A Functional-Structural Plant Model for Cut Roses - New Techniques for Modelling Manipulation of Plant Structure

G.H. Buck-Sorlin, B. Burema and J. Vos
Wageningen UR
Chair Group Crop and Weed Ecology
Droevendaalsesteeg 1
6708 PB Wageningen
The Netherlands

J.H. Lieth
University of California, Davis
Department of Plant Sciences
Mailstop 2, One Shields Ave, Davis
CA 95616
USA

E. Heuvelink[a]
Wageningen UR
Chair Group Horticultural Supply Chains
Droevendaalsesteeg 1
6708 PB Wageningen
The Netherlands

P.H.B. de Visser and L.F.M. Marcelis
Wageningen UR
Greenhouse Horticulture
Droevendaalsesteeg 1
6708 PB Wageningen
The Netherlands

Keywords: crop management, cut-flower, light, plant architecture, virtual plant, *Rosa × hybrida*, simulation

Abstract

Experience is the main guide for cut rose growers to make decisions on crop management and climate control. Because of continuous change in cultivar characteristics and technology there is a need for a general theory, capturing how the number of flower shoots produced and their quality depend on the main determinants: plant structure (as a product of the interaction of natural growth and development with manipulation by the grower), cultivar characteristics and greenhouse environment. 'Virtual Rose' is an interdisciplinary project working on the development of a 3D model that simulates and visualizes shoot production over time. 3D modelling, or rather functional-structural plant modelling, differs fundamentally from previously published rose crop models, the most striking aspect being the 3D simulation and visualization of plant structure. This paper introduces the basic modelling approach, i.e., the use of Relational Growth Grammars (RGG) and the modelling language eXtended L-Systems (XL). The final model needs to be able to use greenhouse climate data from practice as input, most importantly the light regime, consisting of light from the sun and additional assimilation lamps (SON-T). Furthermore, the model needs to be equipped with provisions that allow the model user to execute 'virtual' bending, harvesting, and pruning. In this paper, we will focus on new modelling techniques for simulating complex interventions in plant growth.

INTRODUCTION

Cut rose (*Rosa × hybrida*) represents a high input and high-value ornamental greenhouse crop. Many factors affect number and quality of flowers, major ones being the cultivation system (e.g., substrate type, plant configuration), greenhouse environment (spatial and temporal distribution of photosynthetically active radiation (PAR) and temperature, CO_2 and air humidity) and the plant manipulation strategy exercised by the grower (e.g., the application of the shoot bending system (Kool and Lenssen, 1997) versus the 'hedge row' system, flush or continuous harvesting, cutting height and pruning).

Growers acquire experience on how to best grow plants so as to optimize yield (in terms of numbers and size-class distribution of flowers) and quality. However, it is

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[a] ep.heuvelink@wur.nl

difficult to rely on past experiences when cultivar characteristics, cultivation practices and environmental control options are subject to permanent change. A solid theoretical framework is missing that elucidates how yield and quality change over time in relation to these determinants. 'Virtual rose' is a project with the objective to provide a model to support growers' decisions on cultivation practices. The virtue of modelling is that it integrates in a systematic and objective fashion our proven qualitative and quantitative knowledge of how the system functions.

Realistic modelling of effects of plant manipulation requires the faithful reconstruction of the three-dimensional (3D) architecture of the plants. Recently, new techniques became available to construct 3D functional-structural plant models (FSPM), or 'virtual plants' (e.g., Vos et al., 2007). As implied in the name, these models deal with selected plant functions (e.g., photosynthesis, growth) in combination with the simulation of the number of plant organs, their shape, topology (connection with each other, also implying exchange of material and information) and orientation in space.

The modelling approach we adopted differs from the ones taken for previously published rose models (e.g., Kim and Lieth, 2001, 2003; Dayan et al., 2002, 2004; Costa and Heuvelink, 2004). This paper presents a brief introduction to the modelling approach that is adopted for 'Virtual Rose', i.e., Relational Growth Grammars (RGG) embedded in the eXtended L-Systems (XL) modelling language (Kniemeyer, 2008), and introduces new provisions to make the model suitable for its final purpose. The final model should be able to simulate the course of crop structure and physiology at greenhouse conditions in practice. Therefore, we want to be able to use greenhouse climate data as input, e.g., the light regime, temperature, CO_2, humidity. 3D modelling brings special questions that need to be solved. The light plants receive comes from different angles from the sun and additional assimilation lamps. The quantity of light intercepted by a crop furthermore strongly depends on its structure, and that in turn is in the case of cut-rose highly influenced by human intervention. Therefore, in this paper - after a brief overview of the model elements - we will mainly deal with the provisions that are needed to allow the model user to interfere with the crop, i.e., execute 'virtual bending, harvesting and pruning'.

