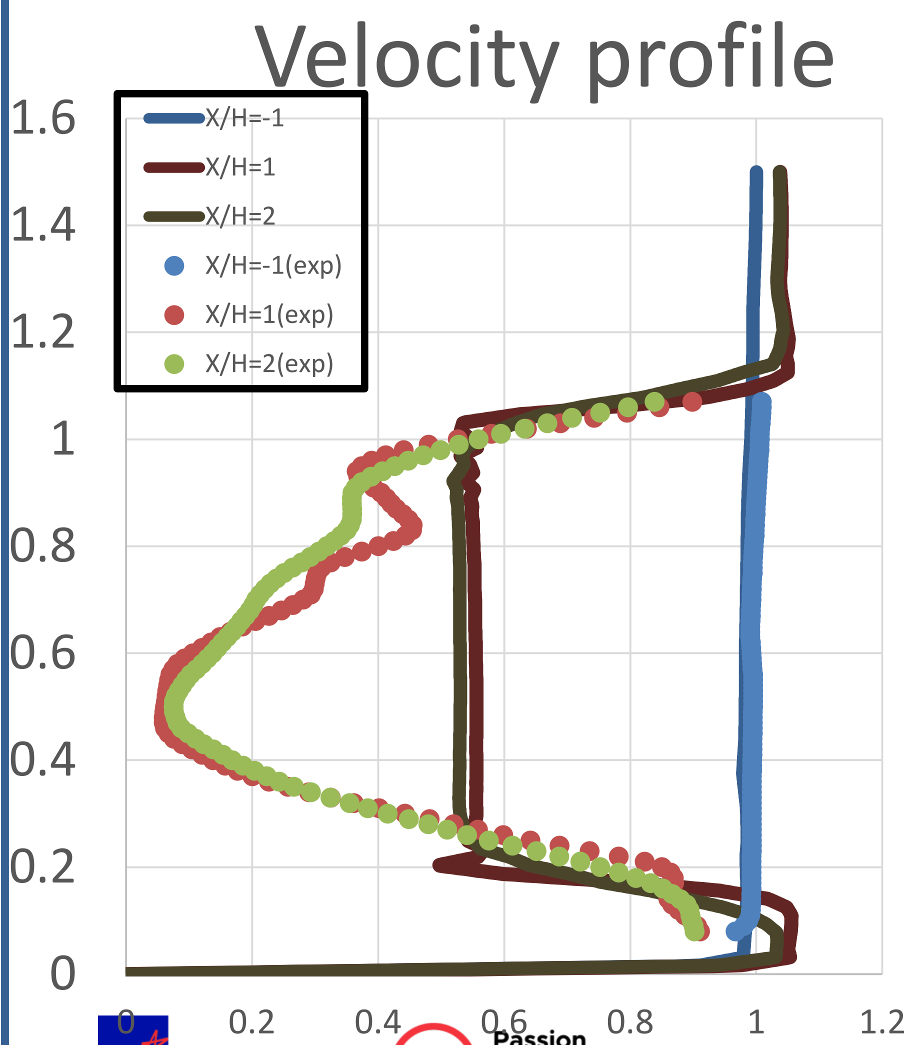
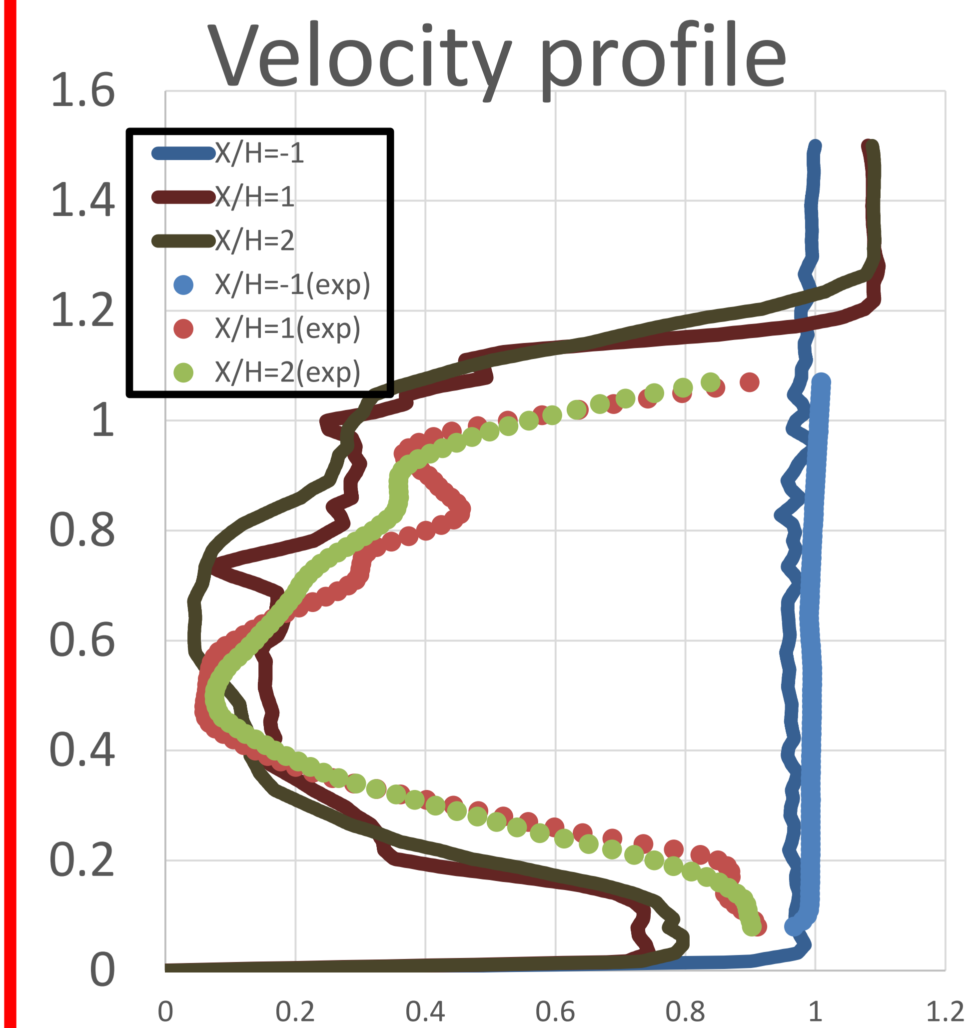
averaged momentum sink



