EFORWOOD
Sustainability Impact Assessment
of the Forestry - Wood Chain

Project no. 518128

EFORWOOD

Tools for Sustainability Impact Assessment

Instrument: IP

Thematic Priority: 6.3 Global Change and Ecosystems

Deliverable PD3.1.5
Draft results of the mapping of properties of forest resources
according to use by generally applicable methods at the Case-study level

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This report, EFORWOOD deliverable PD3.1.5, has been produced within the EFORWOOD workpackage 3.1 "Quality Assessment and Allocation". It describes a concept for the mapping of properties of forest resources and building of Regional Resource Databases. The concept has been developed for optimization of the allocation and processing of wood raw materials into various types of products. The report is written by Sven-Olof Lundqvist and Thomas Grahn, STFI-Packforsk.

The concept of Regional Resource Databases has been developed in previous long-term research and development of STFI-Packforsk within projects of "cluster research programmes", funded by groups of pulp and paper companies. Databases of various sizes (supply area/region/nation) and levels of detail have been built for different applications through modelling and simulation, emphasising fibre properties and pulp and paper issues. The tools for the building and use of Resource Databases were developed in these projects for different pulp and paper companies. In EFORWOOD, the concept has been expanded and adapted for more general applicability.

An important scope of EFORWOOD is to cover all major forestry-wood chains in an integrated way. Therefore, the database for resource mapping and optimized allocation developed has to provide a basis not only for optimal use of the fibres in papermaking or of sawlogs in sawn products but also for optimization among all production chains investigated in the EFORWOOD project. It should be possible to compare effects of allocation to production of various paper products, sawn products or bio energy. For this purpose, it is necessary to provide information about a wide spectrum of properties of wood and fibres in the same format, available in the same database.

Another objective has been to make the concept as generally applicable as possible, to allow its use in many types of applications in different countries and on various species with limited efforts.

The authors acknowledge all funding organisations and companies for their support to the development within EFORWOOD and in previous projects. Special thanks also to Lars Olsson, STFI-Packforsk, for his contributions and to Barry Gardiner, Forest Research, for valuable comments.

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1. Summary

This report describes a concept "Regional Resource Databases" for mapping of properties of forest resources, providing a basis for optimal allocation of wood and fibres. The concept has previously been developed at STFI-Packforsk, emphasizing properties of fibres and use for production of pulp and paper. It has now been expanded and adapted for wider applicability to match the needs of the EFORWOOD project, where all major wood-based production chains are dealt with in an integrated way. This work has been done within the EFORWOOD workpackage WP3.1 "Quality Assessment and Allocation".

In a "Regional Resource Databases", forest data about stands and trees of the resource are complemented with estimated information about properties and volumes of the trees and for different parts of the trees: logs, parts of logs to be chipped or sawn, etc. The estimations are based on simulation, using inventory data of different origins or data from harvesters as input data to sets of integrated models. The resulting database offers a virtual representation of the available resource, which can be used in many types of applications. The size of the database, the properties included and the level of detail in description of the trees and parts of trees are adapted to the application.

An important scope of EFORWOOD is to cover all major forestry-wood chains in an integrated way, to allow not only optimization along single chains but also among all production chains investigated in the project. For this, it is necessary to provide information about a wide spectrum of properties of wood and fibres in the same format, available in the same database.

The EFORWOOD version is designed to facilitate application in different situations during the final phase and after the project: different regions and wood species, and also when a complete description of the resource is not available. Furthermore, it includes properties of relevance for the different forestry-wood chains, dealing with solid wood, fibres and energy.

In this report, the general concept of Regional Resource Databases is briefly presented and some examples of simulations with different levels of detail and sizes of the regions are given to inspire use of the concept. Then the EFORWOOD version is described. The mapping of the forest resources in Västerbotten, one of the regions studied in a case study of the project, is illustrated with two examples: a small-size and a large-size database serving different purposes.

It is also indicated how such information, together with knowledge about the raw material demands of products and processes, may be used to improve allocation of wood, to supply different industries with more uniform and suitable raw materials for specific products, within the constrains set by availability, logistics, economics, etc.

The workpackage WP3.1 also includes case studies in Västerbotten, Baden-Württemberg and Scotland, where model-based approaches are developed for improved allocation of wood. This work is briefly described in this report, but will be more extensively covered in a separate report during 2009.

2. Introduction

Wood shows a large variation in properties; between species and trees, under different growth conditions and in parts of trees. This means that it is possible, but not always economically feasible, to find wood matching a broad spectrum of property specifications for different products and processes. The large variability is, however, also a weakness of wood as a material. Unwanted property variations lead to reduced yield, increased costs and problems with product quality in the industry. Therefore, improved procedures are needed to predict properties of stands, trees, logs and chips and to allocate the wood optimally to different production chains, mills and products. It is also important to provide the mill with information about the properties of the wood supplied, in order to support efficient operation and the right product quality.

The paper illustrates how this can be supported by using models and simulations, as well as through the concept of Regional Resource Databases. Such databases include estimated volumes and properties of stands, trees, logs, chips, wood and fibres representing the forest resources of a region. They are very useful both in research on optimal wood and fibre utilisation and for development of applications.

This report describes:

- The general concept of Forest Resource Databases:
  + how they are built
  + different levels of detail for various applications
  + from local to national databases, depending on use

- The type of databases for mapping of regional resources
  specifically designed for EFORWOOD:
  + objectives, size and level of detail
  + illustration based on inventory data from Västerbotten in the north of Sweden:
    models, size, property variations and examples of use.

The concept applied has earlier been presented in the EFORWOOD Deliverable PD3.1.3 "Draft concept for mapping of properties of forest resources for classification of wood from a product perspective" submitted in November 2007 (Lundqvist et al 2007d). The recent development has also been presented for the larger public in (Grahn, Lundqvist 2008) and (Lundqvist et al 2008).

(The authors will modify this EFORWOOD Deliverable into two publications. A more comprehensive state of the art description will then be added, putting this work into the context of other integrated systems of models for simulation of properties of wood and fibres. The reference list above will then be reduced to include only a selection of these references, while others related to the state of the art description are added.)

3. Sustainability, properties and allocation

The allocation of suitable materials to mills, processes and products is crucial for the sustainability of the forestry wood chains. All aspects of sustainability are influenced: environment, economics and society. If unsuitable material is allocated to a process, this will normally lead to losses in yield and value. The processing will normally be less efficient, with use of more material, energy, etc. than necessary per unit produced. Unsuitable materials may have to be redirected to other processes or mills, which means more transportation. In addition the quality, product functionality and customer satisfaction may be compromised.

3.1 Typical segregation of trees and allocation of materials

In *figure 1*, a typical way to allocate wood to different types of products is illustrated. At the top of the figure, groups of trees of various sizes illustrate different types of silvicultural or harvesting operations: pre-commercial thinning, first and second thinning, final cutting, which are performed at different stand ages, or rather when the trees have reached suitable sizes. Also harvesting of stumps is visualized at the far right. Below this line, a typical segregation scheme for trees from a final cutting is shown. Similar schemes could be drawn for the other harvesting operations at other ages, but are not shown in the figure. The flow chart further down shows how the different entities typically are directed to different processes and products. Five major groups of products are shown, but the grey boxes behind each front box indicate that each group includes several types of products and quality grades.
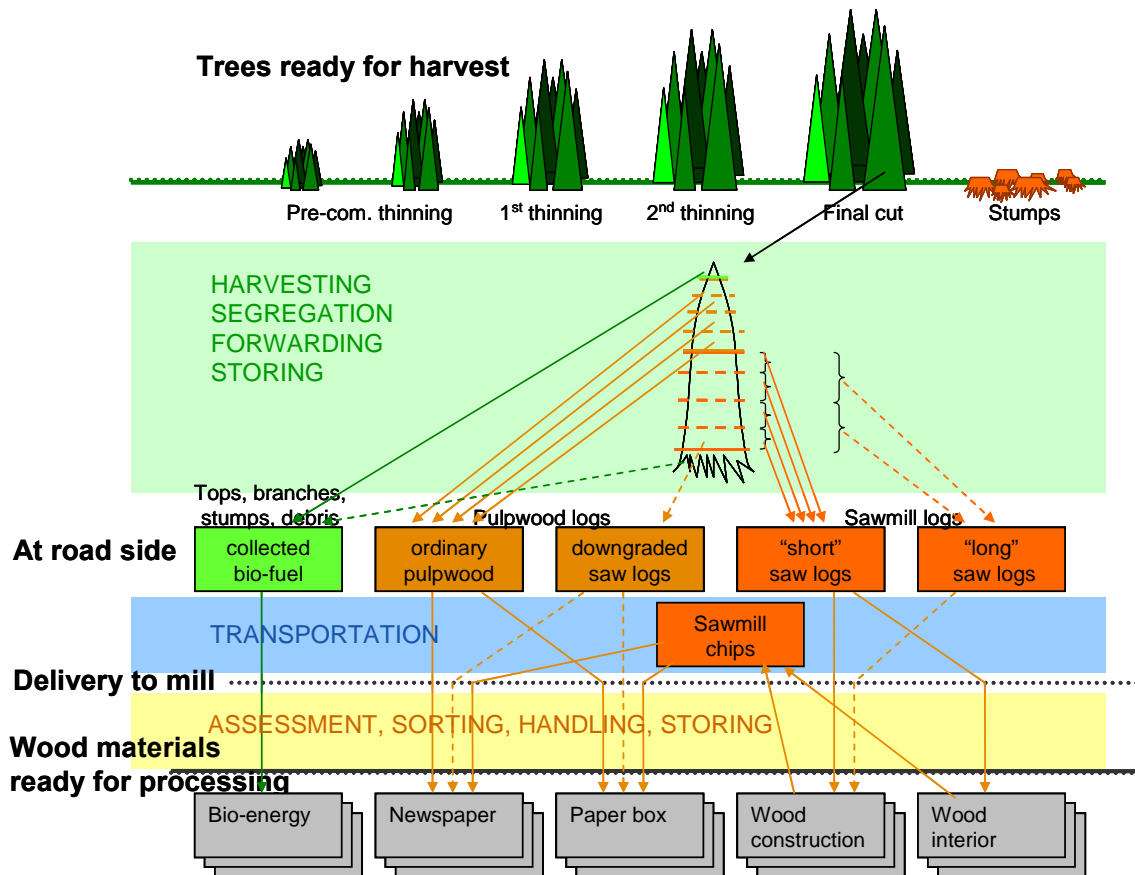
Figure 1. *Typical allocation of materials from final cutting of a softwood stand.*