MODEL IMPLEMENTATION USING RELATIONAL GROWTH GRAMMARS, XL, AND GROIMP

The model was written using the RGG formalism (Kniemeyer et al., 2004; Kniemeyer, 2008) in XL (Buck-Sorlin et al., 2005, 2008; Kniemeyer, 2008). The modelling environment GroIMP (Growth Grammar-related Interactive Modelling Platform, sourceforge.net/projects/groimp) was used for model development, visualisations and simulations.

In the following, we will briefly describe the principle of RGG: they are a generalization and extension of L-systems (Prusinkiewicz and Lindenmayer, 1990), the latter being a subset of RGG. This is a rule-based formalism of the form:

$$(LC)\ LHS\ (RC),\ (C) \rightarrow \{P\}\ RHS \tag{1}$$

where LHS and RHS represent the left- and right-hand side of a rule, and '$\rightarrow$' a transformation symbol meaning 'is replaced by'. Rules are applied to a graph consisting of nodes (objects) and edges (relations between objects, of various forms, e.g., "successor", "branch"). This graph is an internal representation of the simulated structure visible at any time of simulation. By applying rules, elements (nodes, subgraphs) of the graph are transformed. In doing so, an arbitrarily wide left context (LC) or right context (RC) of the element on the LHS can be considered, and/or a condition (C). On the RHS imperative code, represented by {P}, can be executed, as in an imperative programming language (such as Fortran or C).

Taking the example of the present model, the RGG can be used to model development at the organ level in discrete time steps, as shown in the following:

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$$A(p), (p>0) \rightarrow A(p\text{-}1) \qquad\qquad\qquad (2)$$
$$A(p), (p=0) \rightarrow I(len) \; [RL(a1) \; L(a)] \; [RL(a2) \; A(plasto)] \; A(plasto) \qquad (3)$$

Here, *A(p)* symbolizes a bud containing a growing tip (shoot apical meristem), with *p* being a parameter representing the plastochron, the time lag between the formation of two successive phytomers. Developmental progress is represented in degree-days (°C d), which is the sum of the mean daily temperature, minus a base temperature (5.2°C, Pasian and Lieth, 1994). Applying rule (2), the parameter *p* is decreased by one as long as it is larger than zero. Once *p* is zero, rule (3) applies: *A(p)* is replaced by an RHS consisting of several further symbols representing a phytomer, i.e., an internode *I*, a leaf *L*, a lateral bud *A* and a terminal bud *A* (the latter effectively being the continuation of the *A* from the LHS). In other words, with this rule the formation event of the bud to part of a shoot (the phytomer) is described. The parameters in parentheses ( ) represent possible properties of the modelled organs, e.g., length (*len*) of *I*, divergence angle (*a1*) of *L* (the *RL* command describing a rotation around the local x-axis ("Rotate Left") by *a1* degrees), or area (*a*) of *L*. *[* and *]* mark the beginning and end, respectively, of a branch; in the graph data structure they are represented as special branch edges. The two buds *A* are reinitialised with starting values for the plastochron, which are stored in a global variable *plasto*.

Extension of organs (internode length, leaf area) was modelled as a function of thermal time (accumulated degree-days since onset of growth) using the beta growth function proposed by Yin et al. (2003): this function computes organ dimension at time *t*, given the three input parameters, t_m, t_e, and w_{max}, which represent the time of maximum growth/extension, the time when growth/extension ends, and the maximum dimension, respectively. A derivative of this function was used to compute the instantaneous potential growth rate of an organ given unlimited source capacity.

The lowest hierarchical unit in our model is the phytomer, i.e., the basic element each plant is composed of, consisting of an internode, a node, a leaf and an axillary bud. The plant grows by initiating new phytomers and increases in size and volume of each of the components of the phytomer. 'Bud break' is a special type of event the model needs to deal with. Currently experiments are conducted in search for the 'decision rules' that govern bud break of roses. Visualisation is a particularly strong advantage of this modelling approach, facilitating discussions on plant behaviour with growers and their personnel.

