Interactive Simulation of Plant Architecture Based on a Dual-Scale Automaton Model

X. Zhao[1,4] , P. de Reffye[2,4] , D. Barthélémy[2,5], B.-G. Hu[1,3]

[1] *National Laboratory of Pattern Recognition, Institute of Automation, Chinese Academy of Sciences, 2728# Box, 100081, Beijing, China*
[2] *UMR AMAP, CIRAD, TA 40/PS2, 34398 Montpellier Cedex 5, France*
[3] *Sino-French Laboratory in Information Automation and Applied Mathematics, Institute of Automation, Chinese Academy of Sciences, 2728# Box, 100081, Beijing, China*
[4] *INRIA, Projet Metalau, Rocquencourt, France*
[5] *INRA, Département Forêts et Milieux Naturels, France*

Abstract

This paper briefly introduces how to simulate plant topological structure and development by a plant architectural model, dual-scale automaton model. This computer model is faithful to botanical structure and knowledge and its parameters have a strong botanical meaning. The software "Visualplant", based on dual-scale automaton model, can interactively generate almost all kinds of plant architectures by its graphics interface. Several examples of inflorescences and plant architectural models simulated by this model are presented as examples of its functionality.

Keywords: dual-scale, automaton, plant topological structure, inflorescence, plant architectural model

1 Introduction

In recent years, the use of different techniques has resulted in remarkable outcomes in the simulation and visualisation of plants. L-systems were firstly introduced by Lindenmayer[1] for simulating the development of multicellular organisms and were then powerfully and widely used and extend for plant modelling by Prusinkiewicz and collaborators [2, 3]. However, this grammar-based approach mixes plant geometrical aspects and topological structure so that it is difficult to understand in some cases. The IFS (Iterated Function System) method [4] is efficient for the simulation of strict fractal objects, but its application to plant development modelling results difficult. Godin and collaborators [5, 6, 7] introduced a MTG (Multiscale Tree Graph) model to represent the multiscale static topological structure of a plant; this model is suitable to analyse and represent the topological structure and growth of a given plant. The interactive plants modelling method was introduced by Lintermann and Deussen [8] and represents a graph-based model for applications in computer graphics; although it can generate a plant structure interactively by three types of component, it is not a process-based model.

AMAP models [9, 10, 11, 12] were originally developed for simulating mainly trees. They use (1) the qualitative knowledge provided by Hallé et al. [13, 14] in plant architecture and (2) the quantitative methods perfected within the Plants Modeling Unit of CIRAD. These models were first concerned with tree architecture and landscape visualisation and then turned to some agronomic applications but their use is somewhat complex and mainly limited to specialists.

Despite these results an interactive computer model faithful to botanical structure and development is thus still necessary in order to represent plant architectural and morphological diversity. In this paper, we briefly introduce a new model of plant topological structure and development, named dual-scale automaton model. On the basis of just above cited previous results, this mathematical macroscopic model uses the notion of "physiological age" [15] to describe plant development interactively. In this model, the developmental process from one stage to another is processed as a Semi-Markov chain, and is described by a mathematical automaton. This graph-based model separates plant geometrical properties from plant topological structure, and allows a simple and interactive plant architecture simulation. In the following section we briefly introduce the mathematical principles of this model. In section 3, we present the interactive simulation of plant topological structure based on dual-scale automaton model. Several examples are presented in section 4 and 5 to demonstrate the adequacy of this model to simulate inflorescences and plant architectural models. All the figures presented are generated by our software "Visualplant" (see section 3), which is based on this dual-scale automaton model.

2 Brief Introduction of Dual−Scale Automaton Model

The dual-scale automaton is used to generate plant topological structure and its parameters have a high and faithful botanical meaning based on botanical notions related with plant structure.