In the EFORWOOD project, the issues related to assessment of wood and fibre properties and suitable allocation of materials to various processes and products are mainly dealt with in workpackage 3.1 "Quality Assessment and Allocation". In *figure 2*, important prerequisites for and activities involved in allocation from the perspective of WP3.1 are summarised. The figure also illustrates how WP3.1 relates to the other Module 3 workpackages covering harvesting, logistics and integration.

Three main tasks are defined in the figure:

1. Mapping of the resource: volumes available of wood and fibres with different properties

2. Definition of process and product demands on properties of wood and fibres

3. Establishment of allocation alternatives and selection of the most favourable alternative from a holistic perspective

Task 3 is a kind of matchmaking, to match what the mill want with what the forest is offering. Below in this chapter, the tasks are briefly described. In the subsequent text, however, only task 1 is dealt with.

M3 from the WP3.1 perspective

Figure 2. *Important prerequisites for and activities involved in allocation, from the perspective of EFORWOOD WP3.1*

3.2 Mapping of resources with Forest Resource Database (task 1)

One prerequisite for good allocation is obviously information about the available forest resource, part 1 in figure 2. This information can be based on inventory data for stands available for harvesting. (For small scale production, 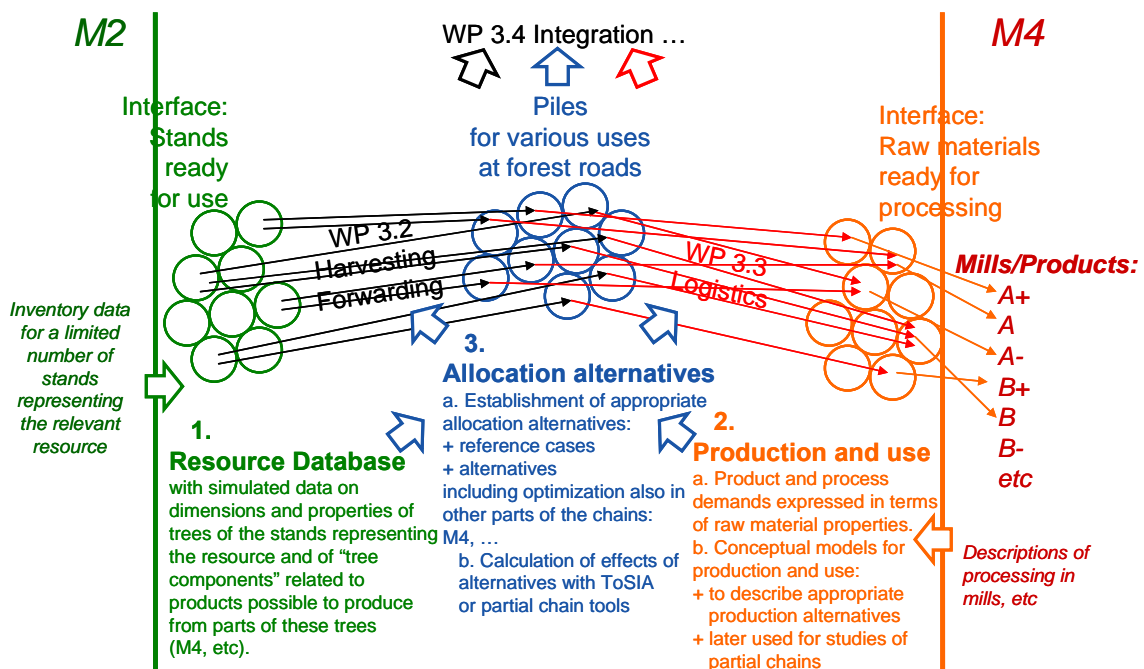visual inspection is sometimes used.) Traditionally, forest inventories have emphasised the sizes of the trees and volumes available. For good allocation the information should, however, also include data on properties of relevance for the products considered: How large volumes of wood with different properties are available for production of various products.

General concept

For this purpose, a concept of Forest "Resource Databases" has been developed at STFI-Packforsk. These databases combine inventory data with simulated data on available volumes, dimensions and properties of the inventoried trees from the specific forest resources. They also include volumes, dimensions and properties of "tree components" related to products possible to produce from these trees when harvested. Examples of "tree components" are pulpwood logs and sawlogs, sawmill chips and sawn goods. The databases include information on properties and volumes for a multitude of such "tree components" originating from thinning and final cutting of stands of different wood species with various ages and growth conditions. All data on stands, trees, logs, chips, wood and fibres are compiled in the database. From the database, tree components can be compared, combined into material flows of relevant sizes according to different criteria, evaluated from various aspects, etc.

Some prerequisites for the building of a "Resource Database" are:

- Data describing the resource: So far, inventory data or harvester data (complemented with information on the stand level) have been used, but remote sensing data from LIDAR or TLS (terrestrial laser scanners) and non-destructive measurements (e.g. acoustic tools) can provide further information.

- A set of integrated models for growth and property variations within and between trees, stands and species

- Dedicated software for simulation and communication with databases for input of stand and tree data and for output of properties and volumes into well defined formats.

The general concept of "Regional Resource Databases" has been used for several years at STFI-Packforsk in different applications with customer companies. Databases have been built for resources of different sizes, depending on application: to start with for supply areas of individual mills but now also for larger areas, including a "National Resource Database" for all Sweden. Databases have also been built with emphasis on different properties and with different levels of detail regarding properties and tree elements, depending on application. Most of the work has been performed as contract work for customers and is confidential. Some examples are, however, given below in the description of how the databases are built and the concept and some more examples of applications are further described in (Lundqvist et al 2003b; Lundqvist et al 2005; Lundqvist et al 2007c; Grahn et al 2008; Lundqvist et al 2008).

Concept specially designed for EFORWOOD

This general concept is based on data, models and tools successively developed in various projects. It includes a number of functionalities relevant for EFORWOOD. Within WP3.1, STFI-Packforsk has used a sub-set of these to design a concept specially adapted to the needs of EFORWOOD regarding size and detail of the Resource Databases.

EFORWOOD is a project involving many countries with large differences in forest resources, operations and use. One aim of the EFORWOOD project is that the tools and methods developed should be generally applicable, possible to use for investigations of various issues in different countries, involving different tree species, silvicultural practices, processes and products, etc. It will not be possible to cover a high level of detail in all situations which may be studied. Detailed property models will not always be available and in some cases complete inventory data may not exist. Therefore, the EFORWOOD version of the concept of "Regional Resource Databases" was built with the following characteristics:

- Use of models with less detail, only estimating averages for the tree elements

- Use of small tree elements representing annual longitudinal growth (distance between whorls) for maximum flexibility in the analysis (allowing also comparison of cross-cutting alternatives), but with the option to work with log-length elements.

- Use of limited size sets of inventory data for selected stands/plots representing the resource of the region (if large data sets are not available or for rapid tests or sensitivity analysis), but with the option to use data from large sets of stands if available and useful.

STFI-Packforsk has within WP3.1 designed new database structures meeting these demands and added models for further wood and fibre properties. Further, a scheme has been compiled, defining the structure of integrated models needed to build this type of database. The scheme is a reduction of the structures used within the general concept. The previously developed tools are used for the simulations and the building of the database.

