

A 3D STAND GENERATOR FOR CENTRAL APPALACHIAN HARDWOOD FORESTS

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ABSTRACT

A 3-dimensional (3D) stand generator was developed for central Appalachian hardwood forests. It was designed for a harvesting simulator to examine the interactions of stand, harvest, and machine. The Component Object Model (COM) was used to design and implement the program. Input to the generator includes species composition, stand density, and spatial pattern. Output is a 3D stand map that lists species, DBH, spatial location, and total height for each individual tree. The stand generator can be used to visualize the structure and composition of hardwood stands and perform dynamic analyses of various management prescriptions.

INTRODUCTION

The stand generator is a computer program that is used to depict the physical characteristics of stands based on the user's input. It has been extensively used in forest harvesting simulation models because of its convenience and efficiency. Newnham and Maloley (1970) stated that a major advantage of using stand generator in harvesting simulation models was the saving in time and money in obtaining the stand data.

There are several models available for simulating growth or harvesting operations in a forest stand. However, most of them were designed for specific species and regions. Many of the earliest models were FORTRAN-based and displays were 2-dimensional (2D). Newnham and Maloley (1970) developed a stand generator with FORTRAN IV especially for simulation studies. Farrar (1981) developed an in situ stand generator for use in harvesting machine simulators. He also validated the model by comparing characteristics of trees created by the generator to those of the trees in the parent forest model. OAKSIM, an individual-tree growth and yield simulator, was developed for managed, even-aged, upland oak stands in the early of 1980s' (Hilt 1985). OAKSIM was written in FORTRAN and especially designed to evaluate stand management alternatives on a mainframe computer.

The Stand Evaluation and Modeling System (STEMS) is also one of the most common models used for projecting growth of timberlands. It was developed to update large inventories of timber (Brand et al. 1987). STEMS was later developed into the Woodsmen's Ideal Growth projection System (TWIGS). TWIGS used the same prediction equations as STEMS, but was applied to analyze long-term management decisions. GROW was then developed from these programs to perform more complex growth simulations. All of these programs were written in FORTRAN. STEMS requires a mainframe while TWIGS operates on a PC under MS DOS. STEMS and TWIGS analyze only one stand at a time. GROW requires the user to program output, input, and management routines. The Decision Tree System (DTREES) was then derived from STEMS and GROW programs and used to determine a harvest schedule. It also provides a list of alternative management routines for each forest stand by simulating management activities and responses (Pelkki and Rose 1988).

The model SIMSAP/SIMTIM is a forest stand-level growth model for even-aged northern hardwoods, which includes two-phases – sapling stand development and poletimber/sawtimber harvest (Solomon 1986). It was written in FORTRAN 77 and can be used interactively or by batch on any mainframe or microcomputer under DOS environment. GROAK (Grow Oak) and GROPOP (Grow Poplar) are also stand-level models, which provide quantitative estimates of growth and yield for even-aged upland oak and yellow poplar stands respectively (Perkey 1986). They were programmed in FORTRAN 77 and run on IBM compatible machines.

The California Conifer Timber Output Simulator (CACTOS) is an interactive computer program designed to simulate the growth and partial harvest of conifer forest stands in northern California (Meerschaert 1988). The CACTOS was written with FORTRAN 77 and run in DOS environment. CACTOS was designed to allow a land manager to predict often-occurring changes in a young coniferous stand. The forest stand generator (STAG) was then developed to estimate missing tree heights, height-to-crown base in the CACTOS (Biging and Wensel 1988).

The Silviculture of Allegheny Hardwoods (SILVAH), first developed in 1985, also includes a simulator to project stand growth and development (Marquis and Ernst 1992). Since then, several versions of SILVAH have been programmed for IBM compatible machines. More recently, Oinas and Sikanen (2000) developed a stand generator and incorporated a means for analyzing harvests into it. A three-parameter Weibull distribution was used to depict the frequency distribution of basal area, and the stand age was uniformly distributed. They also found that the distribution of the basal area was fairly close to a normal distribution. In addition, the beta distribution was introduced in their model to depict the volume proportions of tree species. Using this stand generator, they developed a simulation model for a timber procurement process.

