Towards a generic method for the numerical analysis of tree biomechanics

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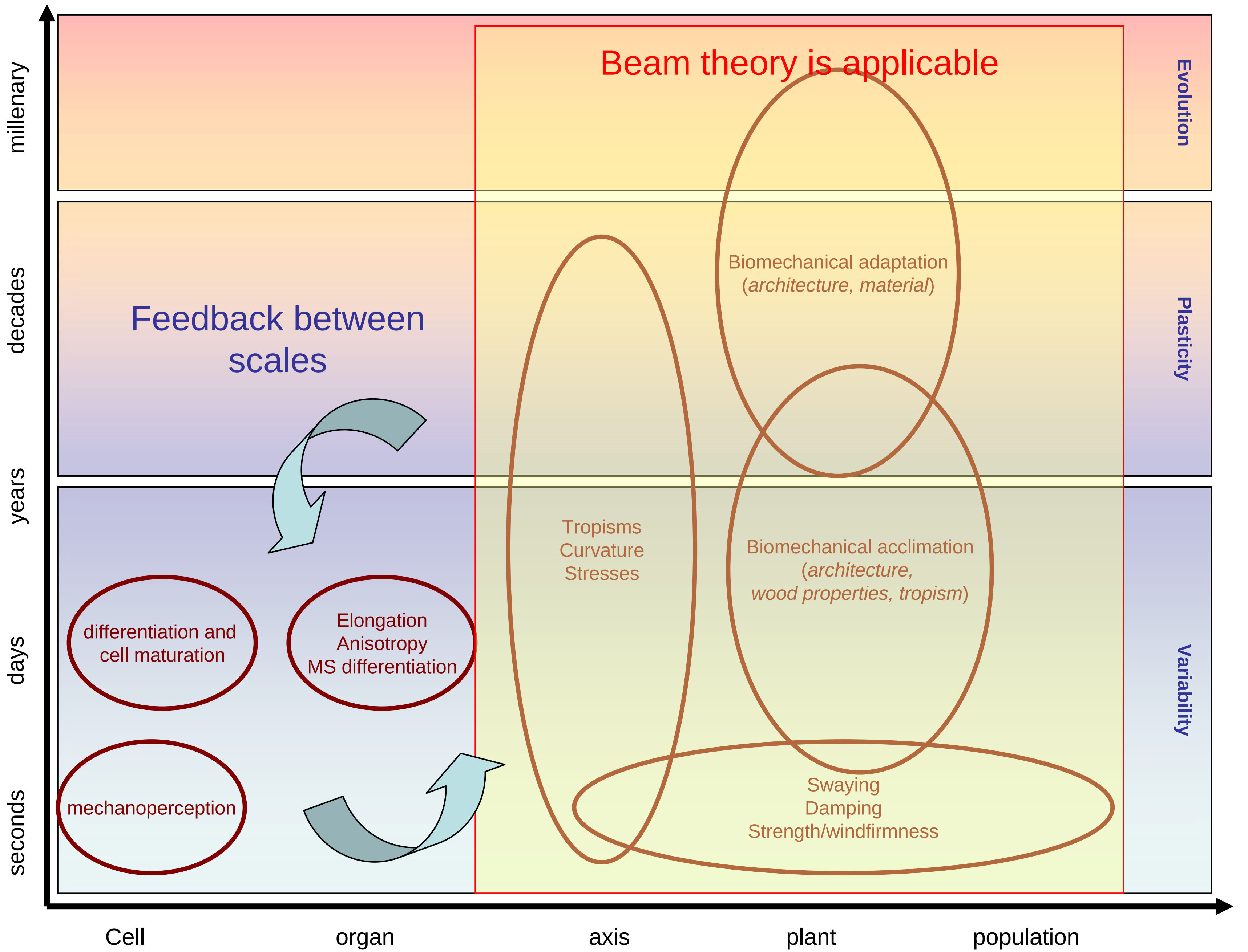
Montpellier, france

Tree biomechanics: time and spatial scales vs objectives

(Adapted from *Fourcaud, Moulia & Constant, PlantVirt 2008*)



Application of the FEM at the tree level : tree anchorage

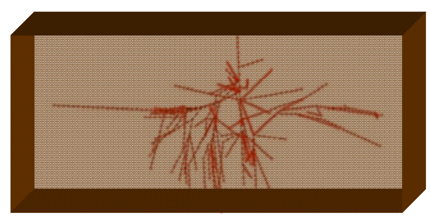
Level of description: tree architecture

Digitizing of real structures

Visualization et architectural analysis

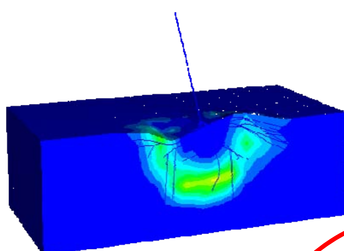
Encoding under MTG AMAP format (Godin *et al.*, 1999)

Meshing of the structure
Beam elements



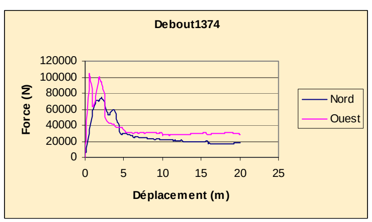
Addition de la matrice de sol

Command files generated for FEM analysis



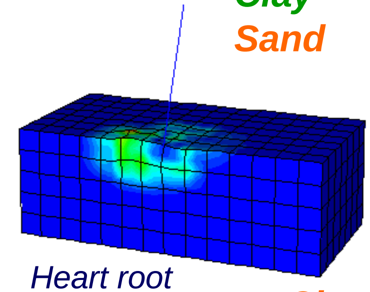
FEM calculation

ABAQUS



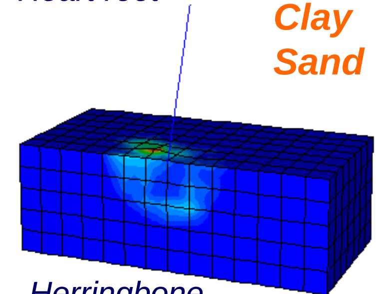
Results analysis and visualization

Clay
Sand



Heart root

Clay
Sand



Herringbone

Clay
Sand

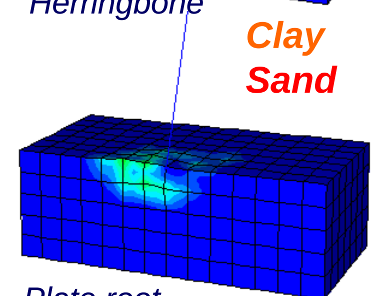
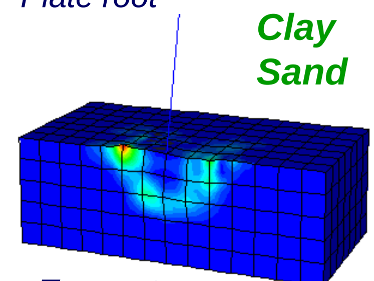