A first draft of this EFORWOOD version and indicative results were presented at the EFORWOOD week in Lisbon 2006 (Lundqvist et al 2006). The structure of the integrated model system was presented at a WP3.1 workshop in Stockholm in 2007 (Lundqvist et al 2007a). A draft concept and further results were presented at a COST E44 conference "Modelling the wood chain: Forestry – Wood industry – Wood product markets" in September 2007 (Lundqvist et al 2007c) and in the Deliverable PD3.1.3 in November 2007 (Lundqvist et al 2007d). In this report, the concept is described in further detail in chapter 5 and further examples of results are presented in chapter 6 and 7 based on the Västerbotten case, one of the three cases studied at the mid stage of the EFORWOOD project.

Some comments

Many models for growth and properties have been developed for different tree species. For use in simulations of this type, it is, however, necessary that models match each other regarding input and output variables (interfaces), and that all of them are valid for the regional growth conditions, etc. The

type of integrated models needed, including properties of wood, fibres, knots, etc. are now in place for Norway spruce and Scots pine, developed based on data from the Nordic countries. In addition some work has been completed for Sitka spruce, based on data from the British Isles. Before they are used under new growth conditions, the models need to be checked carefully and fully validated.

For simulation of other species in other countries, it is normally necessary to compile a set of integrated models: to investigate what models are available, find out if they match or may be adapted to match each other. It will probably be necessary to develop one or more complementary models and model test and validation will be required. Some efforts are, thus, needed before Resource Databases may be built for new species and regions, but the measures taken and the existence of methods and experiences from previous and ongoing development will facilitate work on new species. For use within the EFORWOOD project, with the often expressed need to simplify processes, and with the ambition to describe major trends but not the full detail, it may be possible to cut some corners and in some cases even use models for a similar species.

Another comment is that the combination of small tree elements for large sets of stands will of course involve larger data sets, long computing time and more demanding evaluations. For off-line analysis the computing time during simulation is normally not that important, but if the databases are extremely large, it may also slow down the evaluation. One should consider the objectives of the investigations before designing the content and size of the Resource Database.

3.3 Suitable production and use (Task 2)

Another prerequisite for good allocation is knowledge about products and processes and their demands on the raw materials, expressed in terms of wood and fibres properties. This has been described in the EFORWOOD deliverable D3.1.2 (Lundqvist (editor) 2007b). Conceptual models are also needed for the production of the products and their use, in order to describe appropriate production alternatives. This will be addressed later in studies of partial chains.

3.4 Allocation alternatives (Task 3)

When ToSIA (Tool for Sustainability Impact Assessment) (Lindner et al 2008), the main result of the EFORWOOD project, is ready for use, different policies and alternatives will be evaluated through the calculation of indicators related to environmental, economical and societal effects. However, ToSIA will not check if the calculated alternatives are realistic or not. Also impossible alternatives fed into the tool may get high scores. For example, if one would suggest that products with very high added value should be produced from the poorest quality wood locally available, the calculations would probably supply indicator values suggesting that this is an excellent idea. This would most likely be a totally misleading answer. Therefore, it is crucial that realistic allocation alternatives and scenarios are established for evaluation with ToSIA.

A practical way to do this, not the least regarding allocation, is to establish appropriate current or future "base cases" including effects of operations all along the production chains. The EFORWOOD project has proceeded stepwise with modelling and data collection for single test chains from forest to end-use to multi-chain regional case studies. Data from these exercises may be used as a backbone

in the building of these reference "base cases". The alternative cases would then be designed through modifications in a number of processes along the value chains, as compared to the base case. Example: Procedures in silviculture are improved -> more favourable fibre properties are obtained -> it is possible to produce thinner/lighter paper with the same functionality -> need for transportation is reduced -> etc. Flows, yields, energy consumptions, etc. are stepwise modified along the chains. The creation of such realistic alternatives will often involve several parts of the production chains and can only be designed by experts in the field. Then the effects of the alternatives are calculated with ToSIA or with partial chain tools and the results are expressed with indicator values which are compared.

3.5 Related efforts within EFORWOOD

The Regional Resource Database provides a virtual representation of the forest resource and of the tree components possible to produce on harvesting. It includes data on the size, volume and properties of wood, fibres and knots of each component. With this at hand, standard database tools may then be used to investigate the volumes of wood meeting different combinations of property demands raised by specific product and process and optimal solutions may be sought for.

Apart from the general concept and its application in Västerbotten, three related efforts have been performed within the EFORWOOD project in Västerbotten, Baden-Württemberg and Scotland. These are briefly presented below but will be described in further detail in a separate EFORWOOD report, also including a documentation of the models used (Lundqvist et al 2009).

Mapping and allocation with software for harvesters

A second approach related to assessment of properties with use of models is illustrated by Skogforsk. It is also based on the Västerbotten case and the two approaches are actually quite closely related. Software developed for harvester computers and commonly used in Sweden is used together with price lists for different sizes and qualities of logs, etc. In this way, also effects of cross-cutting may be more directly reflected. This concept and some indicative results were also presented at the EFORWOOD week in Lisbon (Wilhelmsson et al 2006). Its application for optimal allocation of timber to a number of sawmills was illustrated in (Wilhelmsson et al 2007). Examples are also given in (Valinger et al 2008), showing dimensions and properties of logs and knots of sawlogs. Fibre properties may also be included.

The reason why both these approaches have been worked upon is to throw light on mapping and allocation from different perspectives. The Skogforsk approach is closer to an on-line allocation and operation. The approach with "Regional Resource Databases" described above is more dedicated to off-line use in design of allocation strategies, planning, etc. But it can also be used as a basis for on-line allocation tools and it is more generally applicable when it comes to implementation in different countries, etc.

Both approaches have been applied on the Västerbotten case, using inventory data from the same source, the Swedish National Forest Inventory Database (Riksskogstaxeringen). In both cases, more or less the same set of property models has been used, developed some years ago in a joint project among STFI and Skogforsk (Lundqvist et al 2003a). More about these common models in chapter 5.

The Baden-Württemberg case

Another regional case study addresses Baden-Württemberg. This region is very complex with respect to tree species and silviculture applied, resulting in an enormous variation of tree growth and quality related properties. The case includes all activities in the region related to solid wood chains and fibre chains as well as bio-energy chains from the forest to the used and recycled products. The Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg (FVA) has develop special models and tools, which match the inventory data and quality classes of Baden-Württemberg.

The Baden-Württemberg tools reflect the conditions of the regional resource in terms of availability and use models on BW and all German basis to estimate the grades of saw logs from spruce trees in the forest resource. Inventory data and models are used to simulate the size and shape of the spruce trees to derive quantity of roundwood grades of sawlogs both for conventional bucking to pole length and to standard length. Grading criteria are the average annual ring width at the top of each log and the diameter of its largest branch. From these properties, the grade is estimated.

This is a good example of modelling and simulation focused on performing a specific task and the result should be very useful for optimal allocation of sawlogs to the regional mills and their products.

The South Scotland Case

A regional case study has also been developed for the South Scotland region by Forest Research. The case study covers only processes in M2 and M3 (i.e. from forest establishment to the mill yard). The model currently only covers Sitka spruce but managed under a number of different management scenarios. The growth of the trees under the different management options is forecast from growth and yield models. At final harvest the material cut from the trees is sorted into different log lengths based on assortment models adjusted for the predicted straightness of the trees (Macdonald et al., 2008). The final result is a prediction of the volume of logs separated into green sawlogs, red sawlogs (green and red are UK sawlog classifications), pallet logs and pulp logs. This exercise has also been carried out for the entire public forest estate in Scotland up until 2029 with the addition of predictions of the average wood density and knot area ratio of the different log classes (Gardiner, 2008).

4. Building and use of Forest Resource Databases, – The general concept

Starting from scratch, two steps are involved in the building of a Forest Resource Database. First a limited set of more exclusive data from small-scale sampling is used to build models. Then large sets of low cost data are used as input data for large-scale simulations, to provide representative results.

4.1 Sampling, measurements and modelling (Step 1)

In the first step, wood samples are taken from stands and trees, selected to reflect the major sources of property variations of the species in the region. The stands and trees are carefully characterized and the samples are analysed for wood and fibre properties. Based on these data, models are

developed for the property variations. In this phase, the "Wood and Fibre Measurement Centre" is extensively used. The Measurement Centre is equipped with unique equipments from own development and from cooperation with other groups. An array of efficient methods is available for characterisation of wood, fibres and vessel elements of wood from different species. STFI-Packforsk has long experience in the development of measurement methods and the competence to develop and adapt methods to the specific conditions in different projects has been crucial for the development of the models.

An instrument frequently used is the SilviScan instrument developed at CSIRO, providing information about radial variations in wood density, cross-sectional dimensions of fibres and vessels, microfibril angle, wood stiffness (estimated acoustic MOE), content and properties of earlywood and latewood, etc. (Evans et al 1995; Evans 2006). Other techniques applied are CT-scanning for determination of cross-sectional distributions of moisture and basic density in discs (Lindgren et al 2000), analysis of growth rings and earlywood/latewood (Olsson 2000) and image analysis for dimensions and relative numbers of fibres and vessel elements in wood and pulp (Karlsson et al 1999; Granlöf et al 2006).

With efficient measurement methods, the costs can be kept reasonable at representative sample sizes, but it is still desirable to keep down the number of samples and measurements. The number of samples needed for the development of good models is heavily dependent on what variations the models are expected to describe (but also on the scope and layout of the sampling strategy). Therefore, the number of trees sampled varies, but it s typically in the range of 30 to 300.

