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# SIMULATION IN THE WOODS: FROM REMOTE SENSING BASED DATA ACQUISITION AND PROCESSING TO VARIOUS SIMULATION APPLICATIONS

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## ABSTRACT

This paper focuses on joint work towards the development of simulation applications in the forest sector. They are based on advanced "semantic" world modeling techniques which use remote sensing data and processing algorithms to derive tree species classification maps as well as forest stand attributes and single tree databases over large areas. The resulting databases are the basis for a variety of different simulation applications in an integrated systems approach. Forest growth simulations aim to predict the appearance of the forest in the next decades. Forest machine simulators allow for an efficient development of forest machines and their control algorithms as well as for cost-effective driver training. Harvesting cost simulations calculate the harvesting costs long before the lumbermen start to work. Decision support systems enable wood owners and the wood industry to compare different treatment scenarios based on simulations and thus to comprehensively assess ecological and economical chances and consequences.

## 1 INTRODUCTION

Nowadays, simulation algorithms are used in nearly all fields of economics, ecology and research. They deliver the basis to assess the behavior of complex systems and are an important part of decision-making processes. But in the forest sector the use of simulation technology is really rare so far. Various attempts have been made to simulate forest growth, assess the effects of climate change or set up driving simulators for complex forest machines, but compared to other fields of economy this is far away from a wide and accepted usage of simulation technology as a standard tool in everyday tasks.

From our point of view, there is one main reason – **the data acquisition and handling problem**. Simulation applications require a detailed model of the environment to be simulated. But it is a major challenge to set up a detailed model for natural environments like the forest which extends over large areas. It gets even more complicated when taking data acquisition costs into account. **Our concept** to overcome this problem is fairly simple:

- Use state-of-the-art remote sensing techniques, which use already existing remote sensing data for a cost-efficient derivation of a simulation friendly forest model. We call this step "**Semantic World Modeling" because it goes way beyond topographic mapping and even beyond 3D geometric world models**
- Store the model in a **standards based database infrastructure** to allow for the easy exchange of algorithms and data

- Develop **different simulation applications** to optimize various processes in forestry concerning costs and quality under economical as well as ecological aspects
- Provide **easy-to-use user interfaces** to allow users which are not computer experts to use these new methods
- Use the same model multiple times for various applications to decrease the data acquisition costs per application once again

For this we are currently using **three different types of simulation**. At first, standard discrete event simulation (DES) applications calculate the harvesting costs under different boundary conditions long before the lumberman and the forest machines start their work. Quasi-continuous simulation techniques are the basis for driving simulators to train the drivers of highly complex forest machines to drive them efficiently while conserving the forest. Moreover, these simulators are the basis for the development of new automation concepts for the further development of forest machines in Virtual Testbed environments. Using the simulation techniques listed so far, techniques well known in the field of industrial production become applicable to forestry production. Last but not least, application specific simulation techniques simulate the forest growth under the consideration of different treatment and climate scenarios.

We cover Semantic World Modeling, data storage and simulation algorithms with one **integrated system** – the so called "Virtual Forest" (see Figure 1). This way a user can use different simulation algorithms to solve his task, e.g. first determine the trees to be cut in a thinning using the forest growth simulator before using the DES simulator to calculate the harvesting costs or before training this thinning virtually using the driving simulator.