MODELLING OF LIGHT DISTRIBUTION

The 3D radiation model used here is described in detail in Hemmerling et al. (2008). Basically, it uses a reversed path tracer algorithm with Monte Carlo integration based on Veach (1998). A similar radiation model was used by Gautier et al. (2000), combining such a radiation model with an open L-system. The radiation model is invoked once per simulation step and applied to a scene created in the modelling environment GroIMP. The scene contains (amongst others) a number of light sources and visible objects. Essentially, the radiation model computes how much of the radiant power emitted by the light source(s) is absorbed, transmitted and reflected by the objects in the scene (each object having its own specific optical properties, i.e., absorption, reflection and transmission coefficients, which are determined by a shader[1]). It has thus the functionality of a raytracer, only that rays are "inversely" traced from light sources to objects. The amount of radiation absorbed locally by an object may be queried at any point of the simulation in order to be used in a model of e.g., photosynthesis. For convenience, we are converting the radiant power (W) into photons (mol) at the source, using a factor specific to the light source.

In GroIMP, several types of light sources are supported: point lights, spot lights,

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[1] A shader is an object which conveys a colour to a geometric object. In the simplest case it is made up of red, green and blue components.

directional lights, area lights, and a virtual sky. These light sources mainly differ in the way they distribute light: in a point light source, light rays are emitted from a point origin into all directions with equal probability, whereas in a spotlight, the angular distribution is restricted to an opening angle. Directional light sources are solely characterised by parallel light rays coming from one direction (e.g., direct radiation from the sun), whilst area lights are directional lights that are restricted to a flat surface of limited size. Also, recently a model of a SON-T GreenPower 600 W assimilation lamp ($^{©}$Hortilux, Pijnacker, The Netherlands) became available for use in a virtual greenhouse (Buck-Sorlin et al., 2010, forthcoming). A user-specified total number of primary rays is generated by the light sources and traced along their paths across the scene. For a significant, traceable level of light interception of small shaded objects, the number of primary rays should not be less than 1,000,000. For each ray the associated properties origin, direction and spectral composition are known. Here the additive RGB (Red Green Blue) colour model was used to produce visible colours. The colour of a scene at any simulated step is thus the result of the interaction of the colour of the light with the optical properties of the illuminated objects.

Simulated PAR in the form of virtual photons (with a distinct power density depending on the spatial direction, i.e., solid angle) is intercepted by leaf objects. Rose leaves are composed of 1 to 7 leaflets, with odd numbers prevailing (1, 3, 5 and 7). We used a composite 3D object consisting of parallelograms and cylinders to represent the leaflets and midribs (Fig. 1). The number of leaflets per leaf was modelled as a function of normalized leaf rank, with a broad peak of 7-leaflet leaves at median normalized ranks (0.39-0.72). The amount of light intercepted (μmol photons s^{-1}) as well as intercepting area (length*width (m) of the representing parallelograms, times a form factor of 0.7) are summed up automatically for each leaf object at each simulation step. Daily PAR intercepted (mol photons m^{-2} d^{-1}) was estimated assuming 20 hours of assimilation light and summed up for the entire simulated canopy.

Though treated in more details in a forthcoming publication, it should be mentioned here that in the current rose model we have implemented a choice of three different photosynthesis models: by Lieth and Pasian (1990), Nikolov et al. (1995), and Kim and Lieth (2003).

MODEL PROVISIONS FOR SHOOT BENDING, HARVESTING AND PRUNING

The plant architecture encountered in a greenhouse-cut-rose production system is highly artificial and the product of repeated and directed human interaction with the growing and developing structure. Normally, each rose shoot will be upright and produce a terminal flower. Furthermore, the shoot apical meristem (SAM) of a vigorously extending shoot will tend to suppress the breaking of lateral buds further down the same shoot. This phenomenon, also referred to as correlative inhibition, vanishes in the flowering phase (as the apical meristem is used up into a flower), allowing the lifting of inhibition and thus bud break. The model will be described in detail elsewhere. Here we will just give a brief summary of the algorithm used to simulate correlative inhibition:
1) An "inhibitor" I is produced in an actively growing meristem M (activity is an "on/off" flag) and exported at a fixed rate to the subjacent internode.
2) I is not produced in dormant M (all newly produced lateral M are initially dormant).
3) Transport ("diffusion") of I takes place basipetally along the stem, from an internode to its neighbouring subjacent internode, and from an internode to the lateral meristem belonging to the same phytomer; internode-internode transport is only done if the "donating" internode is located above the receiver internode (i.e., location is determined as height of an internode above a reference point, the floor).
4) M stores external I in a pool E. In an active M, E is initially empty.
5) All local I decays at a fixed rate.
6) A lateral M becomes activated (flag=on) when the concentration of its pool E falls below a certain threshold (i.e., due to decay of I and lack of import from the neighbouring internode).