Once the models are available, they are implemented in simulation tools developed for the purpose. For quite a few species and properties models are already available from previous projects or from the literature.

4.2 Inventory data, integrated models and simulations (Step 2)

This number of trees, 30 to 300, is of course too small to reflect the variations within the resource. In the second step, very large sets of low cost data, such as existing inventory data or harvester data, are used as input to the models for simulation of representative numbers of stands and trees, see *figure 3*. Both existing inventory data of forest owners and data from the Swedish National Inventory Database have been used.

Input data needed for the simulation of a stand are the statistical distributions from callipered diameters at breast height, estimated or measured tree ages and tree heights, as well as a set of basic stand data, such as site index, latitude and altitude. Typically, volumes and properties of tenths of thousands of trees, of logs obtained from harvesting and cross-cutting the stems and of chips from the sawing of the larger size logs are compiled in a Forest Resource Database. When using the special EFORWOOD version, the numbers are expected to be smaller.

Today, much work is dedicated to the development of more efficient methods for monitoring forest resources through remote sensing techniques, such as airborne LIDAR. In the future it may well be possible to use data of such origin as input in the generation of the Resource Databases (Fonweban et al 2008; Moberg et al 2008).
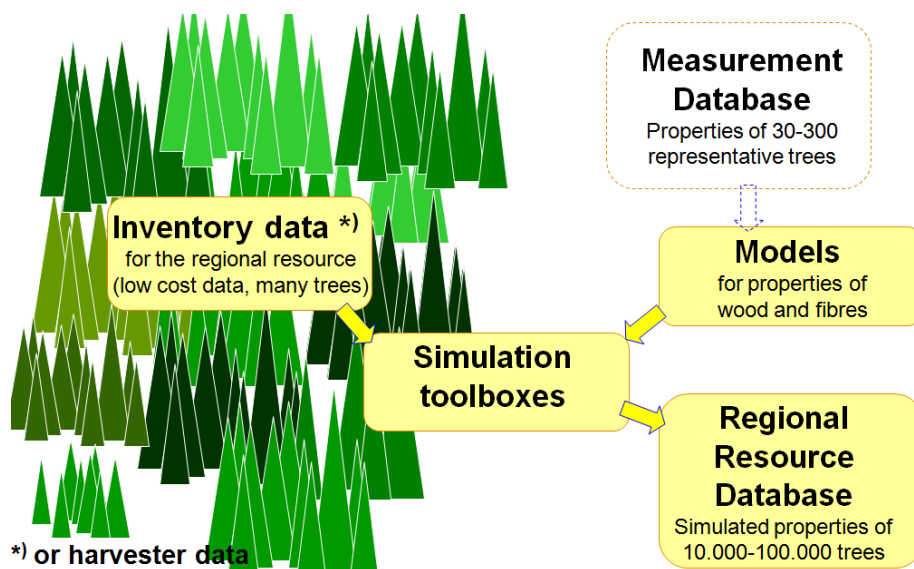
Figure 3. *Illustration of the building of a Forest Resource Databases.*

Stepwise simulations of properties of trees, logs and chips

The simulation of a tree and its properties is performed stepwise, using a set of integrated models, see *figure 4*. The starting point is the measured breast height diameter of the tree. Then measurement data or estimations with models provide the age, height and taper of the tree (A in the figure). The growth pattern is generated (B), normally using average patterns from large sets of measurement data but patterns from increment cores may also be used. The within stem variations are then simulated for the wood and fibre properties of interest (C). In most previous investigations at STFI-Packforsk, fibre properties have been emphasised, such as fibre length (shown in the figure), fibre width and fibre wall thickness. Sometimes, however, wood properties have been simulated, such as density, heartwood, knot properties, etc. In the next step, the volumes and properties of tree parts of technical interest are calculated through a virtual cross-cutting of the stems into pulpwood logs and sawlogs, as well as for the parts of sawlogs which will become sawn products and sawmill chips (D). Finally, fibre populations

Figure 4. *Stepwise simulation of wood and fibre properties of a tree and of logs and chips produced from it.*

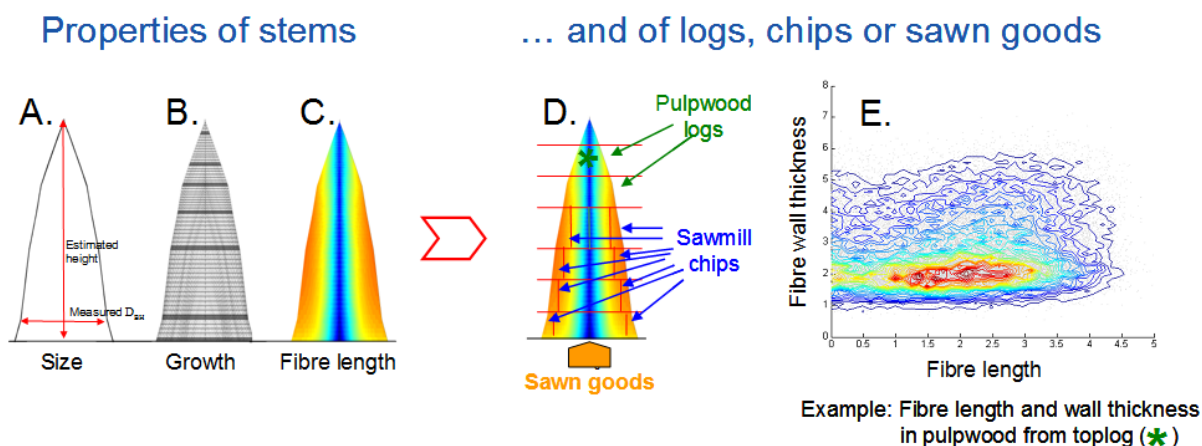may be generated for the parts (E). Typical several thousand fibres are simulated for each wood part, including the length, width and wall thickness of each fibre. In *figure 4E*, a fibre population is illustrated with a contour plot, showing its two dimensional statistical distribution for fibre length and wall thickness. The distributions are quite broad, but the differences are still often relevant in papermaking. The distribution in the illustration relates to the toplog (marked with * in figure 2D). In this log, a majority of the fibres are relatively short and thin walled.

Models and simulations

For this stepwise simulation, the models have to match each other, forming the systems of integrated models mentioned above. The systems include models for taper of trees, fibre dimensions and wood density. Most of the models have been developed within various cooperative projects.

Depending on the purpose of the simulation and on the application considered, models with different levels of detail, such as averages for stem cross-sections, annual rings or parts of rings, and with different sets of independent variables are used. *Figure 5* illustrates a model developed by STFI-Packforsk for wood density of Scots pine (*Pinus sylvestris*) based on data from Sweden (Olsson et al 200x). The model estimates the average wood density of individual growth rings at arbitrary heights in trees. Independent variables are the number and width of the ring and the height of the cross-section in the tree. The R^2 of the model is in this case 0,51 for the ring averages, which is rather typical for models of wood density, but 0,75 for the calculated cross-sectional averages.

$$\ln(WD) = 6.36 - 0.027 * GRW_n + 0.069 * \ln(n) - 0.046 * \ln(h)$$

WD = wood density (dry)
n = ring no
GRW_n = width of growth ring n
h = heigth above ground

$R^2_{ring} = 0.51$; $RMSE_{ring} = 53.8$ kg/m³
($R^2_{disc} = 0.75$; $RMSE_{disc} = 30,0$ kg/m³)
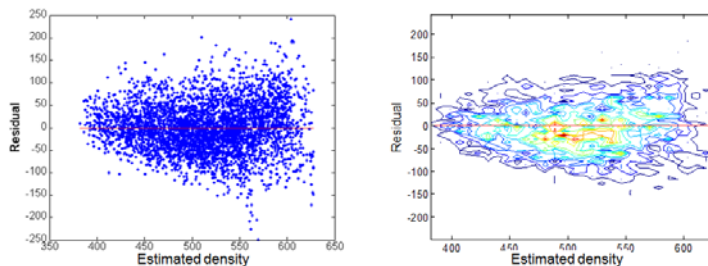
Figure 5. *A model for the average wood density of arbitrary growth rings at arbitrary heights for Scots pine (Pinus sylvestris) (Olsson et al 200x).*

The figure also shows the residuals at different estimated densities with points and with a contour plot. It indicates that the wood density is estimated with reasonably small errors for the major part of the annual rings. The wood densities shown are measured on samples air-dried in a laboratory (conditioned weight/conditioned volume), which gives higher values than the basic density (oven-dried weight/fresh volume.)

Figure 6 illustrates how such a model is combined with a growth structure generated for the stem (left) in order to estimate the variation in the whole stem. This structure is used as input data to the simulation. In the middle, graphs are shown for the estimated density variations at two heights in the tree (solid lines), together with measured data for the growth rings at these heights. As expected, there are large deviations at ring level, due to effect from weather, etc. not included in the simulation. To the right, the variation in the whole stem has been interpolated from radial data at many heights.