Plate root

Clay
Sand



Tap root

Dupuy et al., PLSO 2005
Dupuy et al., AJB, 2007

Application of the FEM at the tree level : tree dynamics

Level of description: tree architecture

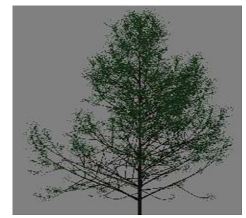
Dynamical model : $M\ddot{u} + C\dot{u} + Ku = F(t)$

Drag forces : $F^e(z,t) = c_D A^e \left(u(z,t) - \frac{\mathrm{d}q^e}{\mathrm{d}t} \right) \left| \left(u(z,t) - \frac{\mathrm{d}q^e}{\mathrm{d}t} \right) \right|.$

Damping matrix (Rayleigh's hypothesis) : $C = \alpha M + \beta K$

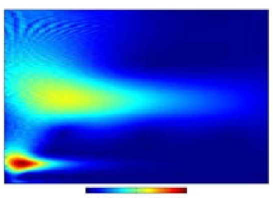
Digitizing of real structures

Encoding under MTG AMAP format (Godin et al., 1999)

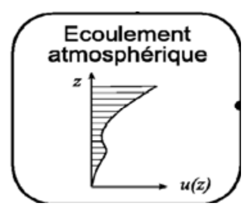


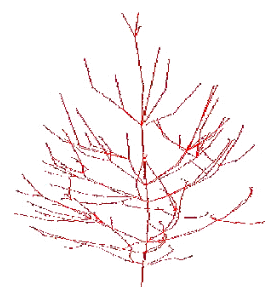
Visualization et architectural analysis

Meshing of the structure
Beam elements



Results analysis and visualization





FEM calculation

Command files generated for FEM analysis

Sellier et al., Tree Physiol 2006
Sellier et al., Forestry, 2008

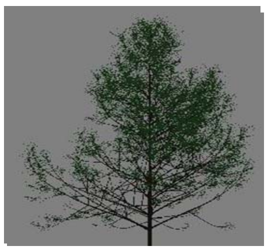
Application of the FEM at the tree level : form regulation and growth stresses

Level of description: tree architecture

Incremental formulation of VWP : $$\int_{\Omega_n} B^T \Delta\sigma_n d\Omega + \int_{\Delta\Omega_n} B^T \Delta\sigma_n d\Omega = \Delta f_n \qquad \sigma_N = \sum_{n=0}^{N-1} \Delta\sigma_n$$

Maturation strains : $$\alpha^e_{L,n} = a^e_n + \frac{\varsigma^e_n}{2}(b^e_n - a^e_n)(1+\cos(\theta-\psi^e_n))$$

START n=1



Simulated structure AMAPpara

Encoding under AMAPpara format

Visualization and analyses of results

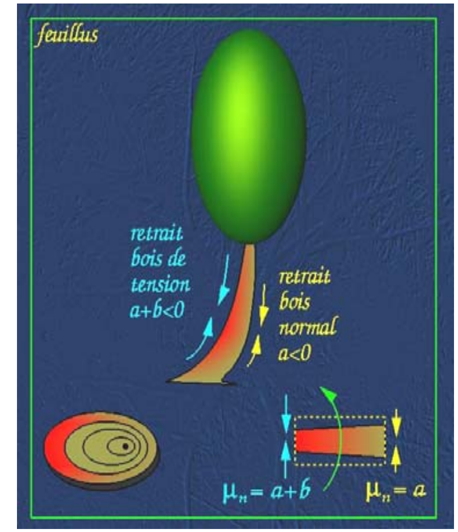
Meshing of the structure with *Beam elements*

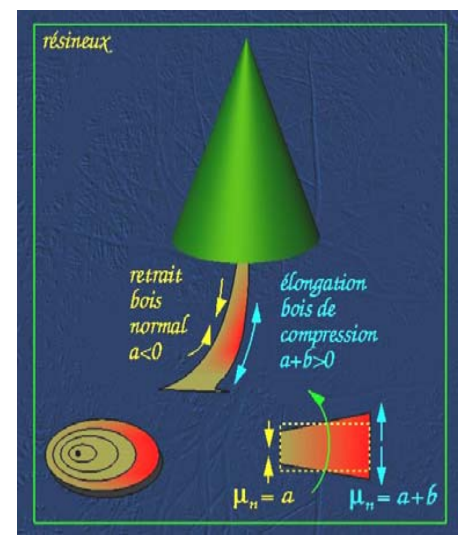
Biomass balance & tropisms

MEF computation
AMAPméca
Fourcaud et Lac, 2003
Fourcaud *et al.*, 2003

Updating of the geometry according to the computed displacements

n=n+1





Fourcaud & lac, Trees 2003
Fourcaud et al., Trees, 2003

Application of the FEM at the tree level : form regulation and growth stresses

Level of description: tree architecture

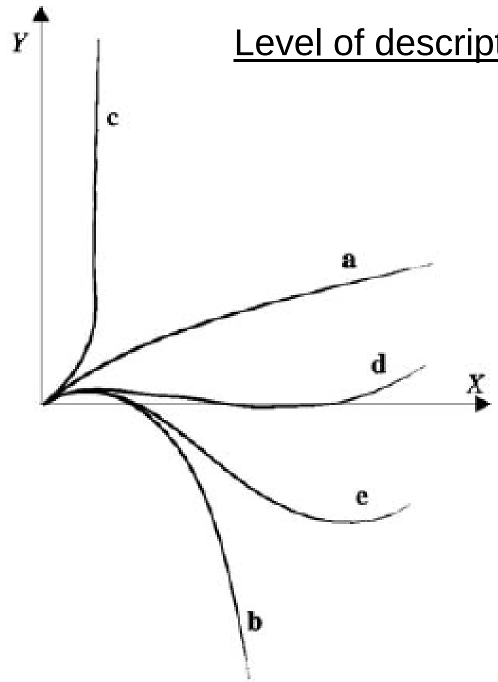


Fig. 3a–e Simulations of shoot bending under self-weight loading. Different shapes have been obtained for each branch, where different mechanical options have been considered (see Table 2). **a** Calculation of the branch curvature in one step where the total weight is applied, i.e. without considering the growth processes; **b** bending without secondary reaction or weeping habit; **c** orthotropic growth due to secondary reorientation; **d** plagiotropic growth due to secondary reaction; **e** bending with primary reaction and inhibited secondary reaction