The 3-dimensional (3D) modeling approach was introduced in 1990s' and has been applied in forest stand visualization (Reutebuch et al. 1997). McGaughey (1997) also reviewed a variety of landscape and stand level visualization techniques. He indicated that all of these systems utilized digital terrain models (DTM) and detailed vegetation inventory information to produce highly detailed, perspective-view renderings of forested landscapes. These systems, however, cannot provide individual tree data such as DBH, total height, and crown size for analyzing the forest stand dynamics and cost/production of alternative silvicultural practices. Furthermore, many of these previous studies were based on techniques or data that are either obsolete or not available. The objective of this study is to develop a Windows-based stand generator for central Appalachian hardwood forests by using 3D modeling and object-oriented programming techniques.

STAND DATA

Two datasets were used to describe the relationship between DBH and height, and model DBH distribution (Table 1). The dataset provided by USDA Forest Service (USFS data set) was collected in the Monongahela National Forest in West Virginia, which included 10 even-aged hardwood stands that were about 35 years old. Data were collected on a total of 185 1/20-acre plots. The other dataset was collected from the West Virginia University forest (WVU data set), a second-growth hardwood forest about 75 years old. Data were collected on a total of 18,626 trees were cruised with 3065 variable radius plots. There were 37 different species included in each of the dataset.

The DBH ranged from 1.0 to 21 inches with an average of 4.5 inches in the USFS dataset while the DBH averaged 14.6 inches and were between 2 and 42 inches in the WVU dataset (Table 1). The total and merchantable heights were measured and recorded for each individual tree in WVU dataset. Five trees in each plot were randomly selected to measure the total height for the USFS dataset. The total height varied from 25 to 95 feet with an average of 64 feet in the USFS dataset. In the WVU dataset, the total height averaged 81 feet and varied from 8 to 143 feet. A cruising program was used to summarize the data in these two datasets. In order to facilitate the analyses, seven major species were identified and categorized based on the number of trees and basal area per acre and the rest of species were classified as "Other" in both datasets (Table 1). American beech, black cherry, northern red oak, red maple, sugar maple, sweet birch, and sassafras were the major species in USFS stands and accounted for 72% of the total trees measured while blue beech, black cherry, chestnut oak, northern red oak, red maple, and sassafras were the major species in the WVU dataset and accounted for 83% of the total trees measured.

Table 1. Summary statistics of the datasets.

Data sets*	Species	No. of trees	%	DBH (inches)				Total height (feet)			
				Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.	Min.	Max.
USFS	American beech	453	8	2.5	1.8	1.0	14.0	53.3	9.3	43.0	61.0
	Black cherry	646	11	7.6	3.8	.0	20.0	69.2	11.4	41.0	94.0
	Northern red oak	324	6	4.0	2.9	.0	21.0	60.0	13.2	35.0	95.0
	Red maple	764	13	4.2	2.6	.0	19.0	60.4	11.4	38.0	85.0
	Sugar maple	1180	19	4.1	3.0	.0	19.0	63.5	7.5	45.0	80.0
	Sweet birch	476	8	4.2	2.4	.0	12.0	60.8	8.2	49.0	85.0
	Sassafras	420	7	3.8	2.9	.0	20.0	51.1	11.9	34.0	62.0
	Other	1714	28	4.2	3.2	1.0	19.0	60.6	12.5	25.0	83.0
WVU	Black cherry	1079	6	15.0	4.3	4.0	32.0	84.5	16.3	20.0	139.0
	Chestnut oak	2527	14	13.0	4.5	4.0	36.0	75.0	13.7	8.0	115.0
	Northern red oak	3651	20	16.4	5.4	3.0	42.0	85.	15.5	10.0	140.0
	Red maple	3047	16	11.1	4.6	2.0	34.0	70.0	19.0	9.0	135.0
	Sassafras	290	2	10.7	2.7	5.0	19.0	63.4	14.3	24.0	103.0
	Yellow poplar	4246	23	17.4	4.7	4.0	40.0	95.7	14.9	9.0	143.0
	Other	3151	17	14.4	5.2	2.0	40.0	78.3	17.1	9.0	136.0

* USFS = dataset provided by USDA Forest Service, WVU = dataset collected from West Virginia University forest.