Interference with the simulated structure is modelled as separate sets of rules grouped together as appropriate into methods which can then be easily invoked by pressing buttons at any time during a model run. Facultatively, the user can select a part of the structure (e.g., the base of a shoot to be cut) to be managed. The structural changes take effect immediately, the effects of all the plant manipulations and the resulting growth are directly visible in the course of the simulation, and they have an effect on the further transport of I and resulting bud break and shoot formation. There are provisions in the model to simulate several types of interventions, most importantly: bending, harvesting, and pruning. Bending of the primary shoot consists of the forced reorientation of the basal internodes of a primary shoot, i.e., abrupt change in the parameter value for angle of orientation of that internode. At the same time, the reorientation of internodes in space might interrupt the transport of I (depending on bending strength), thereby activating one or more lateral buds at the base of the bent shoot, which will then eventually break when the simulation is resumed.

Harvest and pruning are essentially the same process: they consist in the removal of a subset of elements from the graph. A similar method was employed by Prusinkiewicz et al. (1994) to simulate pruning of topiary shrubs; however, this involves removal of symbols from a string data structure and is not user-interactive. Normally, the user selects an internode and presses the harvest button. The internode will then be removed from the graph data structure, along with all neighbouring elements distal to it, i.e., above the cut. Before being removed, the internodes making up the harvested stem can be queried to print out information about harvested stem length to the model console or to an external file importable into a spreadsheet programme. Alternatively, the user can specify a global parameter 'cutting height'; when the appropriate model rule is executed the simulated shoot parts above the cutting height will be removed in a "flush harvest". All interventions mentioned (bending and cutting) can thus be carried out on single internodes selected by the user or globally on internodes that fulfill certain criteria (e.g., location or rank). Further interactions such as the rebending of shoots within the bent canopy, removal of flowers of bent shoots, removal of suckers from the axil of crop shoot leaves, are currently being tested.

Figure 2 illustrates the principle of interaction with a growing virtual cut-rose plant: the model is first run to produce a primary shoot (Fig. 2a). Then the simulation is stopped and a basal internode of the primary shoot is selected, followed by pressing the button "bendPrimaryShoot". This causes an instantaneous bending of the primary shoot (Fig. 2b). When the model is relaunched, one of the basal buds eventually grows out ("bottom break") and forms a new crop shoot (Fig. 2c). Once this shoot is mature, the simulation is stopped again, and virtual harvest is carried out by using the button "flushHarvest". Figure 2d shows the situation after two flush harvests. Repeated harvest, pruning and rebending creates a structure similar to the simulated one shown in Figure 2e.

CONCLUSIONS AND OUTLOOK

A full FSPM is proposed for supporting decisions in cut-rose cultivation. One of the most essential parts (crop structure management) of the model is described here. Simulation of structural development as a product of natural processes and manipulative intervention yielded a realistic appearance. The present model is but an initial framework and a first step towards the faithful, largely generic modelling of timing and location of bud break in cut-rose production systems, based on extensive experiments currently carried out within our group. In this concept model, the simple assumptions about correlative inhibition will thus gradually be replaced with experimental findings on the effects of various environmental (temperature, PAR sum) and physiological (source/sink ratio) factors on bud break and shoot development.

ACKNOWLEDGEMENTS

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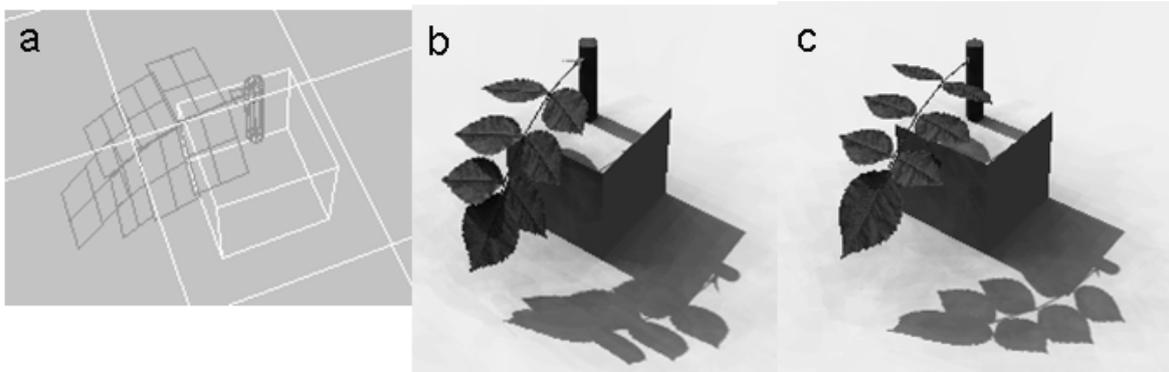
Figures