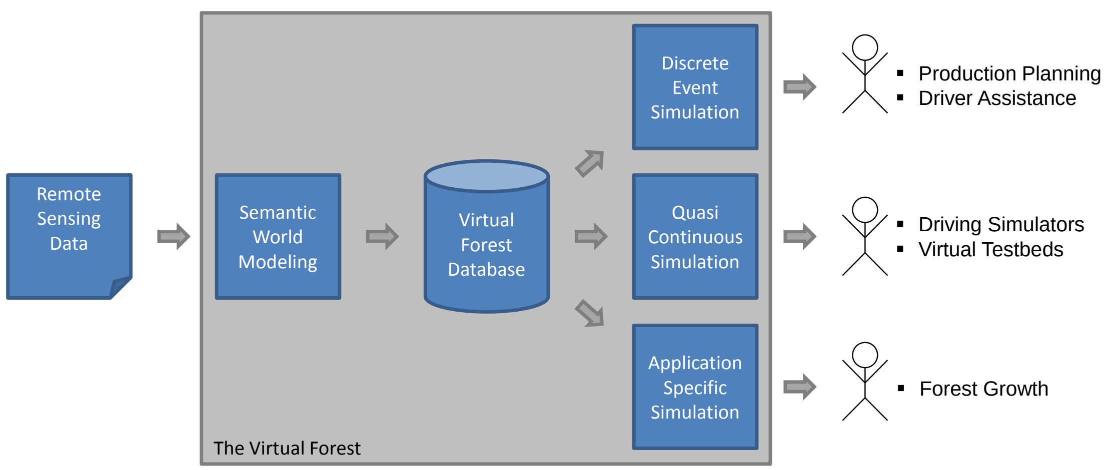



Figure 1: The Virtual Forest integrates Semantic World Modeling with different simulation applications to realize a new integrated system for decision support, assistance, training and development

The Virtual Forest concept **benefits nearly all parties being involved in forestry**. The forest administration and government can use the Virtual Forest to simulate the consequences of political decisions. Wood owners can test treatment scenarios and calculate harvesting costs as well as wood revenues. Forest machine manufacturers as well as researchers can train new drivers and test new automation concepts. Forest machine drivers get useful hints for their work. Forest schools get a comprehensive virtual training environment for education.

The benefits are manifold, but the focus of our current developments is simple: Convince forest owners and provide the necessary methods to use their forest in an economically and ecologically sensible way to ensure raw material basis for the local wood industry while conserving the forest itself for the future. This way our work delivers major contributions to guarantee the environmental sustainability in the forest while enhancing the competitiveness of the forest industry at the same time. The latter is even important in highly industrialized countries like the state of North-Rhine Westphalia in Germany. Here, 27% of the country's territory is covered by wood land, 7.2% of the gross domestic product is generated by forest and wood industry and 3% of all employees are working in the forest cluster.

The rest of this paper is organized as follows. Section 2 gives a short overview of related work in the field of forest management and simulation. Section 3 introduces the 4D-GIS, the software framework and the corresponding data infrastructure which is the basis for nearly all developments introduced later. The Semantic World Modeling techniques, which are used to generate a virtual forest model, are within the focus of section 4. Section 5 illustrates the three major simulation applications of the Virtual Forest and section 6 gives a conclusion.

## 2 RELATED WORK

Different aspects of the Virtual Forest Project are already within the focus of different research activities. These range from the development of methods for the classification of tree species (Leckie et al 2005, Pinard et al 2003, van Aardt 2000, Törmä et al 2000, Persson et al 2004, Kamagata et al 2005, etc.) to forest information systems (ZEUS 2011, Felbermeier et al 2003,Bruchner 2003, Saxon-Bohemian Forest 2011, Forest Inventory Mapmaker 2011, etc.), as well as to collaborative projects that focus on different aspects along the value chain in the forest (MatchWood 2011, etc.). Also the use of simulation techniques is not new. Besides different works in the field of simulation of climate scenarios, driving simulators are sold by all major forest machine manufacturers (e.g. Oryx 2011). But what is still missing is an integrated approach as it is suggested by the Virtual Forest concept, which links the different results to each other and uses the resulting potential for synergy.

## 3 THE 4D-GIS

We are integrating the different simulation algorithms in a 3D geo-information system (3D-GIS) resulting in a new kind of 4D-GIS which not only allows the user to look back into the data history but also simulate what might happen under different conditions in the future.

### 3.1 Basic concept

Figure 2 outlines the basic structure of the 4D-GIS from a simulation system point of view. First of all remote sensing data, as well as other already existing spatial data are fed into a spatial database. After that, Semantic World Modeling techniques (see section 4) are used to derive forest stands as well as single trees and their attributes. The results are written back to the database, building the basis for the three simulation applications (see section 5).

To realize a highly integrated GIS-based simulation system, care has to be taken in developing a powerful yet flexible data infrastructure. It must be fast enough to allow for real-time simulation applications, it must support modern object-oriented data modeling techniques to allow for a semantic world modeling and it has to provide enough storage capacity for vast amounts of geographical and other data. To resolve these partially conflicting requirements we developed a two-tiered architecture that combines an object-oriented internal real-time simulation database with external object-oriented active geo databases using an intelligent database interface that synchronizes their schema and data (see Figure 2).