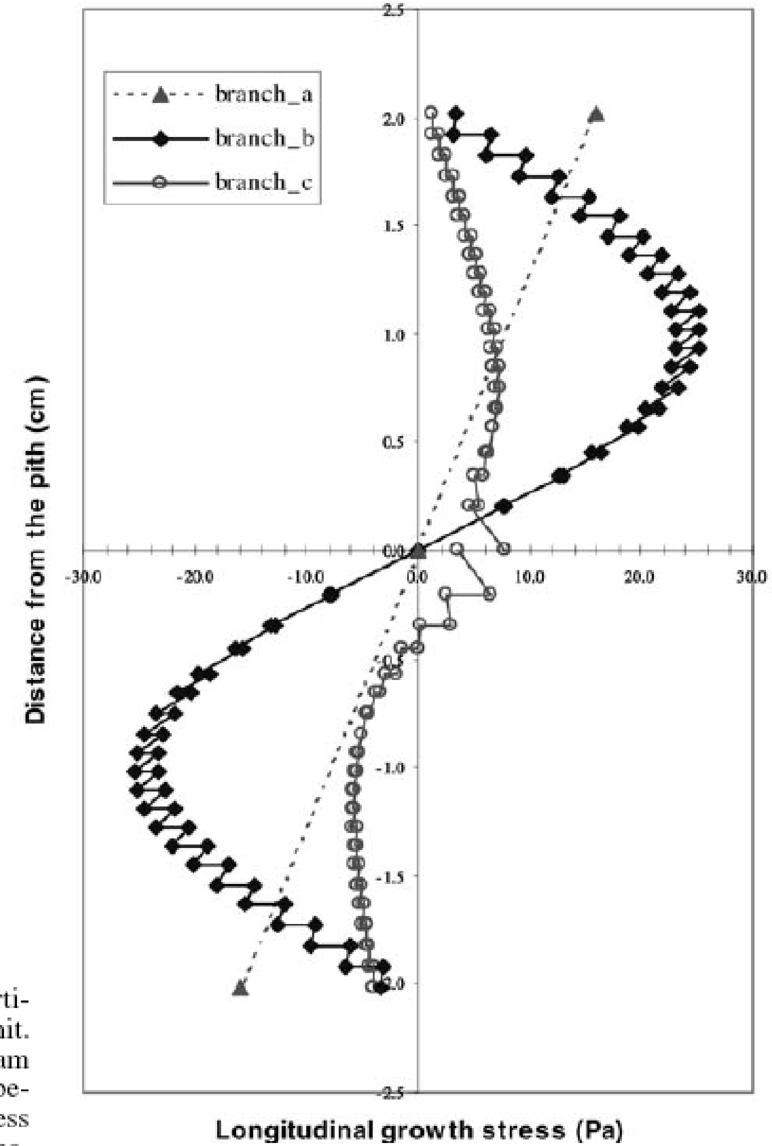


Fig. 4 Distribution of longitudinal growth stresses along the vertical cross section diameter at the middle of the basal growth unit. Curve *a* corresponds to a classical linear profile of a bending beam with maximum longitudinal stresses which are reached at the periphery. Branch *b* profile is the result of increment growth stress accumulation when radial and apical growth and resulting progressive loading are considered. This last distribution is modified when secondary reaction occurs (branch *c*). This is due both to the maturation stresses and to the shape difference in comparison with branch *b*

From Fourcaud et al., Trees, 2003

Application of the TMM at the population level : stand stability to wind

Level of description: tree stem + agregated crown

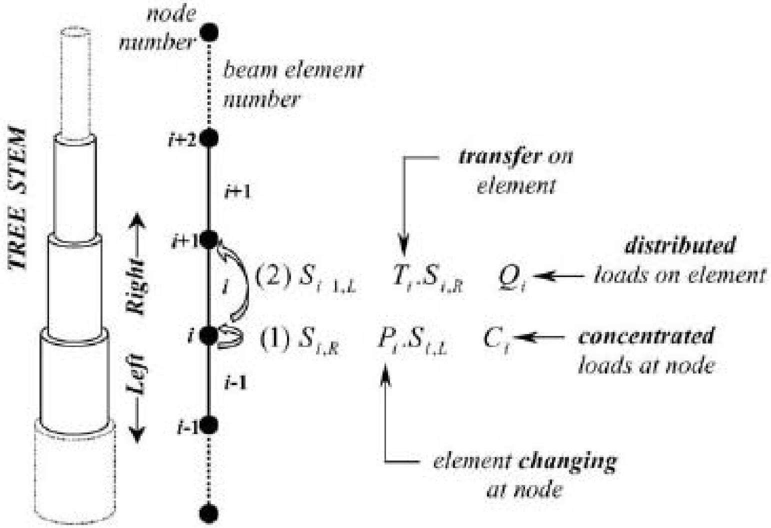


Fig. 1. Functional scheme of the transfer matrix method (TMM) applied on a tree stem. The TMM consists of determining the state vectors tracing the structure node by node. This stepwise process is based on two matrix relations: Eq. (1) to change the element at the nodes (example at node *i*); and relation (2) to operate the transfer on the elements (example on element *i*) and then to change the current node.

$$\begin{cases} S_O = \langle u_O\ v_O\ w_O\ \omega_{xO}\ \omega_{yO}\ \omega_{zO}\ \mid -N_{xO}\ -V_{yO}\ -V_{zO}\ -M_{xO}\ -M_{yO}\ -M_{zO} \rangle^t \\ S_E = \langle u_E\ v_E\ w_E\ \omega_{xE}\ \omega_{yE}\ \omega_{zE}\ \mid N_{xE}\ V_{yE}\ V_{zE}\ M_{xE}\ M_{yE}\ M_{zE} \rangle^t. \end{cases} \tag{A.3}$$