- The metamer (or phytomer) is the basic entity of a plant structure; it corresponds to the set composed by (1) one internode, (2) the node (i.e. point of insertion of the leaves on a stem) located at its tip and (3) the one or several leaves and axillary buds associated with, and borne by, this node [16, 17, 12].
- In rhythmically growing plants, a growth unit is the portion of a stem, i.e. the set of corresponding metamers, elongated during one continuous period of extension between two successive resting phases [14, 10].
- The functioning of a meristem can be characterised by two different ages [15]: (1) the "chronological age" of a meristem depends on the time, or period (i.e. year of formation for instance), in which the structures it produced have been edified, whereas (2) the "physiological age" of a meristem relates to the degree of differentiation of the structures (metamers, growth units, axis…) it produced. The physiological age of a meristem may be estimated *a posteriori* by a series of qualitative and quantitative criteria. For example the short axes of some trees are characteristic of a physiologically-aged structure: growth units are short, bear flowers and have a short lifetime. These highly differentiated axes may be considered to be "physiologically old" whatever their moment of appearance. On the contrary, main axes made of vigorous growth units may be considered to be 'physiologically young' productions and generally appear only in the young tree.

In our model, an axis is made of a succession of growth units produced in successive growth cycles: they are defined as "macrostates" and are repeated along the plant axis with transition laws from a macrostate to another. The growth unit itself is made of a succession of metamers that are considered as "microstates". Our dual-scale automaton model can be well represented as a directed graph, with the metamers or growth units representing states whereas arcs represent transitions.

Our model can be illustrated by a simple structure made of only 3 macrostates respectively corresponding to three different physiological ages each being represented by a different colour for clarity (Fig.1). The first and the second macrostate each consist of two microstates where the first microstate is represented by a metamer that cannot branched (no lateral bud, i.e. no diamond on illustration) whereas the second microstate (i.e. metamer) bears a lateral bud (diamond) that will produce a new metamer, whose physiological age will be immediately "older", during the following growth cycle (indicated by the colour of the diamond). In our example, the third macrostate corresponds to only one microstate (metamer) of the third physiological age and is unable to put forth a branch (no diamond). In this example (Fig.1) we consider a deterministic model: the repetition time of each microstate inside macrostate (i.e. transition probability) is always 1 whereas the repetition time of each macrostate (respectively 3, 2, and 1 for physiological ages 1, 2 and 3) is indicated by real line arrows in Fig.1.

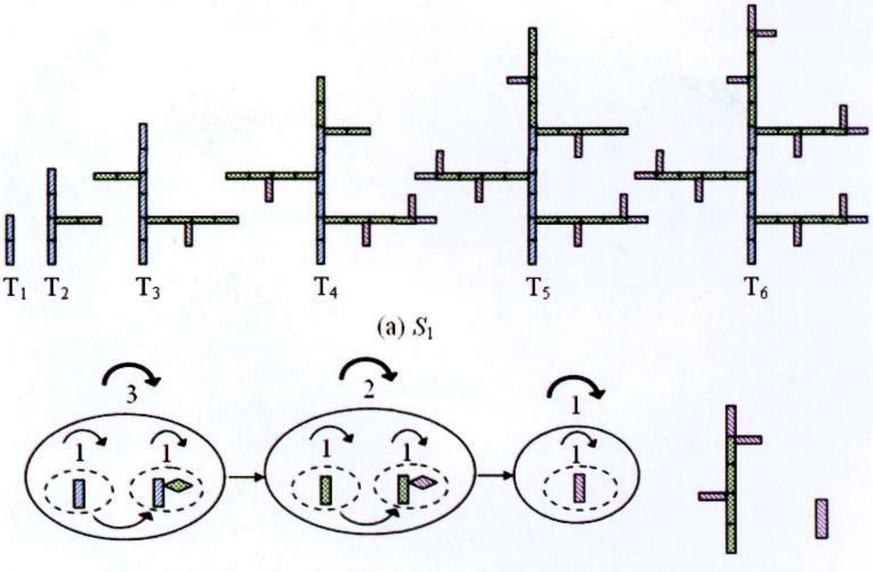


Fig.1 A simple structure S_1 made with three physiological ages and the corresponding automaton. (a) From 1st cycle to 6th cycle, the resulting structure S_1 at each cycle, (b) automaton, (c) substructure S_2, (d) substructure S_3