In this architecture the simulation database can be seen as an abstraction layer of the external database, hiding away the specific DBMS (database management system) from the simulation system and its users. Based on the interface's read-write access the external database also serves as a persistence layer for the simulation system, providing features like access rights management and versioning on attribute level. Attaching more than one simulation client, an active external database can even be used as a central data storage and communication hub for collaborative data access and distributed simulation applications, where changes by one client are actively pushed to all other participating clients

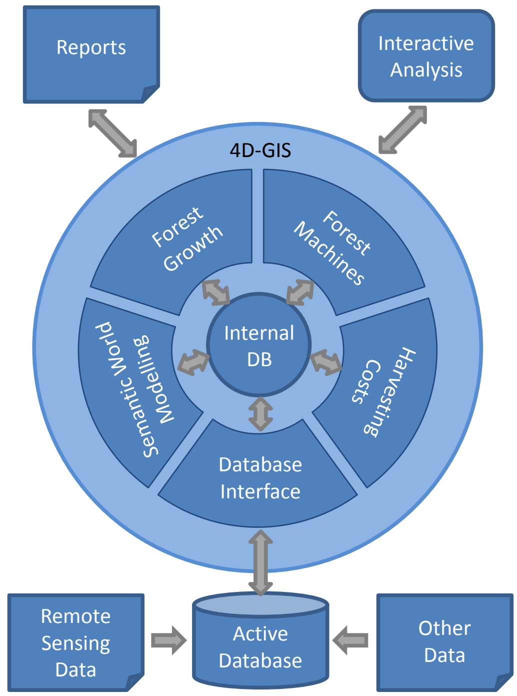



Figure 2: Overall structure of the Virtual Forest 4D-GIS from a simulations point of view

### 3.2 Internal Simulation Database

The internal database is an event driven and object-oriented graph database, which describes components (nodes), as well as their behavior and provides methods for parallel and distributed computing and visualization. Nodes not only provide data encapsulation but also mechanisms for interaction with the simulation environment implementing their behavior – this is what distinguishes this database from standard scene graphs. For example nodes that are derived from a “Simulation Task” provide functions that get called periodically by the simulation core.

All components of the database are derived from an ”Instance” class. Simulation data as well as the topology of the database is stored in so called properties. Using an ”active” database means that whenever a property is changed a signal is sent to all registered listeners. Different aspects of the simulation system only need selected views onto the simulation database, ignoring all nodes not relevant to the task. This is achieved by using indexed element lists provided by the database container, thus eliminating the need of simulation components to traverse the complete database.

Reflection is provided by so called meta-instances describing classes of instances (name, inheritance, etc.) and meta-properties describing their properties (name, type, multiplicity, etc.). This enables the simulation system to query meta-instances and meta-properties by name. Dynamic schema generation allows for the creation of new meta-instances and meta-properties at run-time. This is used to enable the synchronization process of the database interface.

### 3.3 External Database

As an external data management system we are currently using the GML (Geography Markup Language) database management system SGJ (SGJ 2011). This object-oriented geo DBMS offers instantiation of XML Schema Definition (XSD). This allows for the definition of arbitrary classes, inheritance hierarchies, relations and attributes. SGJ can be controlled using its proprietary Java API with a kernel-based architecture that allows full access to schema properties (classes, attributes and relations) and object data.

SGJ complies with several OGC (Open Geospatial Consortium) standards. Data can be modeled conforming to GML, geometries are represented as Simple Features, Styled Layer Descriptors (SLD) can be used to build maps for its Web Map Service (WMS) and data can be read and written using its transactional Web Feature Service (WFS-T). Its standard compliance guarantees access to the data from different applications on different platforms. Thus, different tools on different platforms can be used to build up the environment for a simulation and other clients than the simulation system can access the data.

### 3.4 Database Interface

As mentioned above we use an intelligent database interface that makes data available to the simulation system by synchronizing schema and data. Not only object data is synchronized by replicating objects from the external database to the simulation database and keeping them ”in sync”. The data schema of the external database is also replicated and thereby instantiated in the internal database making both ”speak the same language” and providing a common data schema for the whole system. This way the system shows great flexibility towards changes in the data, i.e. to objects or even to the schema itself.