The transfer relation links S_E to S_O and is written [2]:

$$S_E = T.S_O + D, \tag{A.4}$$

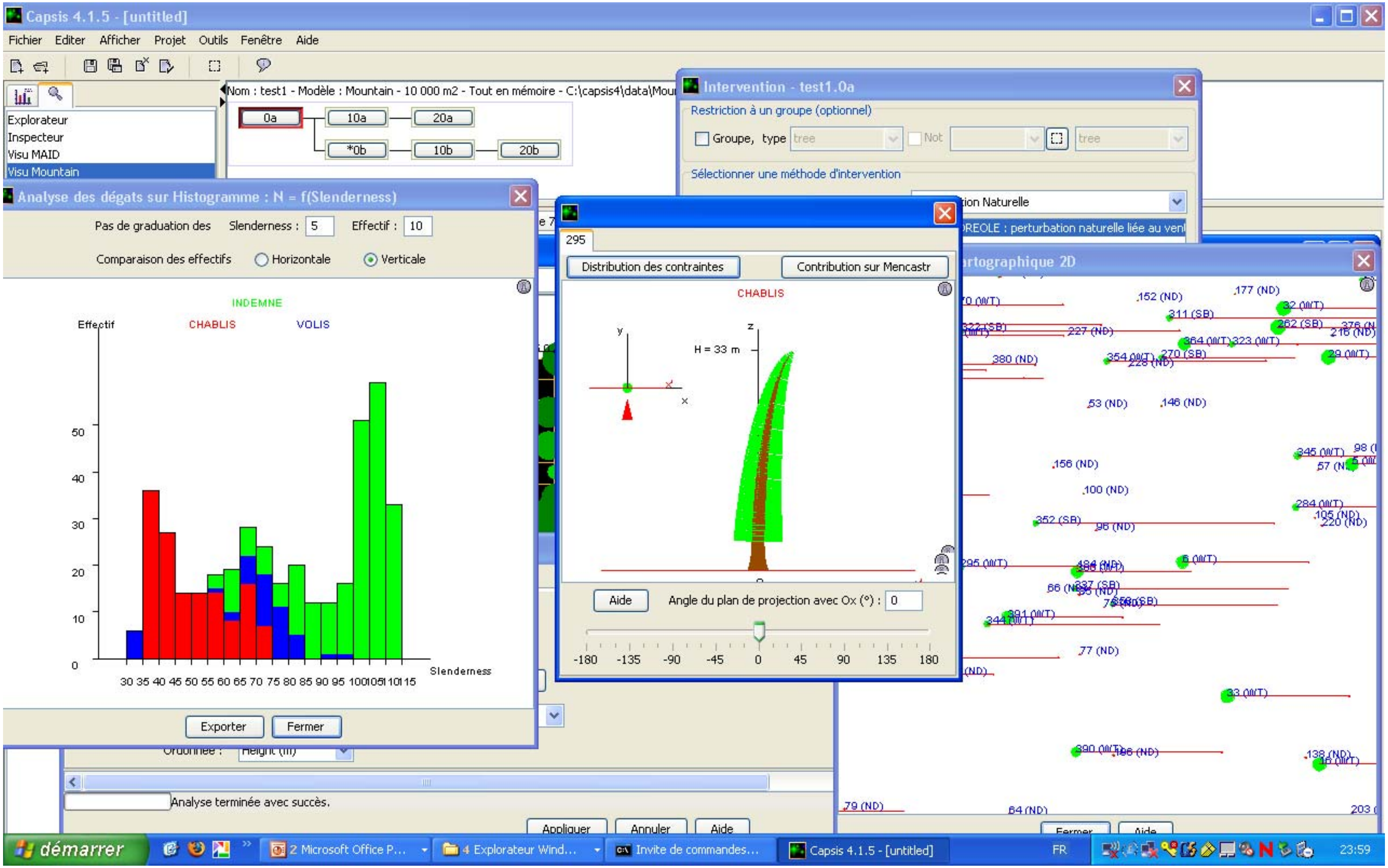
where T is the transfer matrix of the beam and D is the state vector of distributed loads. T and D matrices are given by:

$$T = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}; \qquad D = \begin{pmatrix} D_1 \\ D_2 \end{pmatrix} \tag{A.5}$$

From Ancelin et al., AFS 003
& Ancelin et al., FEM 2004

Application of the TMM at the population level : stand stability to wind

<u>Level of description</u>: tree stem + agregated crown



From Ancelin et al., FEM 2004

Application of the TMM at the population level : form regulation and growth stresses

Level of description: tree stem + agregated crown

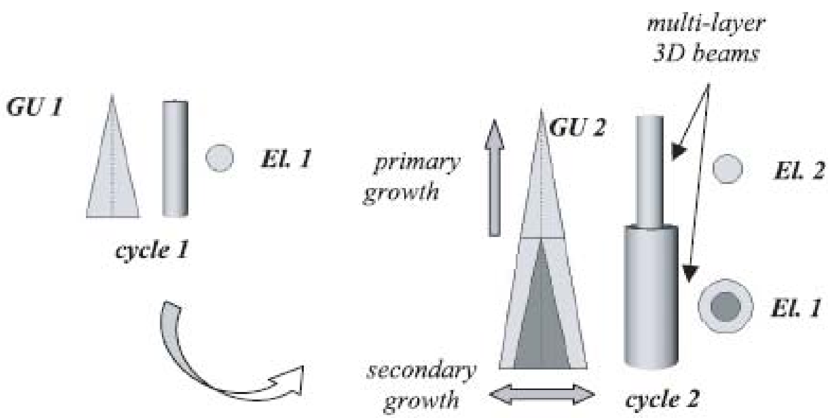


Figure 1. Description and discretization of the stem structure. At each cycle of growth, a new vegetative element is built at the stem tip due to the primary growth. A new layer of wood is formed at the stem periphery due to secondary growth. The tapered trunk is approximated by a series of multi-layer 3D straight beam elements. Primary growth necessitates adding a new element at the top extremity of the slender structure. Secondary growth is taken into account by adding a new external layer to the existing elements.