In our example the complete structure is edified in 6 growth cycles (T_1 to T_6) and the automaton can dynamically generate all the successive topological structures constructed during plant development. When the first growth cycle elapses, the macrostate1, i.e. the first growth unit, is built up (as represented by the diagram at the left end of Fig.1(a)), and includes two metamers with only one axillary bud on its last microstate. During cycle 2 (T_2), the macrostate1 is repeated and the second growth unit is built up; at the same time, the axillary bud of the first growth unit produces a lateral growth unit whose physiological age is older than the one of the main stem. The process goes through the 6 growth cycle in conformity with the automaton and the complete structure (S_1) is thus built up in T_6. Only the last structure S_1 is a complete structure: the other 5 structures of Fig.1(a), also called snapshot of the whole structure S_1 at cycle *t*, are growing structures. According to these rules, incomplete substructures may be identified as substructure S_2 in Fig.1(c) and substructure S_3 in Fig.1(d).

3 Interactive Generation of Plant Topological Structure

The use of this modelling system has been improved with the addition of a graphical user interface, allowing the user interactive modelling. As shown in Fig.2, this graphical user interface is used to input the parameters of the automaton in our software "Visualplant". The upper part of this interface is concerned with the microstates according to their physiological age (5 in this case). Since the model is a multi-scale model, it is easy to input the parameters of models according the level of organisation. Only by clicking the button of microstate covered with the graph of microstate, the microstate is inputted into the corresponding macrostate, which are shown in the lower part of this interface.

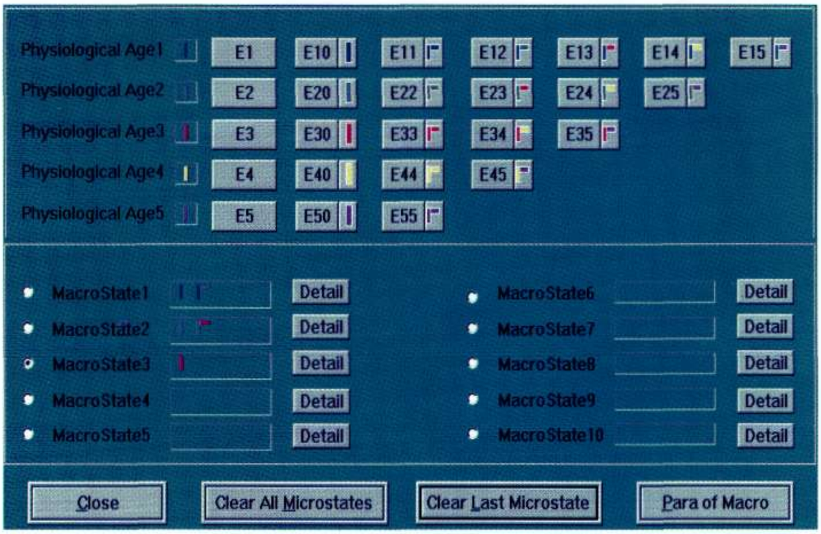
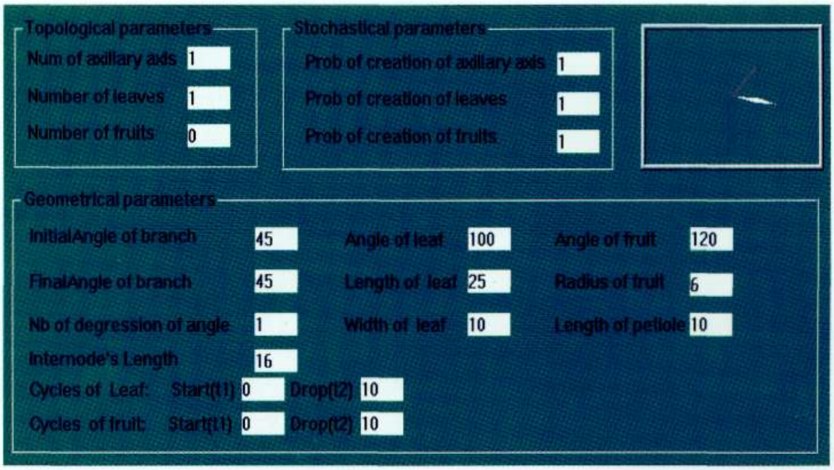