This approach has several advantages over the direct usage of database objects within the simulation system. By using the (replicated) objects in the internal database, details of the actually used database are hidden from all internal components of the simulation system (particles, physics, sensor data processing, rendering, etc.) allowing for transparent data access and real-time visualization and simulation. The internal simulation database works as an ”intelligent” data cache to speed up repeating access patterns, which would otherwise lead to repetitive queries to the external database. Using mechanisms for piecewise data loading and unloading from the external database, e.g. based on the users position in a virtual simulation environment, huge datasets can be accessed (e.g. data from a vast tree database). Additionally, using an external database provides the simulation system with persistence as changes made to replicated objects can be resynchronized back into the database. Other clients or tools can still directly access the database without invalidating the dynamic two-level synchronization as a whole.

## 4 SEMANTIC WORLD MODELING

Setting up the world model of simulation applications it is not enough to derive raster information from remote sensing data, which is common in remote sensing technology today. Simulation applications need “objects” which have a meaning, whose properties are described by a set of attributes and who represent real world entities in a simulation friendly way. We call this process of deriving such objects from remote sensing data “semantic world modeling”. Figure 3 illustrates the different aspects of semantic world modeling within the forestry context. At first a tree species map and a map of potential tress are calculated. Using this, forest stands are delineated and stand attributes are calculated. The modeling process ends with a single tree segmentation step. A tree sample inventory delivers the necessary ground truth information for this.

### 4.1 Tree species classification

Tree species data is a very important source of information in the forest. It is needed for inventories, estimation of age as well as other forestry parameters and simulations of future developments of a forest area. Airborne color (RGB) and color-infrared (CIR) images in combination with airborne LIDAR data and multispectral satellite data have proven to be a good and affordable data basis for this.

As described in (Krahwinkler and Rossmann 2011), a support vector machine based approach is used to classify multiple species. Support vector machines separate two classes by searching for a hyperplane with two accompanying parallel hyperplanes such that the two classes are separated by the margin between the accompanying hyperplanes. Seven classes are used in the classification scheme, namely oak, beech, other coniferous trees, pine, larch, spruce and Douglas fir.

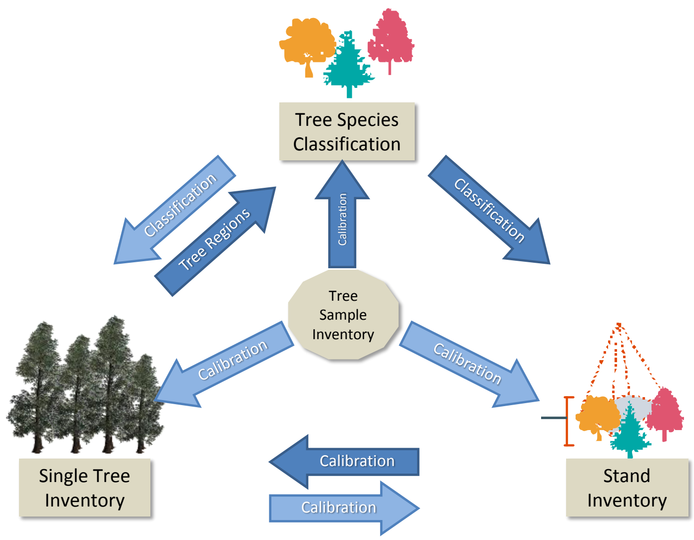



Figure 3: Aspects of Semantic World Modeling in the Forest

For the decision tree induction at each node all possible separations of the classes into two sets of almost the same size are calculated. For each of these combinations the Fisher distance is calculated and the pair of class groups with the highest value for the distance measure is chosen. The support vector machine is trained with the two species groups, as the two input classes. Figure 4 shows a deduced support vector machine based decision tree including 5-fold cross validation results during training at each inner tree node.