Growth ring structure + **Property variations at different heights** = **Map of property variations in the stem**
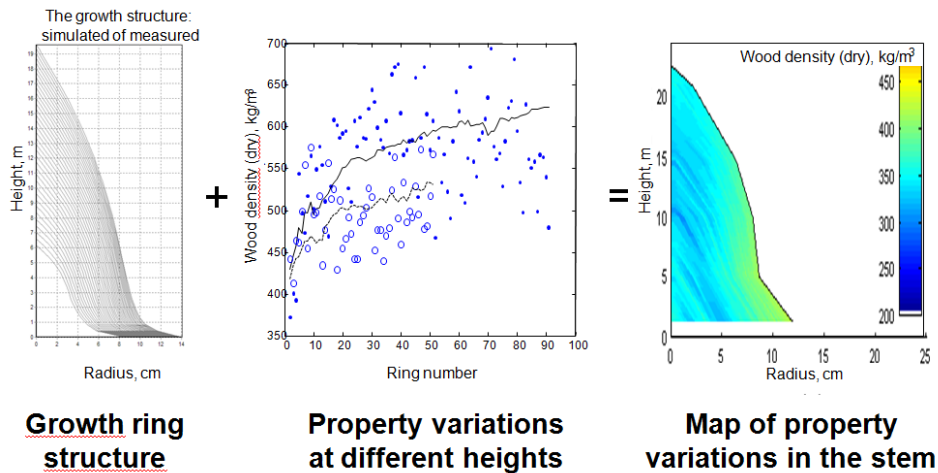
Figure 6. *Illustration of how the model of figure 5 is combined with information about the growth structure to estimate the wood density variation in the whole stem.*

4.3 Different properties, detail and size of database depending on application

In many cases, averages for properties of logs are quite sufficient and then it is most practical to use models for cross-sectional averages. However, for more detailed analyses, such as of fibre effects on paper properties, averages are not enough. Also the statistical distributions behind the average may make a difference. Further, for some product properties, relationships between fibre dimensions may be more essential than the dimensions themselves. For example, the fibre collapsibility and fibre stiffness/flexibility, related to the ratio between the fibre width and the wall thickness, are important for many paper properties. Other such "indicators" closely related to some pulp and paper properties and possible to calculate from the fibre dimensions are fibre coarseness, number of fibres per gram and crowding number (related to sheet formation).

To estimate the content of "hard-to-collapse" fibres in wood of different origins or in the chips to the process, multi-dimensional statistical distributions for fibre ensembles are needed. To estimate these distributions, models for fibre dimensions of earlywood and latewood of individual growth rings are used, see *figure 7*. Radial variations from pith to bark are shown with averages of each growth ring for earlywood (red), transitionwood (blue) and latewood (green).These are the models with the highest detail used in connection with the Resource Databases.
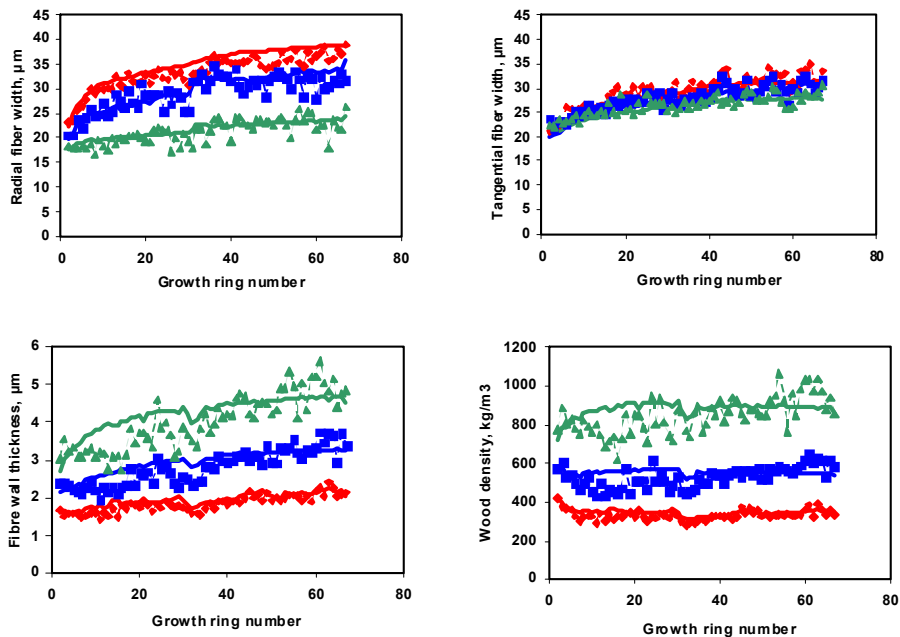
Figure 7. Illustration of detailed models for within stem variations in fibre length, width and wall thickness, as well as wood density. The data represent earlywood (red), transitionwood (blue) and latewood (green).

With this type of models, ensembles of fibres representing wood of different parts of trees may be generated. Each fibre of the ensemble has an estimated length, width and wall thickness. Three-dimensional statistical distributions may be calculated for parts of trees, such as logs, what will become sawn goods, sawmill chips, etc. By aggregating data, such distributions may also be calculated for flows of raw wood raw materials, such as pulpwood (including both the small diameter logs and some downgraded sawlogs) from specified types of stands. The same can be done for chips from sawmills producing different types of products (from spruce or pine, from small or large diameter logs, etc.). In *figure 8*, such a distribution is shown for sawmill chips from pine. Different selection and aggregation criteria may be compared. The "indicators" of pulp and paper properties mentioned above are calculated from such tree-dimensional distributions.

Three-dimensional data on fibres
from sawmill chips, pine
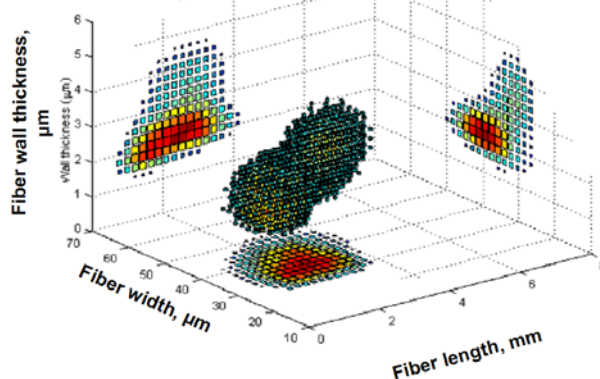
Figure 8. *A fibre ensemble of sawmill chips from pine and its three-dimensional statistical distribution for fibre length, width and wall-thickness.*

Simulations along the value chain

In EFORWOOD, the total chain perspective is often stressed. Further models and simulation tools have been developed to take the fibres some steps further through the simulation of fibre networks similar to paper, starting with fibre ensembles as the one in figure 8. Effects of these differences in fibre properties are visualised in *figure 9*.

Fibres from sawmill chips   Fibres from pulpwood

Figure 9. *Visualization of simulated paper-like fibre networks with fibres from sawmill chips, left, and from pulpwood, right. The upper images show the surfaces and the thin lower images cross-sections of the networks. Both networks have the same grammage, g/m^2, and the same sheet density, kg/m^3.*

Statistical distributions for the basic fibre dimensions have been estimated for fibres of pulpwood and sawmill chips. The formation of paper-like fibre networks from these fibres have been simulated, networks with the same grammage, g/m^3, and sheet density, kg/m^3. For each fibre, the location, bonds and state of collapse are known all along its extension and different structural properties of the network may be calculated. In the figure, the networks are visualised seen from the top, upper image, and in a cross-section, the thin lower image. The fibre network from pulpwood to the right is more

uniform. The smaller fibres from pulpwood produce a sheet with a smoother surface which is also better for printing. The larger fibres of sawmill chips would, however, normally produce a stronger sheet.

In the work on "Forest Resource Databases" and their applications, properties relevant for pulp and paper have so far been emphasized, but properties of knots have also been simulated, using models from the literature.

National Resource Database for all Sweden

As said above, Resource Databases of various sizes may be suitable for different applications. A National Resource Database for all Sweden was developed. This is the largest resource simulated so far. The distribution of the sample plots is shown in *figure 10*. The database includes volume and property information for about 23000 inventory plots, 380000 trees and 1500000 logs. In this case, properties of importance for pulp and paper have been emphasised, but the database may be complemented with further properties of wood, knots, etc. Such databases are now used to investigate what properties and volumes of wood can be obtained for different uses from the forest available in a region, as well as what benefits can be reached with a more selective use of the available wood.