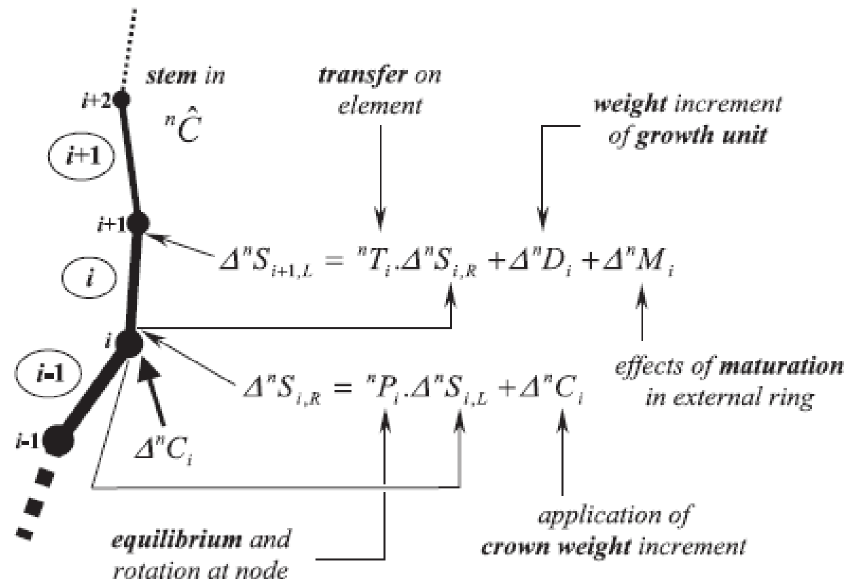
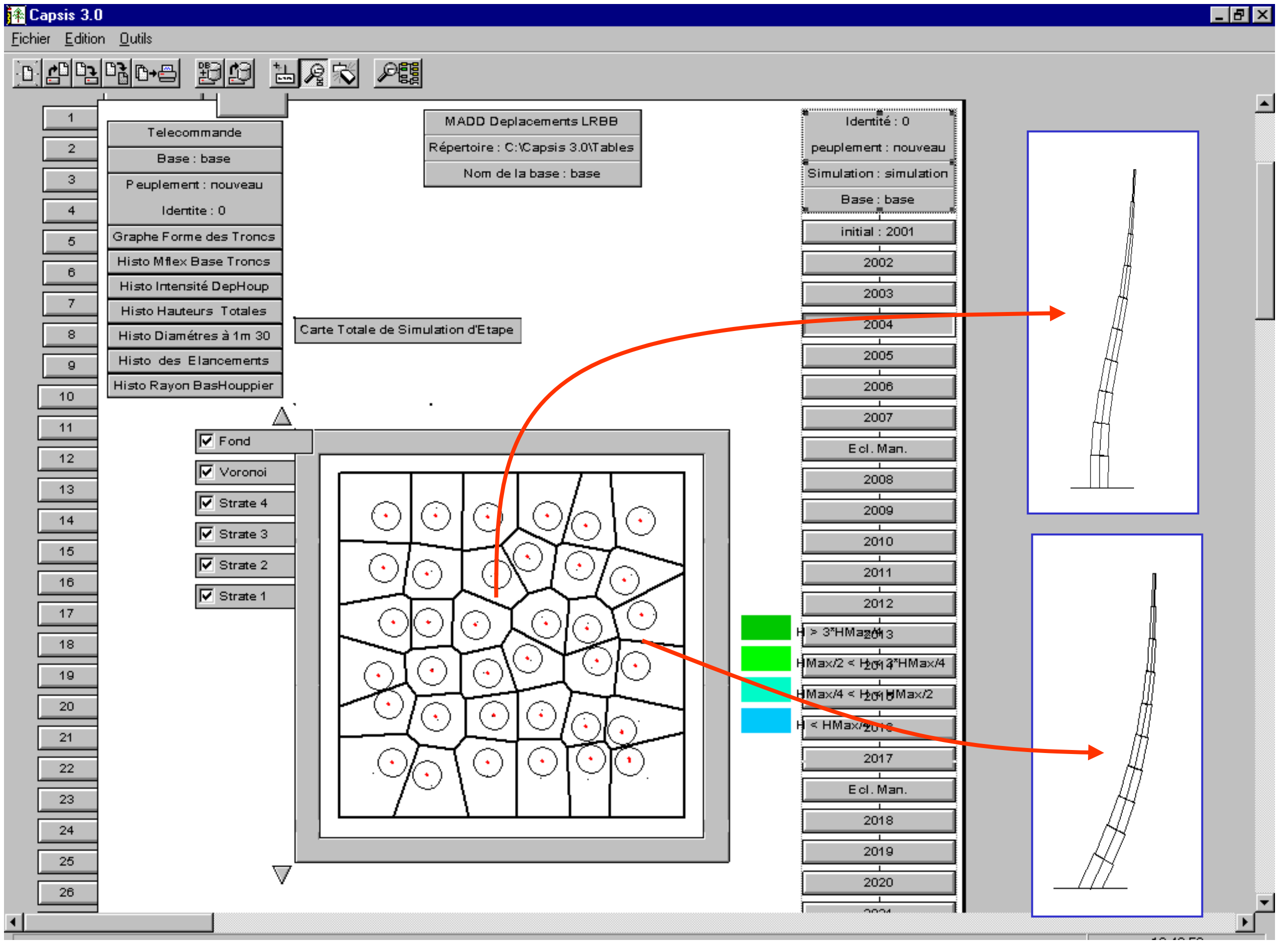


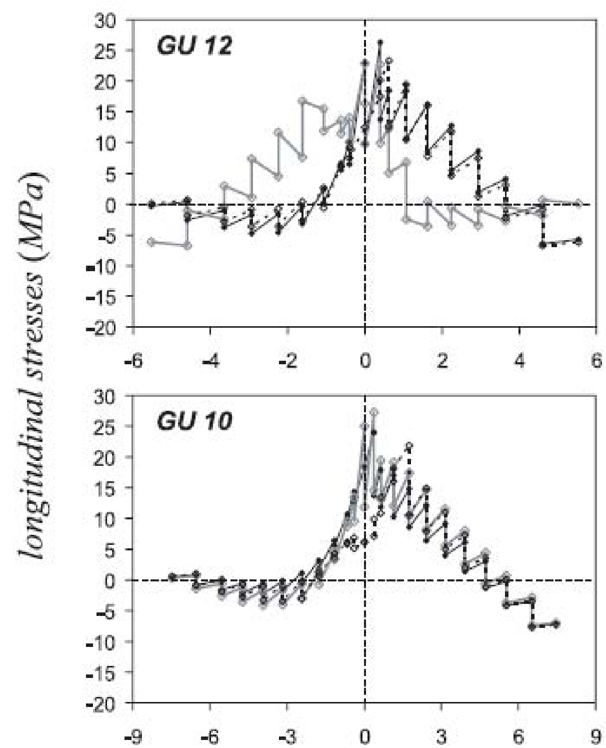
Figure 3. Functional scheme of the Incremental Transfer Matrix Method (*ITMM*) applied on a growing tree trunk. The stem is discretized with beam elements which are connected to each other by nodes. The *ITMM* consists of determining the state vectors tracing the structure node by node. Considering element i, state vector of the beam origin (node i) is determined using the equilibrium equation with the previous adjacent element $i-1$. State vector of the extremity node $i+1$ is calculated using the transfer relation on element i.