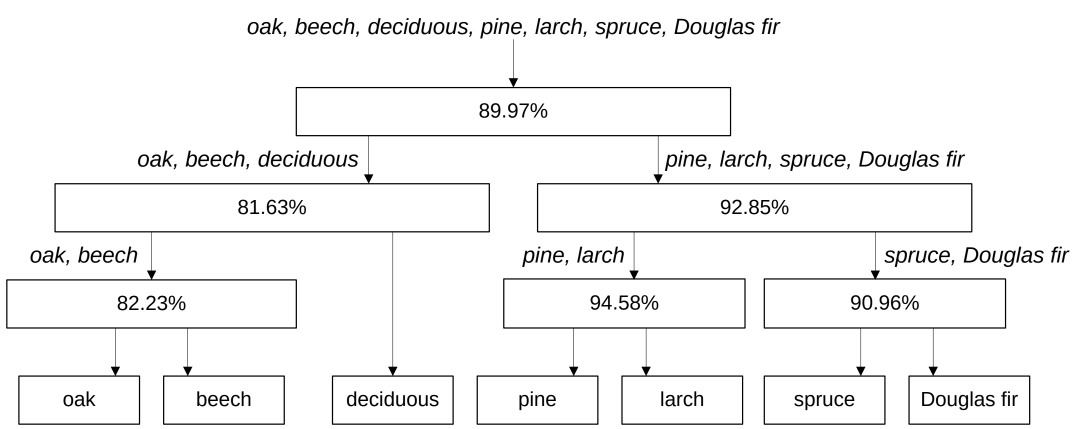



Figure 4: Support vector machine based decision tree and 5-fold cross validation results.

During classification, a value is calculated at each node. To estimate not only the species but also the reliability of the classification not only the sign but also the absolute value must be considered. Smaller values are calculated for input vectors that are close to the decision boundary and therefore the classification is more uncertain than for classifications with large absolute values. Figure 5 (left) illustrates the results of the classification process.

## 4.2 Stand Inventory

In North Rhine-Westphalia (NRW) and other German states the forest is separated into forestry units. To derive the geometry of such forestry units containing generalization algorithms have been developed. They calculate similarity measures to merge similar tree regions into a forest stand. Figure 5 (right) illustrates the results of a generalization of a land parcel (Rossmann, Schluse et al, 2009a).

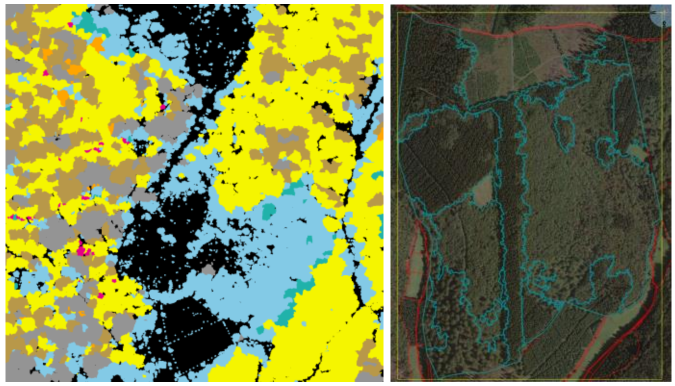


Figure 5: Example of the tree species classification (left) and of the stand generalization (right)

For each tree species within a forestry unit age, dominant height and a so called yield class are used to calculate the timber volume as a dependent value. The species mixture can be calculated out of the tree species (see section 4.1), while the stock density is related to the percentage of sheltered area in the unit.

The second important attribute to characterize the tree of one species in a forestry unit is either the age of the trees or the yield class. In all state owned and some private owned units the age and yield class is known and can be read out of the previous forest inventory. In other units the yield class can be estimated by using information about hydrology and trophic level obtained by a site classification (Asche and Schulz 2006), which is available for most units in North-Rhine-Westphalia. Comparisons on units of about 1200ha have shown that the amount of timber volume that was calculated with this approach differed only by two percent from the volume that was estimated by a surveyor for the same region.

## 4.3 Single Tree Inventory

The stand inventory is the calibration basis for automated single tree delineation algorithms which fill a database of individual trees using remote sensing data. The Volumetric Algorithm (Buecken and Rossmann, 2009) illustrated in Figure 6 provides an effective solution to delineate individual trees in a forest that is described by an nDSM (normalized digital surface model, shown far left). To get volumetric information we, figuratively spoken, fill the nDSM with water (middle left). Then in turns the point with the highest water-level is "opened", the flow of the water is simulated and the amount of water that drains out of the opening is measured (middle right). The interesting feature is that the resulting volume emphasizes peaks that are dominant in the surrounding. For each volume that is higher than a threshold t a tree is generated. With an optimized implementation this algorithm reaches linear complexity.