Fig. 1. Model of the composite leaf of rose, as (a) a wireframe representation showing the constituting geometric objects and (b, c) after application of the Twilight ray tracer of GroIMP, showing textures, light and shade. (b) and (c) also show different leaflet angles (divergence from the midrib and deviation from the horizontal plane).
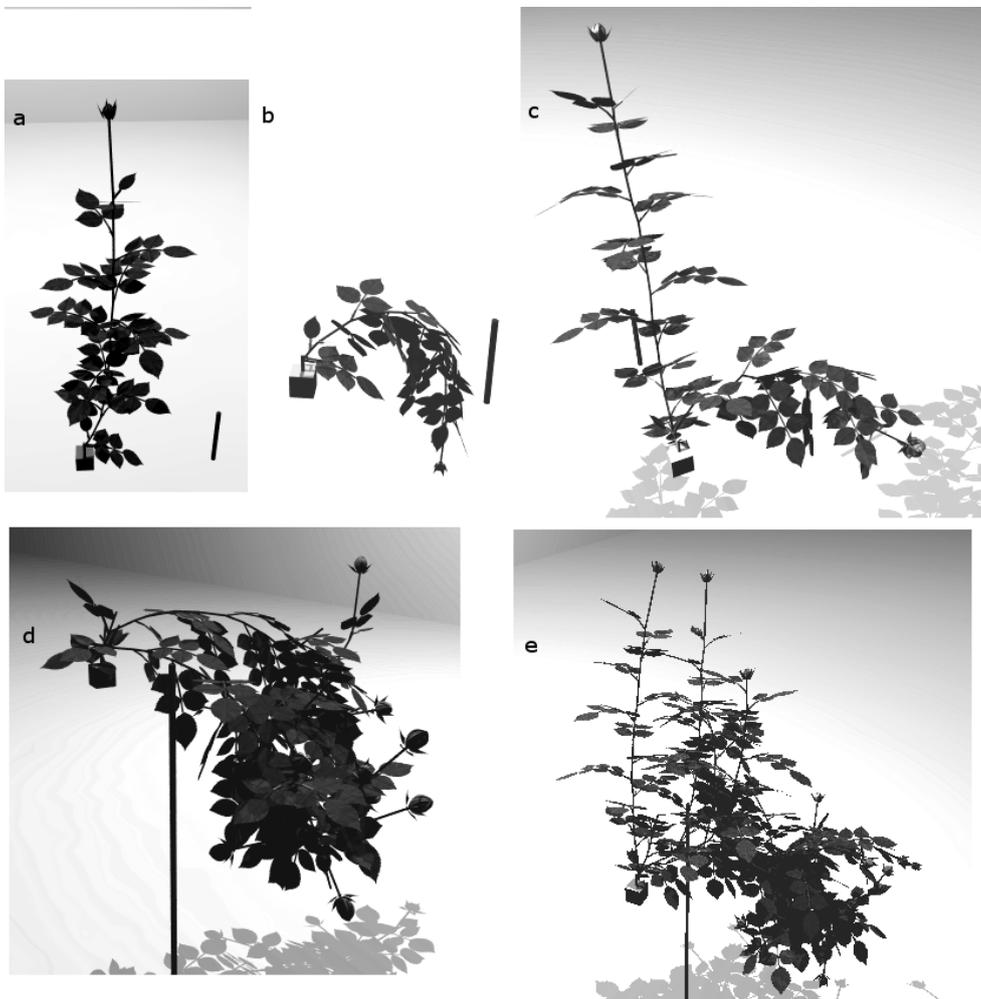

Fig. 2. Simulation of intervention: (a) primary shoot developed from the axillary bud of the cutting, (b) after bending, (c) regrowth of bottom breaks after bending of primary shoots, (d) bent canopy after two harvests, (e) regrowth after several flushes.