Source: Riksskogstaxeringen   Photo: Mats Gerentz, SLU
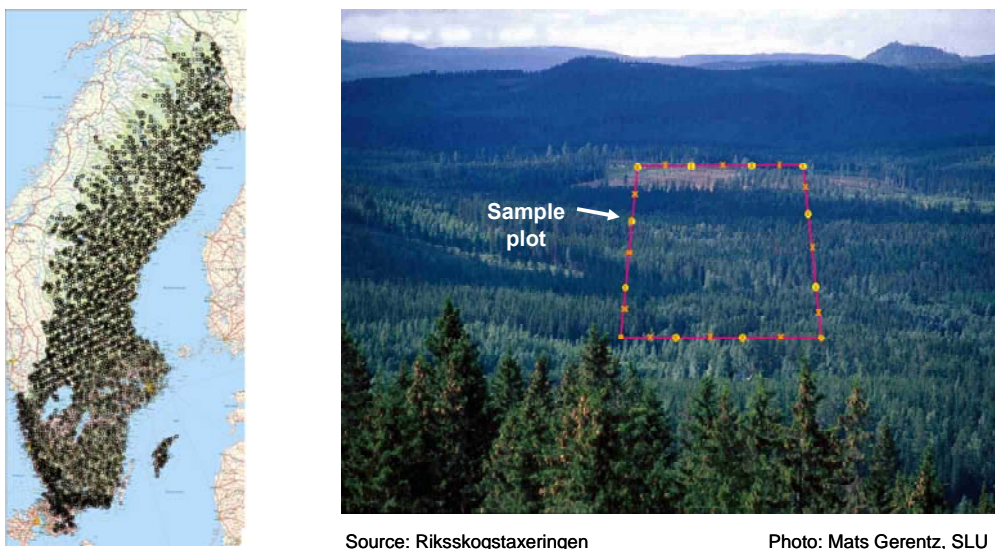
Figure 10. *Locations of inventory plots included in the Swedish National Resource Database.*

Similar databases are also being built for parts of other countries. Often existing models can be used, but if growth conditions not previously dealt with may be expected, complementary sampling and measurements are performed to test and improve the models

Applications

With a Regional Resource Database, you have "the forest in your computer", as well as a variety of potential materials from the forest. There are many potential applications of this. Two examples are shown to promote ideas for applications within the EFORWOOD project.

Figure 11 figure shows the estimated wood density (air-dried) of the sawn part of sawlogs from a selected county in Sweden, in relation to the diameter and mean ring width of each log. As expected, the density increases with diameter for logs with the same mean ring width and decrease with ring width for logs with the same diameter. The distribution of the points also indicates the availability in the county of logs with different characteristics in this respect. Please, note that these distributions are based on the actual distributions for stand age, growth rates, etc. in the specific region, not on general knowledge on the wood species and its properties.
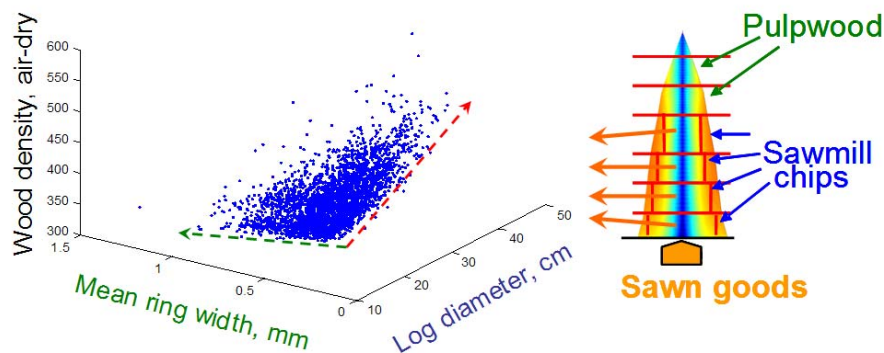
Figure 11. *Wood density estimated for the inner parts of sawlogs (the sawn goods) plotted against log diameter and mean ring width. Data extracted for pine in a specific county from the Swedish Resource database.*

Another example is shown in *figure 12*. A Swedish mill producing pulp and paper from spruce fibres wants to know the differences between different raw materials available in its supply area. Data for the types of material types available in the specific region are extracted from the National Resource Database. Four wood classes of interest for the mill are defined: Pulpwood from final cutting and thinning and chips from sawing of logs from final cutting and thinning. Averages of each wood class are calculated for a number of important wood and fibre properties, also for the "indicators" (coarseness, etc.) mentioned above, closely related to pulp and paper properties. Fibre length and wood density are selected as the properties to be looked at in the initial phase. In the figure, the averages for these properties are shown for each wood class. The figure illustrates that pulpwood on average provides wood with shorter fibres than sawmill chips, while wood from thinning on average provides wood with lower density (thinner fibre walls in relation to the fibre widths) as compared to wood from final cutting. Similar comparisons can easily be done also for other properties of special interest for the mill and its products. From these averages, properties of various mixes of these wood raw materials may be calculated. (It should, however, be noticed that the volume of sawmill chips from thinning is so small that these chips would normally be mixed into the chips from final cutting sawlogs.)
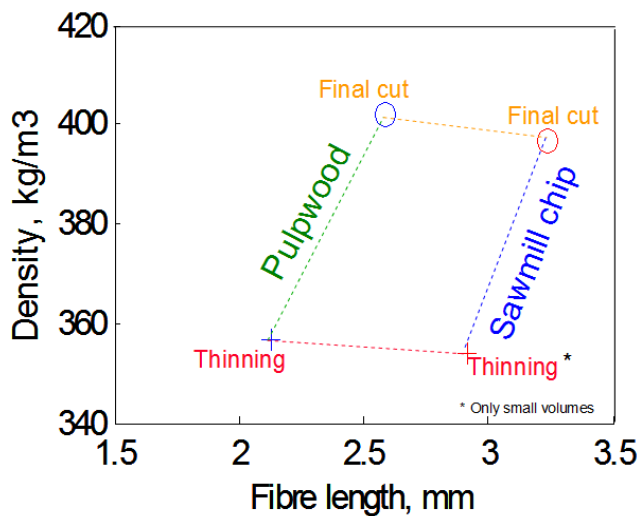
Figure 12. *Averages for wood density and fibre length for the wood available in the supply area of a mill, divided into four major wood classes of spruce which potentially could be delivered to the mill.*

Differences between regions, between stands at different altitudes, ages, etc. may also be estimated and analysed, nota bene based on the actual distributions among species, altitudes, ages, etc. of each region, rather than in general terms. If a pulp mill have to change the supply area for some reason such calculations may be very useful to estimate the expected change in properties of the fibres to be used.

The scope of the presentation above of results from work at STFI-Packforsk with the general concept of "Forest Resource Databases" is to transfer some experiences and ideas about how such databases may be used. The rest of the report will now be dedicated to the EFORWOOD version of Regional Resource Databases.

5. Forest Resource Databases – The EFORWOOD design

The scope of the limited scale version of Forest Resource Databases designed for EFORWOOD is to offer a general method for mapping of properties and volumes of forest resources,

- which is reasonably easy to use during the project and in the future use of the results

- which is possible to apply on different wood species in various countries, also when complete inventory data, etc. are missing

- which includes a wide spectrum of wood and fibre properties and allows comparisons of different cross-cutting strategies

Therefore, the modified version makes use of less detailed models, estimation of properties for tree elements of different sizes and simulation based on small or medium size sets of inventory data. The number of stands needed will depend on the heterogeneity of the resource.

Large-size and small-size Resource Databases

Based on these data, EFORWOOD type databases of two sizes and levels of detail are illustrated:

Example 1: Small-size Resource Database, based on simulation of:

+ a limited set of stands (plots) selected to represent the resource of the region.

+ average properties of fix length logs and their inner part (sawn goods) and outer part (sawmill chips)

One example of results will be presented in this chapter.

Example 2: Large-size Resource Database, based on simulation of:

+ all callipered trees from all inventoried stands (plots)

+ average properties for longitudinal growth units (between whorls) and their inner and outer parts

Many examples of results will be presented in chapter 6 and 7.

5.1 The forest resource and inventory data

The examples are taken from Västerbotten in the north of Sweden. The data cover the administrative unit "Västerbottens län", which includes the county Västerbotten and also the southern half of the county Lapland. The region is located between the latitudes 63.6 and 66.4 and spans across Sweden from the coast of the Baltic Sea to the mountains at the border towards Norway, reaching and passing the altitude of the tree limit. The mix of wood species is Norway spruce 38 %, Scots pine 45 %, birch 15 %, Pinus contorta 0,6% and other species 2%, based on volume. More information about the forests of the region is found in (Valinger et al 2008).