SYSTEM STRUCTURE AND IMPLEMENTATION

The Component Object Model (COM) was employed in the design of this stand generator. This 3D stand generator system mainly consists of two components – Microsoft Visual Basic (MS VB) component and Microsoft Visual C++ (MSVC) component (Figure 1a). A component is a compiled piece of code that can provide a service to the system. The stand generator users access the resources in these two components via the COM interfaces such as IStandGenerator in the model. However, the users are able to find out what interfaces the component supports by using the generic interface called IUnknown. The COM interface is the mechanism by which a user or a client interacts with a component while an

interface is a contract between a consumer and a component that describes the component's functionality to the user without describing the implementation (Lewis 1999). Every COM object must implement the IUnknown interface. The architecture of a COM interface includes a binary description of the layout of a block of memory containing an array of function pointers (Figure 1b). This array has a fixed structure, and is known as a virtual method table (vtable). The pointers in the array point to the functions of the COM object that can be called by the user. Each interface has its own vtable layout, and a COM object can expose any members of the interface. Object-oriented programming (OOP) is vitally important to COM which makes full use of three OOP principles of encapsulation, inheritance, and polymorphism.

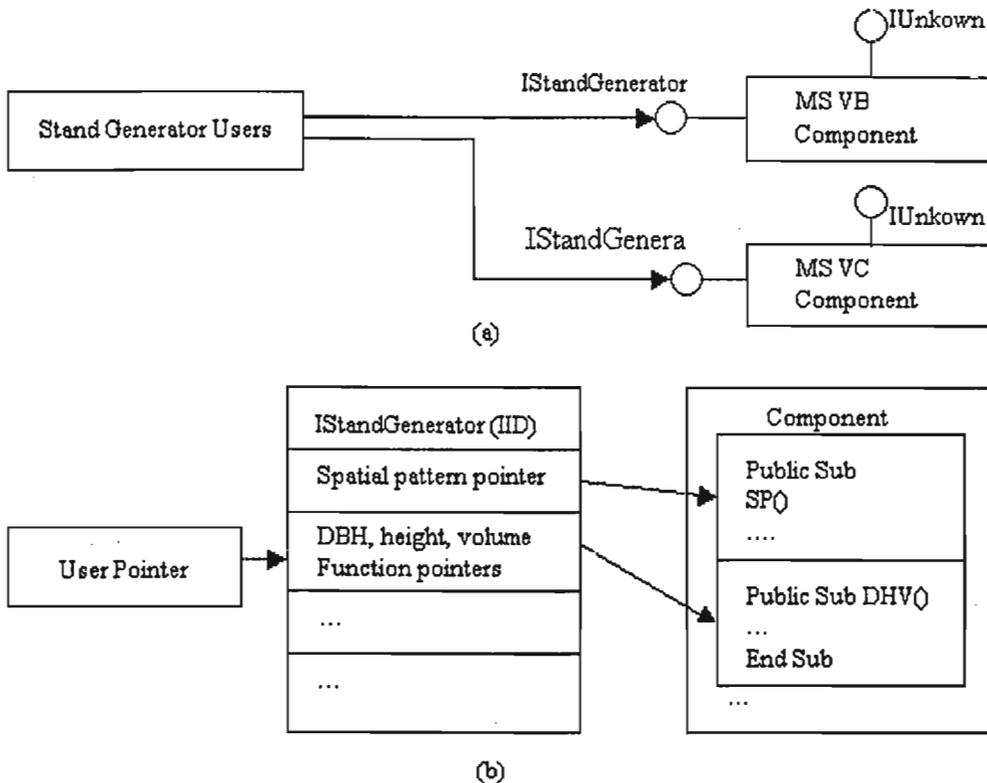


Figure 1. Component object model of the stand generator.

Height Estimation

Total tree height has been popularly modeled as a function of diameter at breast height (DBH) both linearly and non-linearly. Curtis (1967) summarized the available height-DBH models and compared the performances of 13 linear models fitted to second growth Douglas-fir. Since then, many new models have been developed for different species in different regions. Huang et al. (1992) compared and evaluated 20 non-linear height-DBH functions for major species in Alberta. Bechtold et al. (1998) presented a general linear height equation currently used by USDA Southern Research Station Forest Inventory and Analysis (FIA) and modified the model for ocular estimates. The height-diameter relationship for sugar maple was also explored in an uneven-aged Northern hardwood stand (Kenefic and Nyland 1999). Few references are available for modeling the merchantable height. Ek et al. (1984) developed a non-linear model which described the merchantable height as a function of DBH, site index, and basal area per acre. Borders et al. (1990) modeled the merchantable height as a function of the total height and the ratio of top merchantable diameter to DBH for loblolly pine.