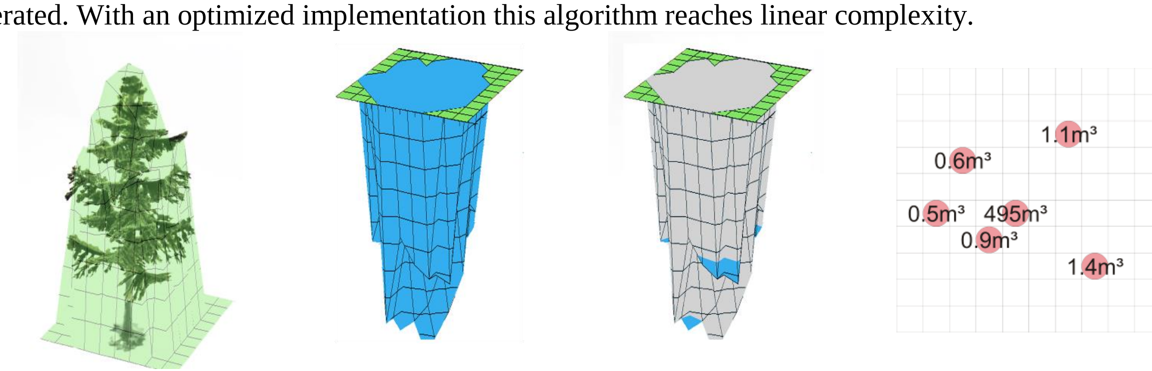



Figure 6: The Volumetric Algorithm: A Tree, its flipped nDSM filled with Water, the first Cycle of the Algorithm and the calculated Volumes.

Each tree is annotated with its height, its species (from the tree species classification) and the average crown diameter that is visible in the remote sensing dataset (Nagel and Schmidt 2001).

## 5 SIMULATION APPLICATIONS

In the Virtual Forest project the single tree database is now the basis for three different simulation applications, forest growth simulations, forest machine simulations and Virtual Testbeds as well as harvesting cost simulations.

### 5.1 Forest Growth Simulations

The perception of sustainability in forest management has dramatically changed from a one-dimensional, timber-production oriented towards a multi-criterial view during the last few decades. Finding an optimal management concept for forest stands and enterprises has become a high-dimensional problem. Therefore forest managers' need for information and decision support has multiplied. This information demand on the one and the available data on the other hand are the basis for a new generation of forest growth models which are very flexible with regard to silvicultural concepts, species mixtures and site conditions and which offer a broad multicriterial spectrum of output variables. It is common that forest growth simulators can provide that kind of essential information for the management of forest enterprises (Moshammer et al., 2009).

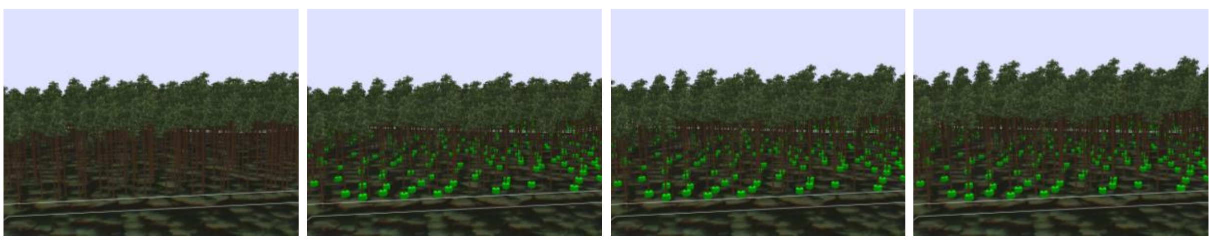


Figure 7: Simulation results of the forest growth simulator, the marked trees are important for the future growths of the stand

The forest growth simulator SILVA which is used for forest growth simulation in the Virtual Forest system (Figure 7) is a distance-dependent and environmentally sensitive individual tree model (Pretzsch et al., 2002). In SILVA each single tree is defined by a compound of several functions, as shown in Figure 8. The smallest simulation time step with SILVA is a period of five years, which is the time interval corresponding with the time intervals provided by yield tables. The implemented algorithms were parameterized from long-term experimental plots in Germany (Kahn, 1994; Pretzsch et al., 2002). The individual-tree approach allows the user to create rules for a virtual thinning which likewise takes place every five years.

For the simulation of realistic silvicultural activities the conventional thinning concepts are embedded in the program along with guidelines for thinning intensity, harvesting intervals and upper limits for the harvested wood volume. Therewith, a large number of management options can be simulated. The simulator automatically decides which concept to use for which stand dependent on its characteristics, e.g. site conditions, species, mixture, development stage. As default, three different scenarios of thinning intensity are calculated automatically in order to make the corridor of action for the forest management evident.