Fig.2 The graphical user interface of the software "Visualplant" (for legend see text)

Although our automaton model is fundamental for the description of meristem activity, it can also be extended to integrate geometrical properties (e.g., size, angle, shape…). Plant geometrical properties are described separately from plant topological structure using the "Microstate properties table". In this table (Fig.3) each microstate is associated with a geometrical property; entering of parameter values being manual it allows an interactive and greater accuracy of modelling. It should be mentioned that most of parameters could be variables and follow certain distributions that may be defined by adequate functions. For example, the numbers of the metamers in a Growth Unit of a certain physiological age are usually defined by statistical distribution [18].



Topological parameters
Num of axillary axis 1
Number of leaves 1
Number of fruits 0

Stochastical parameters
Prob of creation of axillary axis 1
Prob of creation of leaves 1
Prob of creation of fruits 1

Geometrical parameters
InitialAngle of branch 45
FinalAngle of branch 45
Nb of degression of angle 1
Internode's Length 16
Angle of leaf 100
Length of leaf 25
Width of leaf 10
Angle of fruit 120
Radius of fruit 6
Length of petiole 10
Cycles of Leaf: Start(t1) 0 Drop(t2) 10
Cycles of fruit: Start(t1) 0 Drop(t2) 10

Fig.3 The table of microstate properties in visualplant (for legend see text)

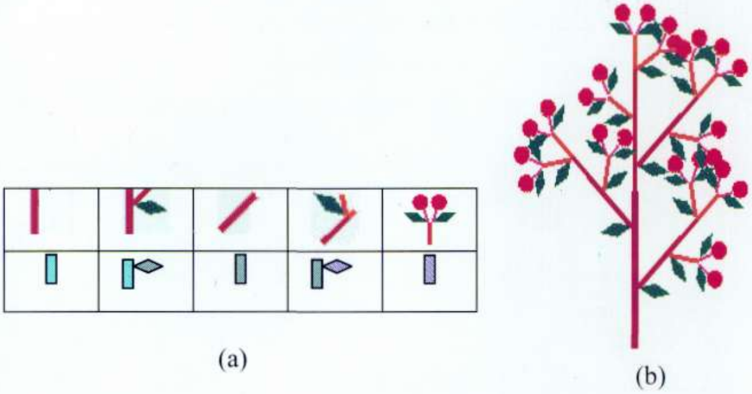


Fig.4 (a) Relations between metamers (i.e. microstates) and their geometrical properties and (b) resulting 2D representation corresponding to the topological structure of Fig.1(a)

Geometrical properties may then be attached to corresponding metamers (i.e.) microstates). If we do so for the automaton shown in Fig.1(b) corresponding metamers may then be represented in relation with their geometrical properties, as shown in Fig.4(a), and finally the 2D representation of Fig.4(b), corresponds to the whole topological structure S_1 shown in Fig.1(a).

4 Simulation of Plant Architectural Models

"For a tree the growth pattern which determines the successive architectural phases is called its architectural model, or shorter, its model." [14]. The architectural model [13] is an inherent growth strategy that defines both the manner in which the plant elaborates its form, and the resulting architecture. It expresses the nature and the sequence of activity of the endogenous morphogenetic processes of the organism, and corresponds to the fundamental growth program on which the entire architecture is established. Each architectural model is named after a well-known botanist and is defined by a particular combination of four major groups of simple morphological features that are well documented [13, 14] i.e. (1) growth pattern (rhythmic or continuous growth), (2) branching pattern (presence or absence of vegetative branching - terminal or lateral branching - monopodial or sympodial branching - rhythmic, continuous or diffuse branching), (3) morphological differentiation of axes (orthotropy or plagiotropy), and (4) position of sexuality (terminal or lateral). Though the number of these combinations is theoretically very high, there are apparently only 23 architectural models found in nature. The ability to simulate these architectural models is an important criterion for the validation of plant model. Dual-scale automaton model has been tested for generating almost all the architectural models and is illustrated by several examples in this section (please refer to as: Holttum architectural model, Corner architectural model, etc.). In the following figures, the number of repetition of each state and the transition relations between states are also shown in the figure. The stochastic condition is not taken into account in this article, although it is integrated in our model [19].