In this study, the models have been developed to estimate the total height and merchantable height based on the WVU data set, which would facilitate the use of local volume equations (Rennie 1996, Wiant 1978 and 1986). The total tree height was recorded in feet while the merchantable height was measured in the number of 16-foot logs. Three linear and five non-linear models were fitted for the major species in the region (Table 2). The best for each major species was selected based on the following criteria: (1) root of mean square error (RMSE), (2) F and P-value, (3) coefficient of correlation (R^2), and the plot of residual vs. predicted height. The merchantable height was also modeled as a function of DBH, which was assumed to be in the same family as the selected DBH-total height equations for each species. The

family lines were described as lines that have either equal slopes or common intercepts (Ergun 1956). Equation (2) in Table 2 was first fitted for both DBH-total height and DBH-merchantable height and then the intercept in DBH-total height was adopted in the DBH-merchantable equation. These two equations were also compared to each other with observed data.

Table 2. Linear and non-linear DBH-height functions examined and fitted for major species on West Virginia University forest.

	Model*	Reference
(1)	$H = a + bD + cD^2$	Curtis 1967, Kenefic and Nyland 1999
(2)	$\text{Log}H = a + bD^{-1}$	Curtis 1967, Clutter et al. 1983
(3)	$H = a + b(\log_{10} D)^{0.5} + cD^2$	Bechtold et al. 1998
(4)	$H = 1.3 + a(1 - e^{-bD^c})$	Huang et al. 1992
(5)	$H = 1.3 + a(1 - e^{-bD})^c$	Huang et al. 1992
(6)	$H = 1.3 + ae^{b/(D+c)}$	Huang et al. 1992
(7)	$H = 1.3 + a/(1 + b^{-1}D^{-c})$	Huang et al. 1992
(8)	$H = 1.3 + e^{a+bD^c}$	Huang et al. 1992

*a, b, and c are the parameters. In equations (1) to (3), H in feet, D in inches; otherwise H in meter and D in cm, Log is natural logarithm.

DBH Distribution

Many distribution functions such as beta, gamma, Weibull, and others, have been used to describe the diameter distributions of stands. Nelson (1964) used the gamma distribution to predict the diameter distribution of loblolly pine. Bliss and Reinker (1964) reported a log-normal approach for diameter distributions in even-aged stands. The Weibull function has been widely used in diameter distribution due to its simplicity and flexibility (Bailey and Dell 1973). The three-parameter Weibull distribution is especially popular for depicting diameter distributions. The estimation of the three Weibull parameters is of great importance and has attracted a lot of attention. Three methods of maximum likelihood estimation, modified moments estimation, and percentile estimation for prediction of the three parameters were evaluated for unthinned slash pine plantation (Shiver 1988).

A method of joining different segments of modified Weibull cumulative distribution functions (cdf) together to form a single smooth cdf was developed for modeling diameter distributions of irregular stands such as thinned stands or mixed stands (Cao and Burkhart 1984). They reported that the segmented cdf was superior to single Weibull distribution for thinned stands. Some studies also incorporated the effects of interspecific competition in diameter distribution models (Burkhart and Sprinz 1984, Knowe et al. 1992). Newberry et al. (1993) evaluated eight distribution-free methods for estimating the quartiles in the process of modeling DBH distributions with either Weibull or Johnson's S_B distribution for even-aged Douglas-fir stands in the Inland Northwest and concluded that two of the quantile estimation methods consistently gave better results.

The beta function is also commonly used to model the DBH distribution. Beta and Weibull functions were compared for modeling basal area/diameter distribution in stands of Scots pines and Norway spruce (Maltamo et al. 1995). The results did not reveal any major differences between suitability of the beta and two-parameter Weibull distributions. A bivariate generalized beta distribution (GBD-2) was used to model the joint distribution of tree diameters and heights of Douglas-fir stand (Li et al. 2002). They compared the model to Johnson's S_B and found that GBD-2 was more flexible and accurate than Johnson's S_B .