discretized momentum sink



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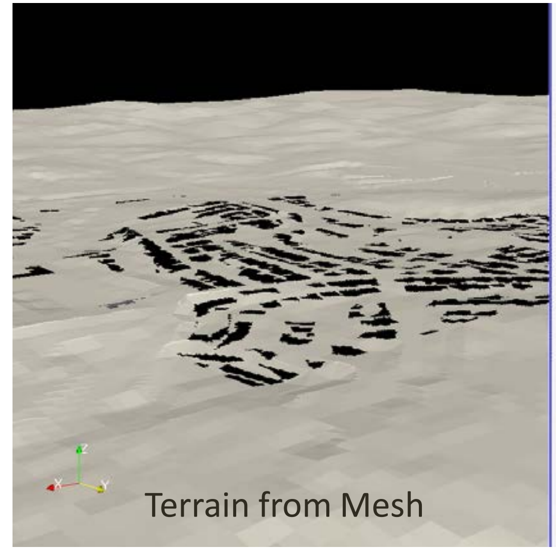

Generation of STL files with buildings, terrain and trees for Upper Thompson site, with 5450 trees identified in this site

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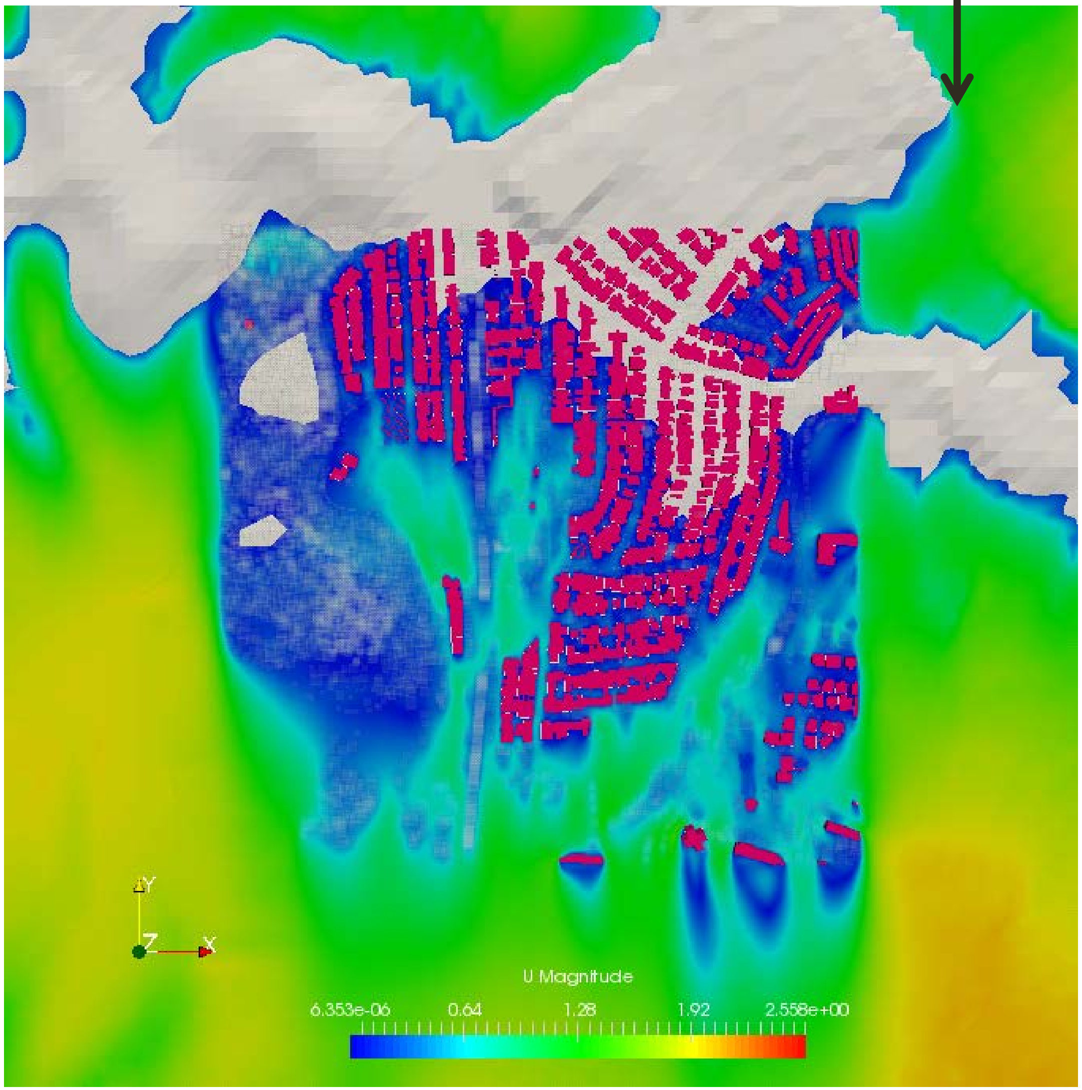
Wind direction



Trees = translucent white boxes spread through the region (rest same as before)