4.1 Simulation of Holttum architectural model and corner architectural model

In Holttum architectural model (see Fig.5), two macrostates are necessary to describe meristem functioning. Each macrostate includes only one microstate. The first macrostate is a repetition of the same metamer and the second corresponds to a terminal flower or inflorescence. When the automaton reaches the second macrostate, growth is finished and the stem ends by an inflorescence.

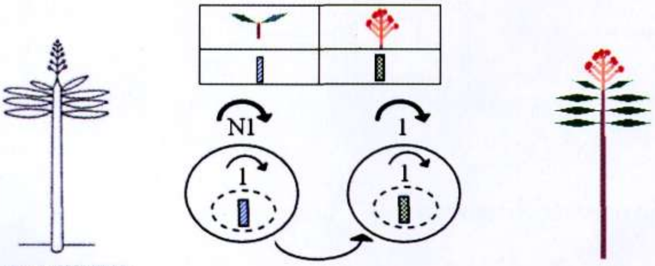


Fig.5 Simulation of Holttum model. (a) Holttum model (from Hallé et al., 1978), (b) automaton with two macrostates, (c) simulation

Corner architectural model is similar to the previous one but flowering is lateral (see Fig.6): papaya tree belongs to this model. The automaton for the simulation of this model is similar to that of Holttum model but the second microstate corresponds to a metamer with lateral flowering.

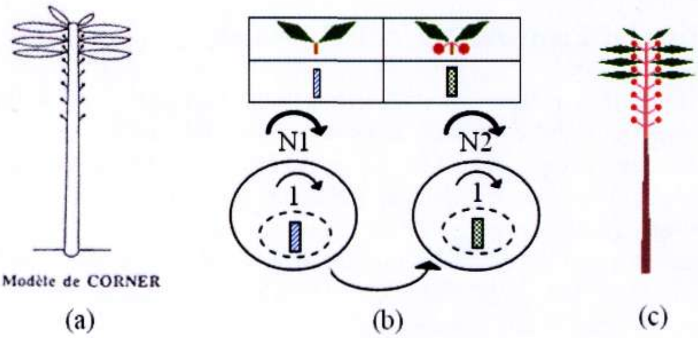


Fig.6 Simulation of Corner model. (a) Corner model (from Hallé et al., 1978), (b) automaton a: vegetative metamer, b: metamer with lateral flowering, (c) simulation

4.2 Simulation of Leeuwenberg architectural model

Leeuwenberg architectural model is a typical sympodial structure and consists of a succession of equivalent units called "modules" (PREVOST, 1967, 1978; HALLE, 1986), each of which is orthotropic and determinate in its growth by virtue of the ultimate production of an inflorescence. Examples of this model are "cassava" (*Manihot esculenta* Crantz) or the "castor-oil plant" (*Ricinus communis* L.). It may be simulated by the repetition of two successive macrostates and Fig.7(c) illustrates such a model generated after 4 growth cycles.

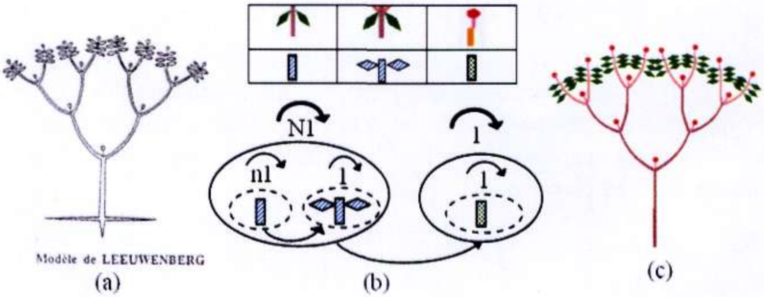


Fig.7 Simulation of Leeuwenberg model. (a) Leeuwenberg model (from Hallé 1978), (b) automaton, (c) simulation

5 Simulation of Inflorescences

Inflorescence is a general term corresponding to the arrangement of flowers or groups of flowers on the reproductive parts of a plant. Two main types of inflorescences may be distinguished: the racemose type and the cymose type, each of which is further subdivided. Two examples of simulation are shown.