The simulations are based on an excerpt of data from the Swedish National Forest Inventory Database including plots inventoried during 5 consecutive years, distributed according to *figure 13.*. Only Norway spruce and Scots pine trees have been simulated. Approximate numbers are:

- Sample plots   ~2000
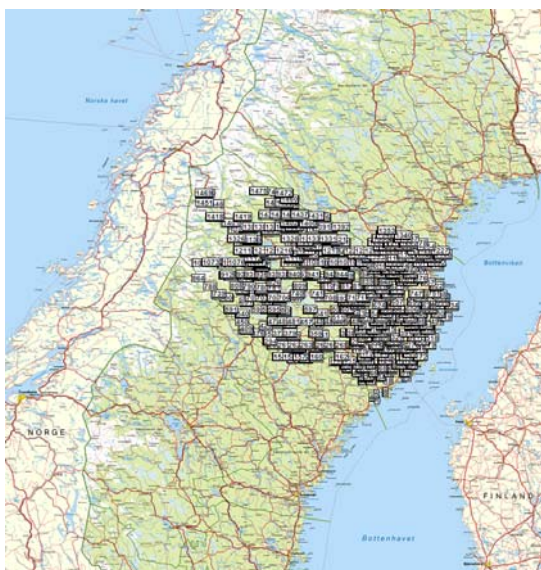- Spruce trees ~11500
- Pine trees   ~12800

Figure 13. *Distribution of plots with inventory data in the Västerbotten region.*

5.2 Models

The set of integrated models used in the simulations of the Västerbotten resource originate largely from projects run in cooperation between STFI-Packforsk and Skogforsk or from further work based on data from these common projects (Lundqvist et al 2003a). It includes models for taper (Spångberg et al 2001), number of annual rings at different diameters (Wilhelmsson et al 2001) and ring width distributions within stem cross-sections (Olsson et al 2004) for the estimation of the shape and growth structure of the stem. It also includes models for wood and fibre properties. A set of models used for simulation of cross-sectional averages at arbitrary heights of Scots pine is shown below: Eq. 1 for wood density (Wilhelmsson et al 2002b) and Eq. 2-4 for fibre length, fibre width and fibre wall thickness (Lundqvist et al 2005). The models are based on data from Swedish conditions.

$$WD_h = 364.4 - 17.58 * AGW_h - 0.607 * (\ln N_{bh})^3 + 0.417 * (\ln N_{bh})^3 * e^{(\frac{d_h}{d_{bh}})^7} \tag{1}$$

$$FL_h = -0.56 + 0.69 * \ln(N_h) + 0.33 * \ln(AGW_h) - 0.65 * e^{(\frac{-h_{rel}}{0.13})} + 0.00043 * tsum \tag{2}$$

$$FW_h = 23.99 + 3.18 * \ln(\frac{d_h}{2}) - 5.25 * e^{(\frac{-AGW_h}{1.87})} \tag{3}$$

$$FWT_h = 1.16 + 0.24 * \ln(\frac{d_h}{2}) - 0.23 * \ln(h_{rel}) + 0.00030 * tsum \tag{4}$$

Where: WD_h = average wood density of cross-section at height h
FL_h = average fibre length of cross-section at height h
FW_h = average fibre width of cross-section at height h
FWT_h = average fibre wall thickness of cross-section at height h
d_h = diameter under bark at height h; d_{bh} = diameter at breast height 1.3 m
N_h = number of growth rings at height h; N_{bh} = number at breast height 1.3 m
AGW_h = average growth ring width in cross-section at height h
h_{rel} = relative height in tree ($0 < h_{rel} < 1$)

Properties included in the database

In *table 1*, examples are given of properties which are included in the Västerbotten Resource Database: inventory data from measurements in the forest and estimated data from simulations using models of different origins. The models used in these simulations and those used in the applications of Skogforsk, FVA and Forest Research in Västerbotten, Baden-Württemberg and Scotland will be compiled in the EFORWOOD report referred to above, also including further details about the applications (Lundqvist et al 2009).

5.3 Small-size Resource Database with log data from selected plots

Selection of stands (plots) to represent the regional resource

A limited number of variables influencing the most important properties are selected, such as the age of the tree. Based on the local variation of these variables, a limited number of classes are defined for each variable, for instance age classes representing the variations in the resource.

Table 1. *Examples of properties which are included in the Västerbotten Resource Database, referring to the detailed estimations performed for the large-scale database*

- Per growth internode & whorl

▪ Stand	▪ Tree	▪ Wood	▪ Fibres
▪ Stand age	▪ Species	▪ Density	▪ Length
▪ Site index	▪ DBH	▪ Juvenile wood	▪ Width
▪ Volume wood/ha	▪ Height	▪ Latewood cont.	▪ Wall thickness
▪ Altitude	▪ Age	▪ Heartwood	▪ Coarseness
▪ Latitude, Long.	▪ Taper (diam)	▪ …	▪ …
▪ Cutting class	▪ Bark thickn.		
▪ …	▪ …	▪ Whorls/Knots	
		▪ Internode length	
		▪ Length of	
		+ sound knot	
		+ dead knot	
		▪ Knots per whorl	
		▪ Knot angle	
		▪ Max and mean diam	
		▪ …	

For Västerbotten, stand/tree age, altitude and site index were identified as the most influential variables. Regional statistics showed that, for Scots pine in this region, the resource and also the wood from thinning and final cutting could be reasonably well represented with 4 age classes, centred round the ages 50, 75, 100 and 125 years, see *figure 14*. Analogously, 2 altitude classes (close to 200 m and 350 m) and two site index classes (close to P16 and P18 (the estimated height for large trees in a 100 years old pine stand)) were defined. In this way, 4 x 2 x 2 = 16 types of stands were defined to represent the pine resource of the region.

Age classes representing the resource
(25) 50 75 100 125 (150) years
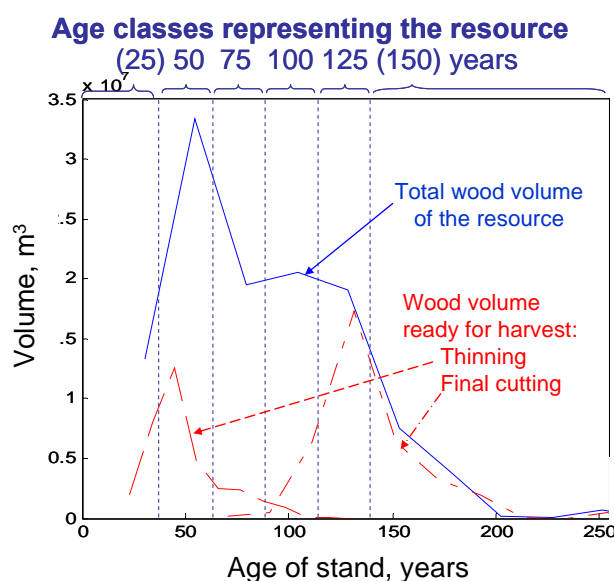
Figure 14. *Age distribution for the total volume of wood in the region of Västerbotten in the north of Sweden, as well as for wood ready to harvest in thinning and final cutting. Age classes centred around 50, 75, 100 and 125 years of age were defined to represent the resource and the wood obtained from different harvesting operations.*

When applying this approach to other regions, similar analyses should be done to identify the major sources of property variations. It may happen that other stand characteristics should be chosen to select suitable stands and trees representing the resource.

In this example, only one stand of each class was selected, with typically 15-30 trees per stand. The number of selected stands is, however, easily increased. Data on these stands and trees were compiled for the simulation of a small scale Regional Resource Database; a total of 363 pine trees. *Figure 15* illustrates the sizes of these trees of various ages and growth conditions: breast height diameter (callipered) and tree height (estimated by SLU).
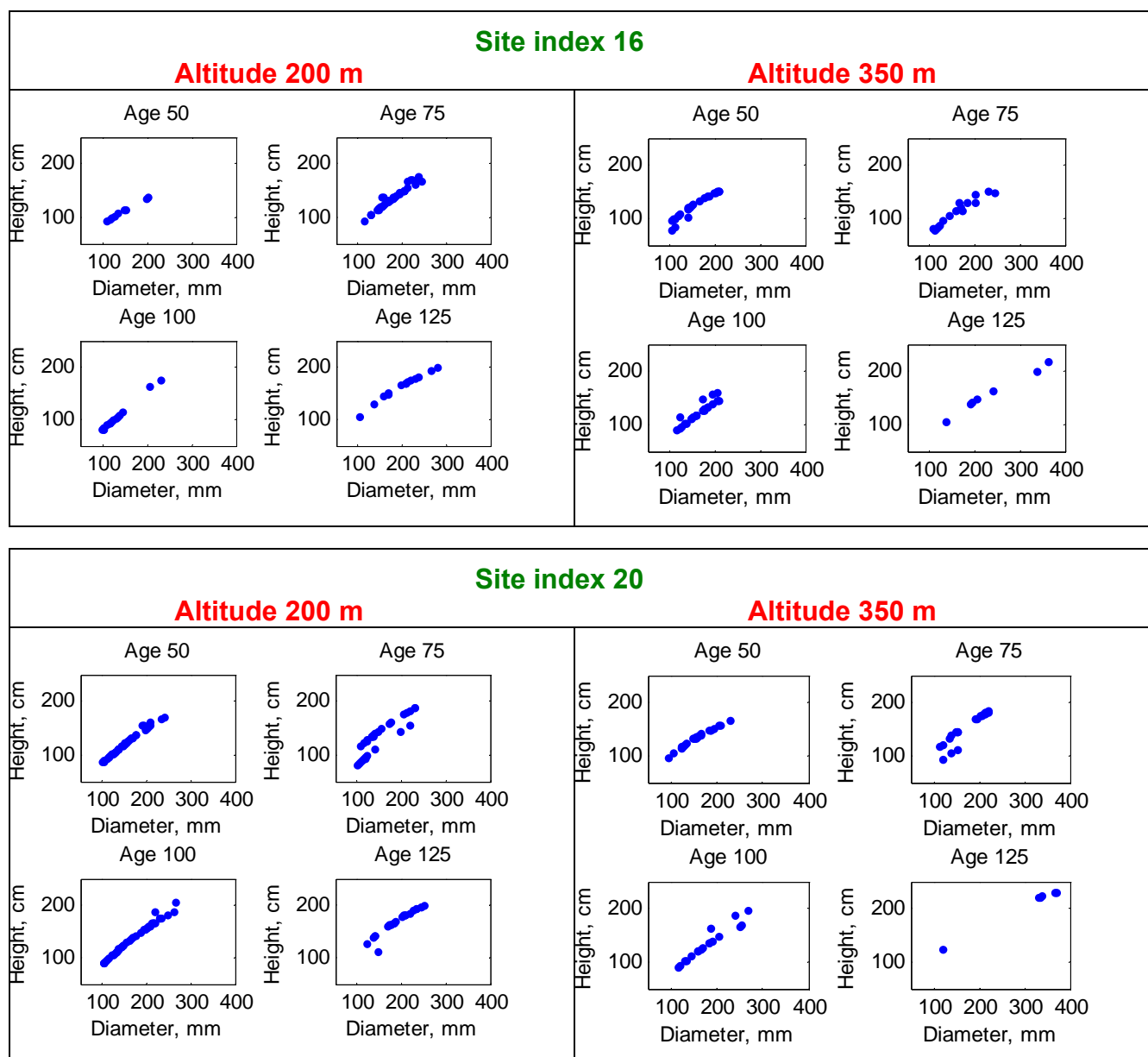
Figure 15. *Breast height diameter (callipered) and tree height (estimated by SLU) of the trees from the 16 stands selected to represent the pine resource of Västerbotten in the north of Sweden.*