8 species & 1 "others" category (Total: ~**5450 trees**)

Drag Coefficient (C_d) = 0.2

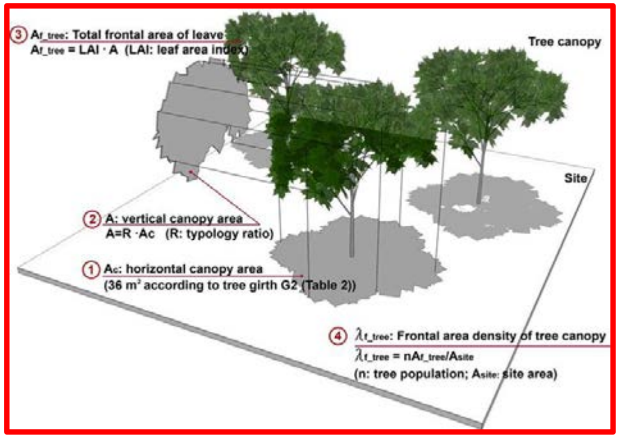
Specie	LAI	Ht (m)
Archontophoenix alexandra	5.76*	9.79#
Hopea odorata	6.32*	8.98#
Khaya senegalensis	5.9+	22.58#
Syzygium grande	4.82*	16.18#
Syzygium myrtifolium	6.13*	7.49#
Tabebouia rosea	3.45^	12.83#
Peltophorum pterocarpum	3.67^	12.52#
Samanea saman	0.5+	10.43#
Others	4.57**	11.54#