5.1 Simulation of a Compound Umbel Inflorescence

Compound umbel inflorescence is an umbel where each stalk of the umbel produces a smaller umbel of flowers. Many plants of the Celery family present this type of inflorescence (see Fig.8).

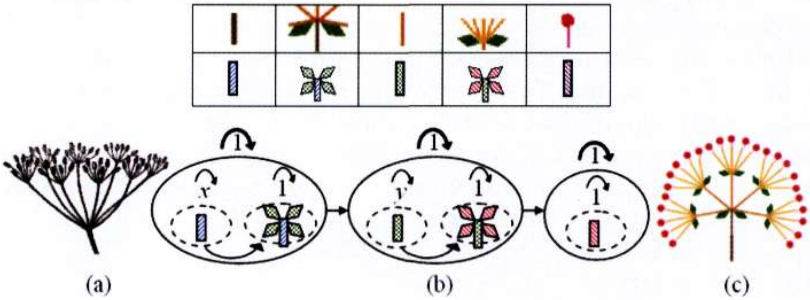


Fig.8 Simulation of compound umbel inflorescence. (a) Botanical model, (b) automaton, (c) simulation

5.2 Simulation of cymose inflorescence

The typical cymose type of inflorescence is the dichasial cyme that repeatedly forms flowers in pairs arising from the axils of opposite bracts on the pedicels of the preceding flowers. Two macrostates are necessary for the corresponding automaton that generates the inflorescence structure (Fig.9(a)): the first one is composed of two microstates, and the second by only one microstate (Fig.9(b)). If the allowed level of repetition is limited to 4, the automaton gives rise to the topological cymose structure shown in Fig.9(d).

If the second microstate of the first macrostate has only one axillary bud, then the model produces a scorpioid cyme (Fig.9(f)) or helicoidal (Fig.9(e)), Which differ only by geometrical parameters.

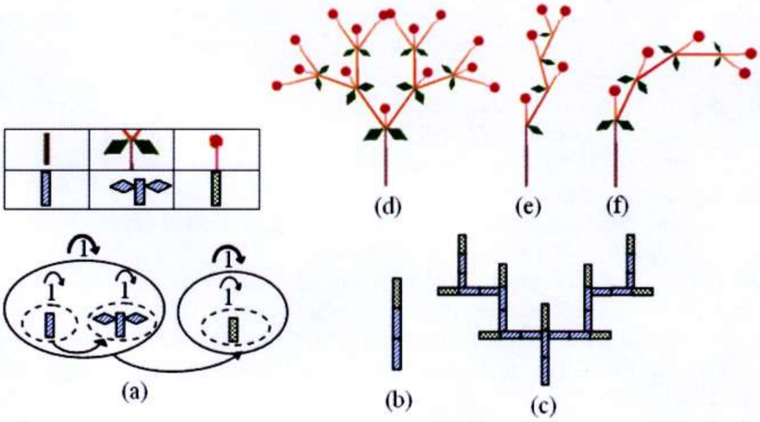


Fig.9 Simulation of cyme. (a) Automaton, (b) structure S_1, (c) the resulting topological structure, (d) the corresponding images of dichasial cyme, (e) and (f) scorpioid cymes

6 Conclusion

In this paper, we briefly introduced our dual-scale automaton model, which allows the interactive generation of plant topological structure and development. This model separates the plant geometrical aspects from plant topological structure, which makes it clearer to understand. Several examples have been presented to demonstrate how to simulate inflorescences and plant architectural models with this model. In order to validate this model almost all plant architectural models and inflorescence types presented in the botanical literature have been generated. In this paper, only several examples have been shown to illustrate this model. At this stage several morphological features [17] such as (1) annual shoots (i.e. the final result of the functioning of the terminal bud for a period of one year), (2) polycyclism, (3) preformation and neoformation have not been implemented and represent future problems to be solved in further research.