ExpertFit was used to automatically and accurately determine which of 39 probability distributions best represents the DBH distribution of each major species in this study. The ExpertFit contains four modules of reading data, fitting the model, testing the model, and applying the model (Law and Vincent 1999). The best probability density function (pdf) for each major species was selected based on the distribution function differences and goodness-of-fit tests. The distribution

function differences shows the differences between the selected distribution function and the sample distribution function over the range of the data. The small vertical differences (errors) suggested that these models provide good-fits.

Spatial Patterns

Spatial pattern is an important aspect of the stand generator that has to be considered during the development process. Cottam *et al.* (1953) addressed the distribution pattern of randomly dispersed individuals for sampling a population, which was one of the earliest attempts to spatial pattern. The uniform pattern is popularly used for the generation of planted stands while random pattern is commonly used for generating natural stands. A method to generate clustered stand was developed based on the Neyman Type A and the Thomas Series Distributions (Pielou 1957). Two parameters were used in the model - the cluster density or average number of cluster centers per quadrant, and the number of trees per cluster. A reasonable clustered pattern could be produced by this generator. The cluster area, however, was heavily dependent on the number of individuals in the cluster (Newnham 1968).

Newnham (1968) reviewed most of the basic spatial distribution methods and developed a simulator that incorporated many features of previous methodologies in which a Weibull distribution was used as the form for DBH distributions of planted stands and the exponential function was used to characterize the reverse J shape DBH distributions for natural stands. Newnham and Maloley (1970) reported that it was unrealistic that one tree was completely independent of the others for a stand generator because of the physical size of the trees. A minimum spacing restriction should be imposed on the stand generator in order to get more realistic and representative stands.

Both random and clustered patterns were modeled for the natural hardwood stands in the region. If a random spatial pattern is requested, a ratio of the stand density to the total number of possible tree locations based on minimum X and Y spacing is first calculated. Then a random number with a uniform distribution between 0.0 and 1.0 is generated for each possible tree location. If this number is less than or equal to the ratio described, the coordinate location is assigned a tree. If the random number is greater than the ratio, the coordinate location is considered to be unoccupied (Farrar 1981). The minimum X and Y spacing are considered in this procedure when natural stands are modeled. At each location, tree DBH is assigned randomly. The total height, merchantable height, and volume of that tree are then calculated based on the assigned DBH.

When the clustered pattern is used, the number of cluster centers specified by the user is located randomly within a plot. By generating the X and Y coordinates randomly using a pair of random numbers, each tree is provided an initial location. The distances from that tree location to each of the cluster centers are determined and the nearest center is selected. The distance from this center to the tree is then multiplied by a random number between 0.0 and 1.0 to give a new location for that tree relative to the cluster center (Farrar 1981). New coordinates are then calculated for the tree and the distances between that location and the neighboring trees are checked to assure that minimum nearest distances are maintained. If a tree location has violated the distance parameter, the procedure is repeated; otherwise, the location is assigned as a tree location.

Programming Components

The VB component was implemented to provide the interfaces, which allows the user to get input, assign tree characteristics, calculate the DBH distribution, display the 2D stand map, and save the generated stand map. The VC component can retrieve the generated stand data from the database, display the 3D stand map, and perform basic functionality on the 3D stand map.

Once the stand generator is started, the user needs to enter species composition, stand density, DBH range, spatial pattern, and stand age. Along with the DBH distribution, the stand information is also displayed with the stand map. The output of the stand generator is either a 2D or 3D map and a data file in the formats of both ASCII and relational database.

A Microsoft Foundation Class (MFC) based Open Graphics Library (OpenGL) programming was adopted for 3D modeling of stand. Because of its powerfulness and higher flexibility, OpenGL is extensively used for creating high quality 2D or 3D images (Woo *et al.* 1999). Two OpenGL libraries, OpenGL Utility Library (GLU) and OpenGL Utility Toolkit (GLUT), were incorporated in the project for programming component. The former is used for performing some lower-level OpenGL commands, such as setting up matrices for specific viewing orientations and projections, performing polygon tessellation, and rendering surfaces. The latter contains more complicated routines, such as opening windows for drawing, detecting input, creating more complicated 3D objects. An OpenGL Rendering Context (GLRC), the complete set of OpenGL state variables, is required for drawing OpenGL images. First, an OpenGL-capable window is created and initialized in MS VC++ environment, then a GLRC is created and made current.