From Ancelin et al., FEM 2004

Application of the TMM at the population level : form regulation and growth stresses

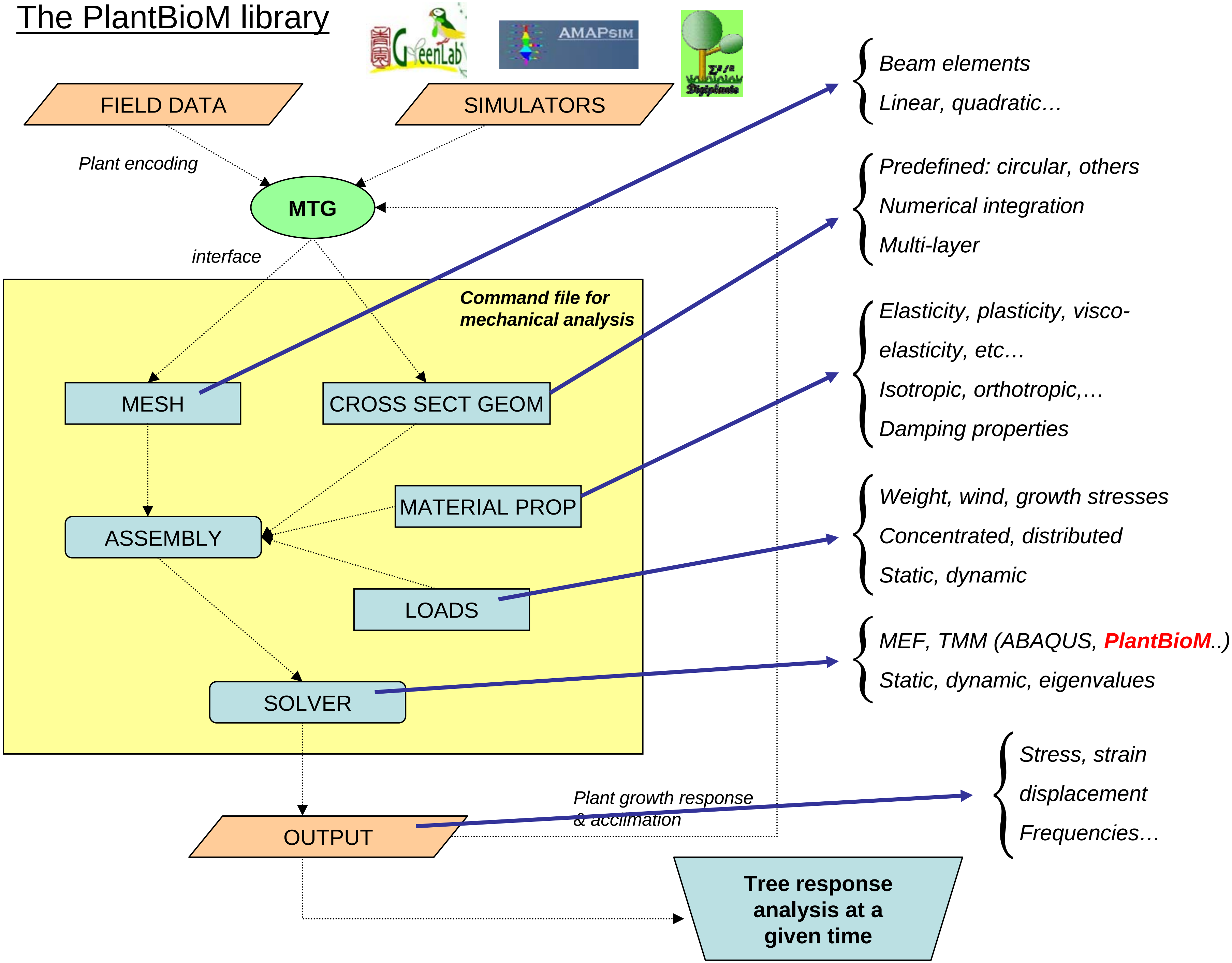
Level of description: tree stem + agregated crown