Acknowledgements

This research is supported by Sino-French Laboratory for Computer Sciences, Automation and Applied Mathematics (LIAMA), National Natural Science Foundation of China (#60073007), Centre de coopération internationale en recherche agronomique pour le dévelopement (CIRAD) and The National Institute for Research in Computer Science and Control (INRIA).

References

1 A. Lindenmayer. Mathematical models for cellular interaction in development, parts I and II. Journal of Theoretical Biology. vol.18, pp. 280-315, 1968.

2 P. Prusinkiewicz and A. Lindenmayer. The algorithmic beauty of plants. New York, Springer-Verlag. 1990.

3 B. Lane and P. Prusinkiewicz. Generating spatial distributions for multilevel models of plant communities. In Proceedings of Graphics Interface 2002 (Calgary, Alberta, May), pp. 69-80, 2002.

4 J. A. Kaandorp. *Fractal modeling growth and form in biology*. New York, Springer-Verlag. 1994.

5 C. Godin, Representing and encoding plant architecture: a review. *Annals of Forest Science*, vol. 57(5/6), pp. 413-438, 2000.

6 C. Godin and Y. Caraglio. A multiscale model of plant topological structures. *Journal of Theoretical Biology*, vol. 191, pp. 1-46, 1998.

7 C. Godin, E. Costes and H. Sinoquet. A method for describing plant architecture which integrates topology and geometry. *Annals of Botany*, vol. 84(3), pp. 343-357, 1999.

8 B. Lintermann and O. Deussen. Interactive modeling of branching structures. *IEEE Computer Graphics & Applications*. vol. 19(1), pp. 56-65, 1999.

9 P. De Reffye, C. Edelin, J. Françon, M. Jaeger and C. Puech. Plant models faithful to botanical structure and development. Computer Graphics. vol. 22(4), pp.151-158, 1988.

10 P. De Reffye, F. Houllier, F. Blaise, D. Barthélémy, J. Dauzat and D. Auclair. A model simulating above- and below-ground tree architecture with agroforestry applications. Agroforestry Systems. vol. 30, pp.175-197, 1995.

11 P. De Reffye, T. Fourcaud, F. Blaise, D. Barthélémy and F. Houllier. A functional model of tree growth and tree architecture. *Silva Fennica*. vol. 31, pp. 297-311, 1997.

12 F. Blaise, J. F. Barczi, M. Jaeger, P. Dinouard and P. De Reffye. Simulation of the growth of plants modeling of metamorphosis and spatial interactions in the architecture and development of plants. *Cyberworlds*. Tokyo, Springer-Verlag, pp. 81-109, 1998.

13 F. Hallé and R. A. A. Oldeman. Essai sur l'architecture et la dynamique de croissance des arbres tropocaux. Masson and Cie. 1970.

14 F. Hallé, R. A. A. Oldeman and P. B. Tomlinson. Tropical trees and forest: an architectural analysis. Berlin, Springer-Verlag. 1978.

15 D. Barthélémy, Y. Caraglio and E. Costes. Architecture, gradients morphogénétiques et âge physiologique chez les végétaux. *Modélisation et simulation de l'architecture des végétaux.* Sciences Update, Editions Inra, pp. 89-136, 1997.

16 J. White. The plant as a metapopulation. Annu. Rev. Ecol. Syst, vol. 10, pp. 109-145, 1979.

17 Y. Caraglio and D. Barthélémy. Revue critique des terms relatifs à la croissance et à la ramification des tiges des végétaux vasculaires. In: Modélisation et simulation de l'architecture des végétaux, Science Update. Paris: INRA éditions, pp. 11-87, 1997.

18 B. G. Hu, X. Zhao, , H. P. Yan, P. De Reffye, F. Blaise, F. L. Xiong and Y. M. Wang. Plant Growth Modeling and Visualization -Review and Perspective. Acta Automatica Sinica. vol. 27(4), pp. 567-584, 2001.

19 X. Zhao, P. De Reffye, F.L., Xiong, B. G. Hu, Z.G. Zhan. Dual-scale automaton model for virtual plant development. The Chinese Journal of Computers, 24(60), 2001, 608-617 (Chinese in English abstract)