Modeling Transformations

In order to make the generated 3D image stand look more realistic on the 2D computer screen, some transformations were used in the application. The viewing transformation is specified with `gluLookAt()` which is a built-in function of

GLU library to define the position of the camera (or position of the eyes). In this 3D stand generator system, the viewing position was implemented to change with the view modes of projective view, profile view, and overhead view. Three basic transformations of rotate, scale, and translate were modeled in the system and represented by three functions of `glRotate*()`, `glScale*()`, and `glTranslate*()` respectively in OpenGL (Figure 2).

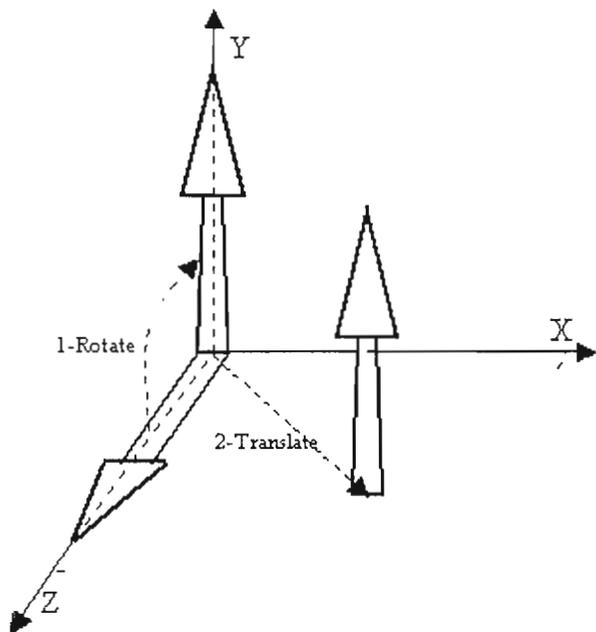


Figure 2. Modeling transformations.

Rotate. Rotate is performed by calling `glRotate*(α , x, y, z)` which generates the rotation matrix by defining the axis to be rotated about (x-axis, y-axis, or z-axis) and the degrees to be rotated (α).

Scale. Scale is performed by calling `glScale*(S_x, S_y, S_z)` function which creates the scale matrix ΔS .

Translate. Similarly, the translation is performed by calling `glTranslate*(dx,dy,dz)` function which generates the following translation matrix ΔT .

Projection Transformation. Projection transformation determines how objects are projected onto the screen, that is, the field of view and the objects inside it and to some extent how those objects look. Two kinds of projection modes were implemented in the system – perspective and parallel projections. The perspective projection matches how we see things in daily life, which is that more distant objects appear smaller, while the parallel (orthographic) projection maps objects directly onto the screen without affecting their relative sizes.

When a 3D stand map is being drawn in the system, an important function `SwapBuffers()` is always called to swap the viewable and reusable buffers. By doing this, the users can reuse the viewable buffers while the drawing process is still being conducted.

APPLICATION EXAMPLE

A natural hardwood stand in central Appalachia was generated so as to illustrate the performance of this 3D stand generator. Assuming the species composition is yellow poplar 40%, red oak 30%, chestnut oak 15%, and red maple 15%. The stand density is 400 trees per acre and plot size is 0.4-acre. It is also assumed that the stand is about 75 years old and trees are randomly distributed.

Once the above information is entered, a 2D stand map will be first generated and displayed (Figure 3a). Meanwhile a stand map data file is created and saved in the system. The 3D stand map could be displayed by changing the display mode (Figure 3b). Some functionality could be performed on the 3D stand map. For example, we could rotate the image left or right continuously and examine the stand structure from different directions. The user could also change the crown

height and diameter by using the "tree design" module. In order to differentiate species on the map, a unique color is randomly generated and assigned to each individual species. Additionally, the tree height and DBH are also drawn to scale for better visualization.

Two projection modes of perspective projection and parallel projection and three view modes of projective view, profile view, and overhead view were also enhanced in the system. Perspective projection and projective view are the default projection mode and view mode, respectively (Figure 3b). Overhead view and profile view could be enabled by changing the view mode in the menu bar (Figure 3c and d). The 3D component can also allow the user to mark trees to be harvested, fell marked trees, remove the felled trees, and save the operation data into the database for later analyses (Figure 3e and f).