Interacting with the 4D-GIS environment SILVA can be used in two different ways. On the one hand side the basis for forest simulations can be delivered out of the 4D-GIS database by processed remote sensing data. On the other hand side SILVA can be used to generate virtual single tree based stands out of stand descriptions of the forest management to fill in the 4D-GIS database where no or not sufficient remote sensing data is available.

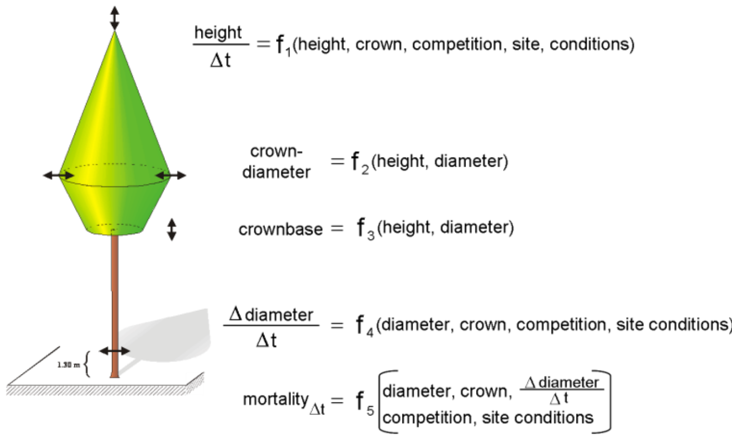



Figure 8: Functions for regulation of the individual tree growth

### 5.2 Forest Machine Simulation and Virtual Testbeds

Simulation combined with original board computers and machine controls has become an essential part in education and training of forest machine operators who can get used to the machine controls and get an intuition for the dynamic behavior of the crane and the whole machine.

Early training simulators were based on purely kinematic simulation techniques concerning the simulation of motion (e.g. Freund et al 2002). For the machines themselves this would be acceptable, as their analogy to industrial robots allow the use of well-known modeling techniques from this area. However, once these machines interact with the natural environment of the wood, these modeling techniques fail - for example in predicting the varying behaviors of cut trees or the many problems that may appear when a forwarder loads logs into its loading area.