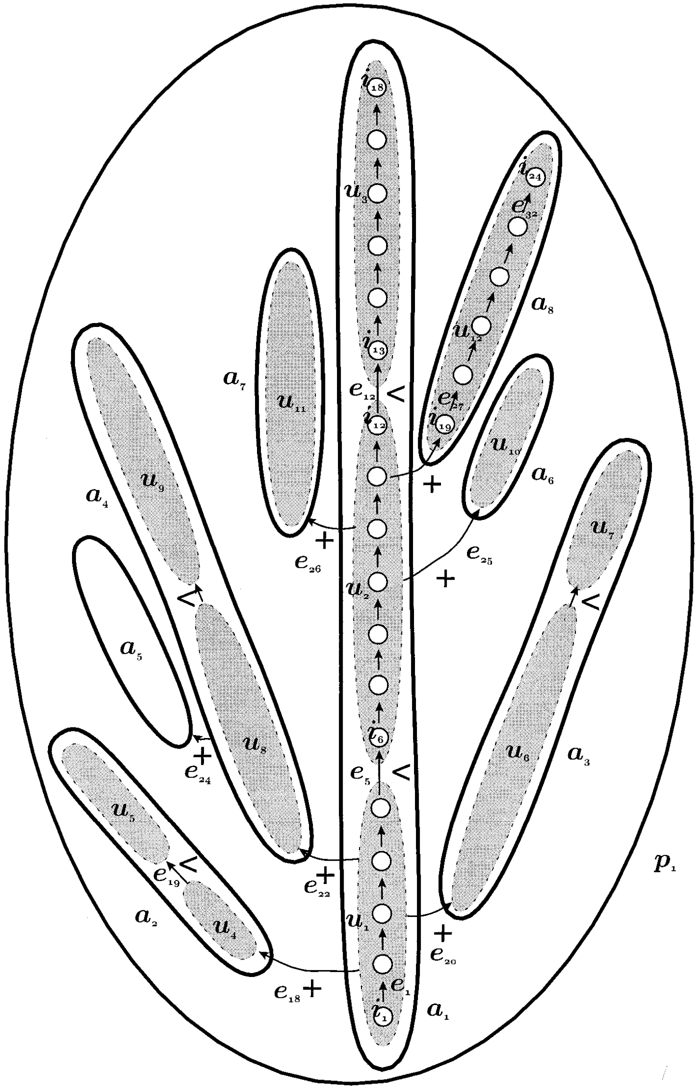
Ancelin et al., AFS 2003

The PlantBioM library



Encoding plant architecture

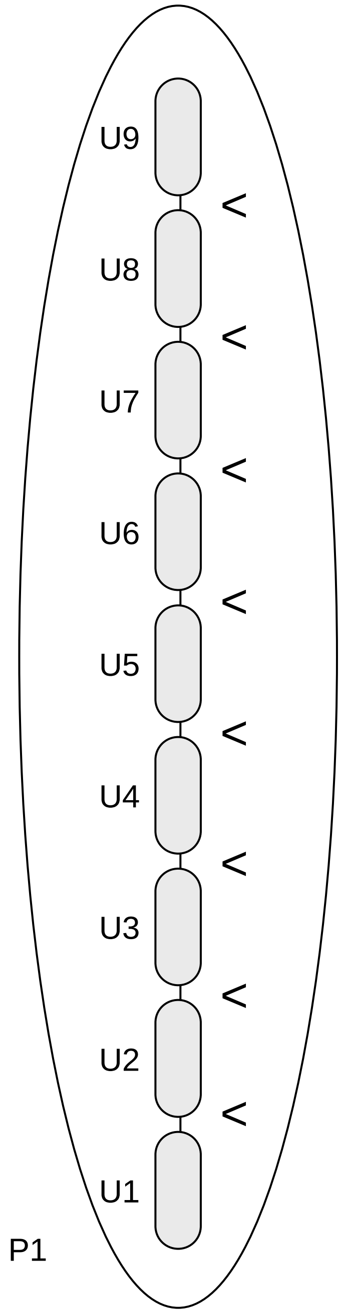
MTG



from Godin and Caraglio, JTB 1998

```
#D:/Mes Donnees/WorkDir/AMAPsim/Output\pinoir_9_0.mtg
#Tue Oct 07 22:07:48 2008

CODE:           FORM-A

CLASSES:
SYMBOL          SCALE           DECOMPOSITIC INDEXATION    DEFINITION
$                             0 FREE          FREE          IMPLICIT
P                             1 CONNECTED     FREE          EXPLICIT
B                             2 LINEAR        FREE          EXPLICIT
U                             3 LINEAR        FREE          EXPLICIT
E                             5 LINEAR        FREE          EXPLICIT

DESCRIPTION :
LEFT            RIGHT           RELTYPE         MAX
B               B               +               ?
U               U               +               ?
U               U               <                           1
E               E               +               ?
E               E               <                           1

FEATURES:
NAME            TYPE
XX              REAL
YY              REAL
ZZ              REAL
Dia             REAL

MTG:

ENTITY-CODE                                                 XX              YY              ZZ              Dia
/P1
^/B1                                                                      0               0               0 3.9048
^/U1
^/E1                                                        9.99997e-005                    0               2 3.864
^<E2                                                        0.0002                          0               3 3.8436
^<E3                                                        0.0003                          0               4 3.8232
^<E4                                                        0.0004                          0               5 3.8028
^<E5                                                        0.0005                          0               6 3.7824
^<E6                                                        0.0006                          0               7 3.762
^<E7                                                        0.0007                          0               8 3.7416
                ^/U1
                ^/E1                                        -2.7744         -1.13116        16.117          0.869943
                ^<E2                                        -3.69839        -1.50768        16.1839         0.859257
                ^<E3                                        -4.62142        -1.88381        16.2648         0.848571
                ^<E4                                        -5.54331        -2.25947        16.3596         0.837886
                ^<E5                                        -6.46389        -2.6346         16.4683         0.816514
                                ^/U1
                                ^/E1                        -7.75945        0.39673         16.0269         0.5958
                                ^<E2                        -8.15103        1.31293         15.9418         0.5856
                                ^<E3                        -8.54327        2.23068         15.8795         0.5754
                                ^<E4                        -8.93597        3.1495          15.84           0.5652
                                ^<U2
                                ^/E1                        -10.1148        5.90758         15.8586         0.5346
                                ^<E2                        -10.5072        6.82588         15.9104         0.5244
                                ^<E3                        -10.8991        7.74285         15.985          0.5142
                                ^<E4                        -11.2903        8.65802         16.0824         0.504
                ^<U2
                ^/E1                                        -9.2159         -3.75603        16.8778         0.763086
                ^<E2                                        -10.1294        -4.12827        17.0419         0.7524
                ^<E3                                        -11.0407        -4.49962        17.2198         0.741714
                ^<E4                                        -11.9496        -4.86999        17.4115         0.720343
                ^<E5                                        -12.8559        -5.23931        17.6169         0.709657
                ^<E6                                        -13.7595        -5.60751        17.8359         0.698971
                ^<E7                                        -14.6601        -5.97452        18.0686         0.688286
```

Encoding plant architecture



MTG for a single stem…

```
#Mon Sep 03 16:26:45 2007

#file D:/AmapsimTravail/pinoirmil.fpa
#age 9
#seed 0

CODE:       FORM-A

CLASSES:
SYMBOL      SCALE       DECOMPOSI  INDEXATION  DEFINITION
$                   0   FREE       FREE        IMPLICIT
P                   1   CONNECTED  FREE        EXPLICIT
U                   3   LINEAR     FREE        EXPLICIT

DESCRIPTION :
LEFT        RIGHT       RELTYPE    MAX
U           U           +          ?

FEATURES:
NAME        TYPE

XX          REAL
YY          REAL
ZZ          REAL
Dia         REAL
Mass        REAL

MTG:

ENTITY-CODE         XX            YY             ZZ    Dia      Mass
/P1                           0              0      0  4.7616   0,00
^/U1                0.000704967   2.07293e-013      8  4.6188   0,00
^<U2                0.0019097     3.73978e-013     20  4.374    3,21
^<U3                0.00331413    5.01184e-013     34  4.0884   2,90
^<U4                0.00701883    5.0703e-013      71  3.3336   3,08
^<U5                0.0105239     5.05157e-013    106  2.6196   2,50
^<U6                0.0135287     5.18161e-013    136  2.0076   1,12
^<U7                0.0163337     5.36991e-013    164  1.4364   0,76
^<U8                0.0185386     5.85053e-013    186  0.9876   0,78
^<U9                0.020443      6.21346e-013    205  0.6      0,35
```