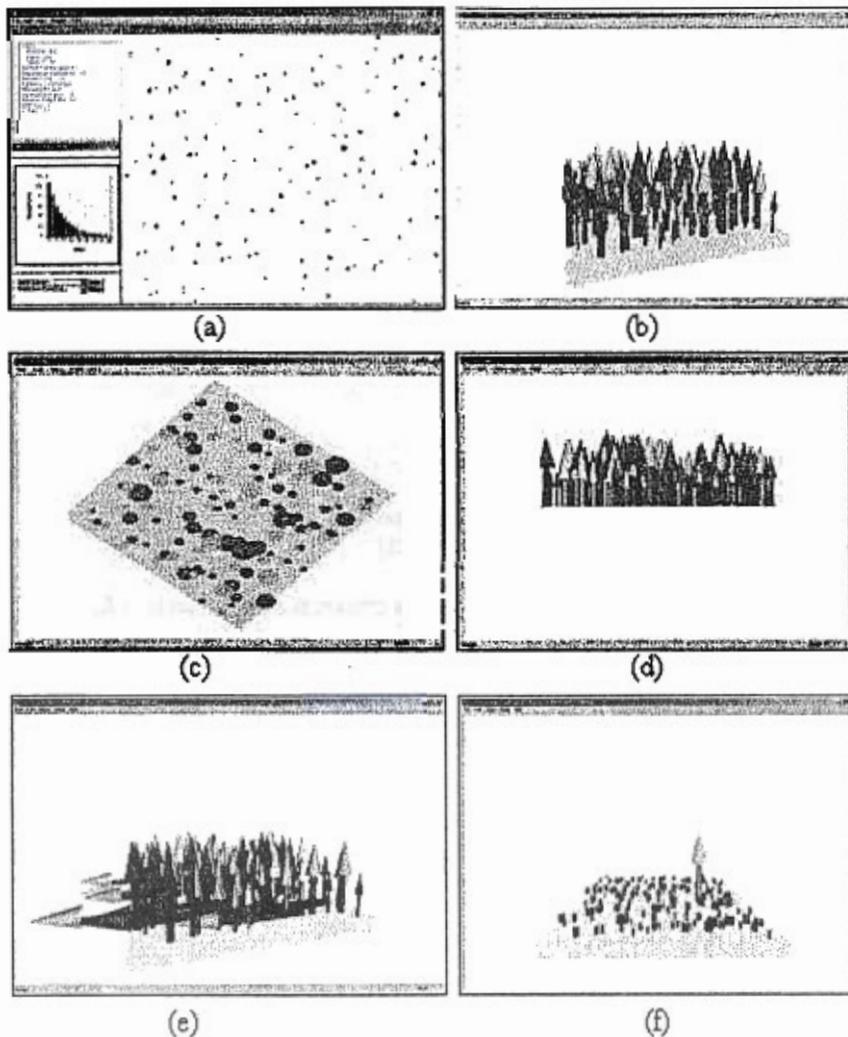


Figure 3. Views of 3D stand generation.

DISCUSSION

The MS COM technique is a viable method to design and develop the 3D stand generator. The COM objects make it possible for us to implement components in the 3D stand generator with both MS VB and MS VC++ languages. MS VB is well known for the interface design while MS VC++ is well suited for implementing the business functions. Traditionally, applications were distributed in single, large executable files, which are now known as procedural programming or

monolithic applications. These had many inherent problems, paramount of which was that if one line of code needed to be modified, then the entire application needed to be rebuilt. The COM with object-oriented design technique overcomes these problems and enhances the application's modularity and modifiability. No programming skills are required to use this 3D stand generator. The graphical user interface allows the user easy access to any modules or components in the system.

The 3D stand generator developed is a powerful tool that can be used to facilitate forest management planning such as harvesting simulation, layout, and landscape visualization. It could be potentially used to aid other research projects and analyze forest stand structure and dynamics. However, the current model does not contain a mortality function or a growth function. Other modules and components will be added into the system to enhance its functionality and flexibility. Modules to be added later will provide forest harvesting simulations and the related environmental and landscape impact evaluations. The tree design module needs to be improved to provide the user with more capabilities to design trees by species and make them look more realistic. In addition, further validation will be carried out to examine and evaluate the stand generator. This 3D stand generator can be applied to other regions by slightly modifying species and some other related equations used in the system.

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