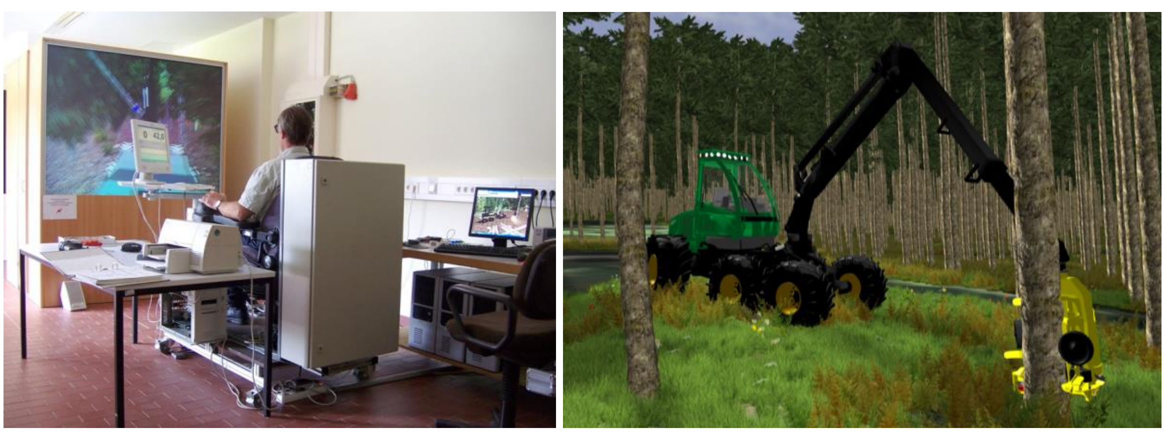


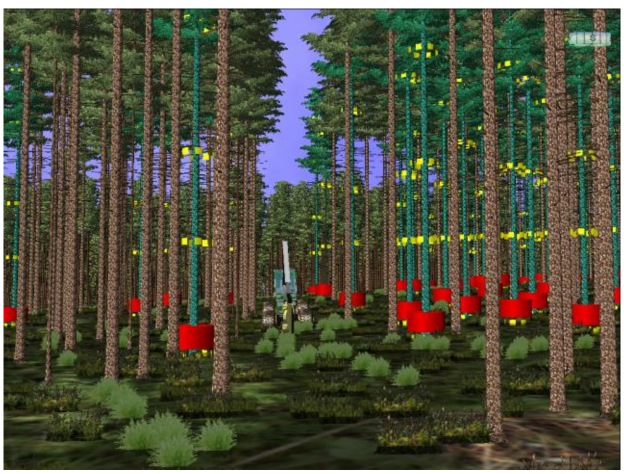
Figure 9: Photo of a forest machine simulator in the field taken in a forestry schools in Germany (left), screenshot of a Virtual Testbed scenario (right)

To overcome these weaknesses, modern forest machine simulators are based on physics based simulation systems (e.g. Jung & Rossmann 2007). Figure 9 gives impressions of current 3D-forest machine simulations. This results in a more realistic dynamic behavior and even reduces the efforts for creating new simulations.  While previous wood environments were mainly results of artistic freedom, the Virtual Forest database supplies the forest machine simulators with training environments which are as close to reality as possible. Trainees can learn in an environment, which looks like their future workplace. Machine operators can plan and simulate actual wood harvests. Practicability of potential skidroads can be evaluated in advance, as the Virtual Forest supplies the simulated environment with information about soil conditions and slope. Herein the latter is not just presented as abstract, numerical information. The operator can even evaluate the quality of a skidroad with respect to the reachability of single trees. It automatically offers a nearly infinite number of simulation environments, so that no additional modeling effort has to be taken. From a developers point of view this approach dramatically reduces the costs for modeling virtual wood environments for the simulators.

In addition to this, these simulation algorithms are the basis of a comprehensive engineering tool for the further development of automation concepts of forest machines, the so called Virtual Testbed. For this, various sensors and actuators as well as their sensor data processing and control algorithms can be added to the simulation model, e.g. to test new localization concepts using laser scanners (Rossmann, Schluse et al 2009b).

### 5.3 Harvesting Cost Simulations

The harvesting cost simulation application delivers important economic data for a goal oriented planning of efficient harvesting measures. It uses methods based on the work of (Hemm, Ziesak and Warkotsch 2006, Hemm 2006) and is implemented as a discrete event simulation (DES), which allows to quickly calculate harvesting scenarios (see also Rossmann, Alves 2009). The simulation starts with trees marked for felling by the forest growth simulation and incorporates the available roads and resources.



| | |
|---|---|
| **Wood revenue** | + 3935 € |
| **Harvesting costs harvester** | - 975 € |
| **Harvesting costs forwarder** | - 863 € |
| **Total revenue** | = 2097 € |

Figure 10: Results of the harvesting costs simulation (trees to fell, segments to cut, costs and revenues)

The simulation results can be viewed either in an online visualization or as a table summary as shown in Figure 10. One major aspect of the simulation is the routing of the used vehicles, based on a graph which is created from geo data. The routing algorithm takes into account the reachability of the trees, which are added from the database and are associated with the nearest edge of the graph. The harvesting costs are deduced by calculating the duration of the harvest and applying time/cost tables.

Besides its function as a planning tool the harvesting cost simulation with the routing information can also be used as the basis for a single tree navigation system, which assists the driver in finding the most efficient way to the nearest tree to be felled.

## 6 CONCLUSION AND OUTLOOK

This paper introduces the combination of modern remote sensing with state-of-the-art simulation technology resulting in an integrated forest management system, the Virtual Forest. This paves the way for the wide usage of simulation technology in everyday tasks in the forest sector. Whereas the overall goal is ambitious, the first results are really promising. The remote sensing algorithms are able to derive a close-to-reality model of the real forest which has already been tested in large test areas of approx. 1.000 km². The forest growth simulator calculates the future development of forests and provides a sustainable basis for complex decisions concerning the forest treatment. Real-time simulators are accepted to be a standard tool in driver education and training.

What's missing so far is an intensive evaluation of the harvesting cost simulator's results and its use for harvester driver assistance which will be two of our next tasks. In addition to this we plan to integrate the results of simulation applications mentioned above in easy-to-use (desktop and online) decision-support-systems for forest owners, forest administration as well as forest and wood industry.

## ACKNOWLEDGMENTS

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