Example of an Abaqus input file

Nodes definition

```
*HEADING
*** *** *** - NODES - *** *** ***
*NODE, NSET=NALL
1,      0.0,    0.0,    0.0
2,      -1.86169e-012,      0.0,    0.01
3,      9.99998e-007, 0.0,    0.02
4,      2e-006,       0.0,    0.03
(...)
105,    3.1e-005,     0.0,    0.32
106,    3.2e-005,     0.0,    0.33
*NSET, NSET=NBASE
1
*NSET, NSET=NTOP
106
*NSET, NSET=NDEUXTIERS
94
```

Elements definition

```
*** *** *** - ELEMENTS - *** *** ***
*ELEMENT,TYPE=B31, ELSET=ELALL
1,      1,      2
2,      2,      6
3,      6,      8
(...)
32,     87,     92
*** *** *** - ELEMENT SETS suivant lordre de ramif - *** *** ***
*** *** *** - ELEMENT SETS suivant les branches - *** *** ***
*ELSET, ELSET=TRONC
1,
2,
3,
10,
```

Beam section definition

```
*** *** *** - NODE SETS suivant les branches - *** *** ***
*** *** *** - PROPRIETES DES ELEMENTS - *** *** ***
*BEAM SECTION, ELSET=EL-1, SECTION=CIRC, MATERIAL=WOOD-1-nonNee
0.006264
0,-1.0,0.0
*BEAM SECTION, ELSET=EL-2, SECTION=CIRC, MATERIAL=WOOD-2-Nee
0.00606
0,-4.0,0.0
(...)
*BEAM SECTION, ELSET=EL-31, SECTION=CIRC, MATERIAL=WOOD-31-Nee
0.0019721425
0,-3.6301,0.307934325603
*BEAM SECTION, ELSET=EL-32, SECTION=CIRC, MATERIAL=WOOD-32-Nee
0.001705
0,-3.6617,0.304921990915
```

Material definition

```
*** *** *** - MATERIAUX - *** *** ***
*MATERIAL, NAME=WOOD-1-nonNee
*ELASTIC
1000000000.0,0.38
*DENSITY
900
*DAMPING, ALPHA=0.32,BETA=0.001
***
*MATERIAL, NAME=WOOD-2-Nee
*ELASTIC
1000000000.0,0.38
*DENSITY
1983.46501359
*DAMPING, ALPHA=0.516649500858,BETA=0.001
***
(...)
*MATERIAL, NAME=WOOD-32-Nee
*ELASTIC
1000000000.0,0.38
*DENSITY
7743.54895004
*DAMPING, ALPHA=0.638158719976,BETA=0.001
***
```

Loads and boundary conditions

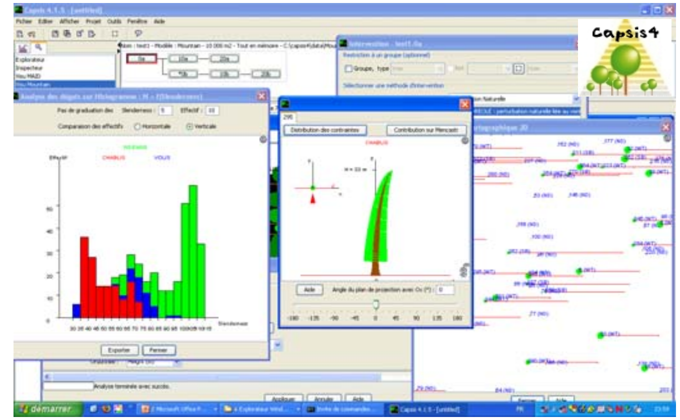
```
*** *** *** - CONDITIONS LIMITES - *** *** ***
*BOUNDARY
NBASE, ENCASTRE
```

Calculation steps

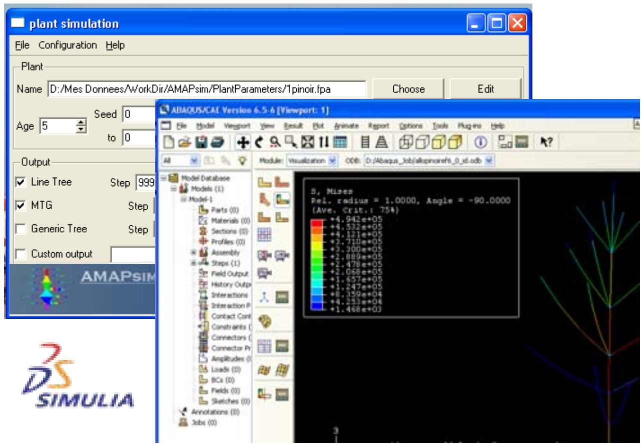
```
*** *** *** - ANALYSE MODALE - *** *** ***
*STEP
*FREQUENCY
100,,,,,
*OUTPUT, HISTORY, VARIABLE=PRESELECT
*OUTPUT, FIELD, VARIABLE=PRESELECT
*NODE OUTPUT, NSET=NALL
coord
*ELEMENT OUTPUT, ELSET=ELALL
s,se
*END STEP
```

Open discussion and demos…

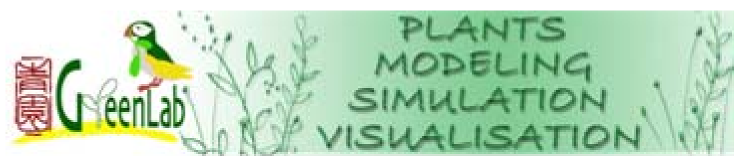
FOREOLE in Capsis



from AMAPsim to Abaqus



PlantBioM in Scilab…



about AMAPméca

Other…