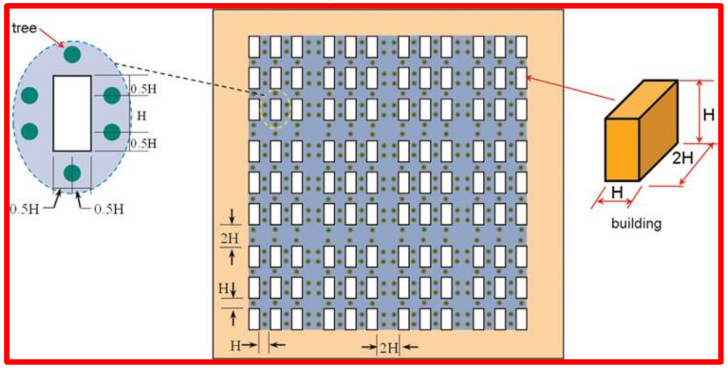
Note:
* = World Database
^ = NParks Photo Estimate
# = Median of dataset
+ = NParks Test
** = Average above

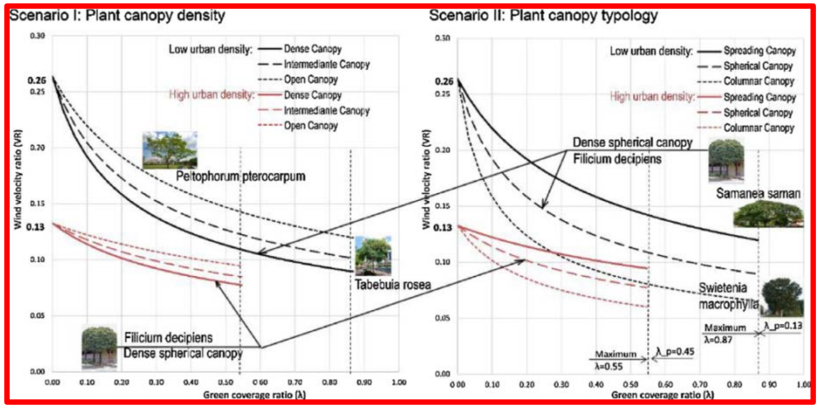
Future Applications – wind-tree simulation and tree management tool @ VS

Preliminary proposal [normalized tree wind load as a function of the site exposure/competition index] - WIP

1. Tree stability index (TSI) assessment based on tree crown ratio (CR), crown asymmetry index (CAI), tree height (H) & tree pressure loss coefficient [tree permeability] (λ)
2. Site index in terms of $\lambda_f = A_{front}/A_{site}$. $\lambda_{f,\ building} = (A_{front,\ building}/A_{site})$ & $\lambda_{f,\ tree} = (A_{front,\ tree}/A_{site})$
3. Index development based on 1km x 1km urban area simulation and analysis







Concluding Remarks

1. IEM deliverable - An integrated multi-physics urban microclimatic modelling platform for wind (Computational Fluid Dynamics-CFD), solar irradiance, shading analysis and environmental noise modelling for planning and urban design purposes

2. A VS-IEM widget has been constructed at VS platform

3. VS2 application:

    - To examine the influence of urban forest composition and structure on wind loads
    - To provide info urban forest planning and management policies by identifying landscape features associated with increased wind speed and turbulence.
    - To help prioritize tree pruning activities by identifying situations in which trees are more vulnerable to fast, turbulent flows.

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Thank you

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