Tree elements

In this small-size example, the trees elements are defined as 4 m logs. For the logs with a top diameter of 14 cm, 2 cm of the outer wood has been defined as sawmill chips.

Example from simulations: Property differences between logs and sawn goods/sawmill chips

The properties of the trees are simulated and the stems are divided into parts, as described above. Averages are calculated for each part. This is illustrated in *figure 16* with simulated data for fibre length from one tree. The tree is close to 20 m high and produces 3 sawlogs and 2 pulpwood logs. The average fibre length of the pulpwood log at the top of the tree is estimated to about 1,8 mm only. The fibre length of the chips from the sawlogs is estimated to about 3,1 mm. The data may also be presented from a mill perspective as a function of log diameter, shown to the right, or in more detailed ways similar to figure 11 or 12, but then data on more stands would be preferred.
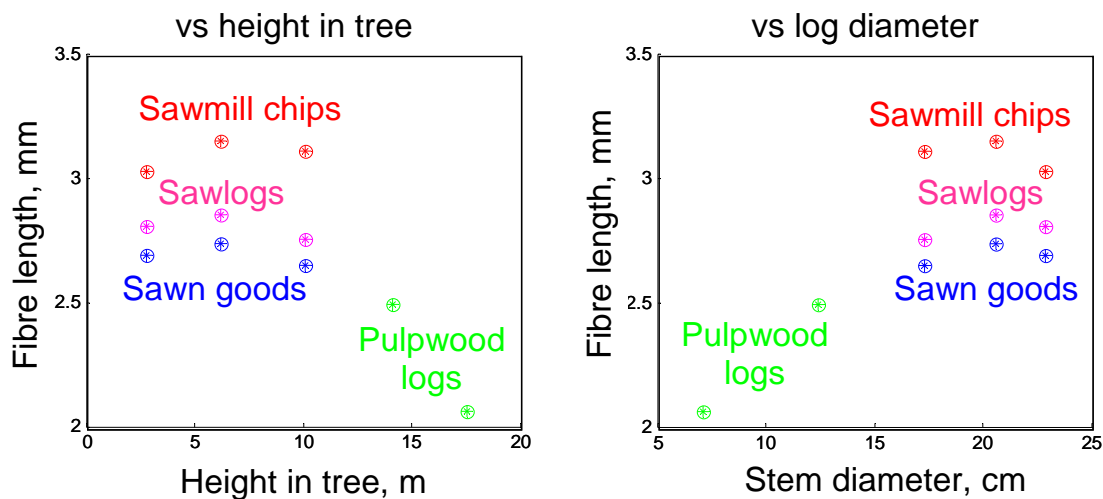
Figure 16. *Average fibre lengths of pulpwood logs and what will become sawn goods and sawmill as a function of the position along the stem, left, and the diameter of the log, right.*

For this tree, averages are calculated and available in the Resource Database for 11 tree parts, representing various uses:

- 2 pulpwood logs

- 3 sawlogs, which are further divided into 3 sets of sawn goods and 3 batches of sawmill chips.

5.4 Large-size Resource Database with internode data from all plots

The stands and trees

For the simulation of the large-scale Västerbotten Resource Database, no selection of representative stands is made. Some insignificant or untypical plots and trees were removed. Then, all remaining trees available in the set of inventory data were simulated: about 12000 spruce trees and 13000 pine trees from 200 plots.

The tree elements

The trees consist of roots, stems (wood and bark), branches and leaves/needles. In *figure 17*, the woody part of the stem is divided into tops (often left in the forest), pulpwood logs and sawlogs, indicating their main current use. These major parts are also divided into sub-parts, which are often used for different products, for instance small and large diameter sawlogs.
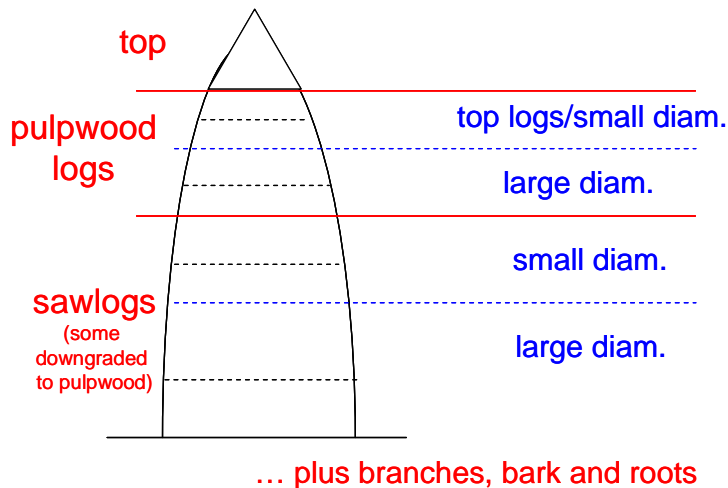
Figure 17. *The wooden part of the stem is divided into parts according to their current main uses in the industry: Tops (often left in the forest), pulpwood logs and sawlogs of different dimensions. Allocation is, however, flexible and for analysis of current and future alternative uses, data on properties and volumes should be available also for smaller parts of the stem.*

However, the allocation of the various parts of the trees shows a high degree of flexibility, e.g. downgraded sawlogs are used as pulpwood, and changing price relationships, new technology and differences in local operation costs means that products and mills will compete for some parts of the stems. Logs indicated as pulpwood in the figure, especially the small diameter top logs, may be used for bio-energy, but sometimes even sawlogs. For full flexibility also in the analysis of different current and future allocation alternatives, data on properties and volumes have to be available also for smaller parts of the stem.

To allow the comparison of different allocation strategies from a full-scale sustainability analysis with ToSIA, the trees in this large-size EFORWOOD version of the Resource Database been divided in very small elements. These elements may then be "reassembled" into logs, etc., of more or less arbitrary sizes, representing various cross-cutting and allocation alternatives. Small tree elements for many trees results in large databases, long computation times on simulation and more time demanding evaluations. Thus, one should not include more detail than necessary.

In this case, properties are only estimated for the woody part of the stem with diameters of interest for the wood and fibre based industries. For the other parts of the tree, volumes and mass may be estimated for calculation of carbon content, heating value, etc. For this woody part of the stem, we

have gone to the extreme of estimating averages for each internode, representing the annual longitudinal growth of the stem.

The tree elements are longitudinally defined as the part of the woody stem between two whorls and the whorl above it, see *figure 18*. For stem diameters large enough, the internode is also divided into an outer element, which may become sawmill chips, and an inner element which would become the sawn product. If the cross-section is considered to be used as an entity, such as for a pulpwood log or for a pole, this full-cross-section tree element is used in the further evaluation. If sawing is considered, the smaller elements are used.

To reduce the size of the database only the parts where detailed information is relevant for allocation have been divided into these small elements (see *figure 19*). It has been assumed that diameters below 5 cm (under bark) are not of interest for pulping and averages for full cross-sections are estimated for internodes/whorls down to this diameter. It is further assumed that diameters below 14 cm (u.b.) are not of interest for sawing and averages for inner and outer tree elements are estimated for internodes down to this diameter. An average of 2 cm wood has been assumed to be removed as sawmill chips on sawing. In figure 19, the current "standard uses" of different parts of the stem are indicated. As discussed above, there are alternative uses and these may be investigated through combination of tree elements as illustrated in *figure* 18.
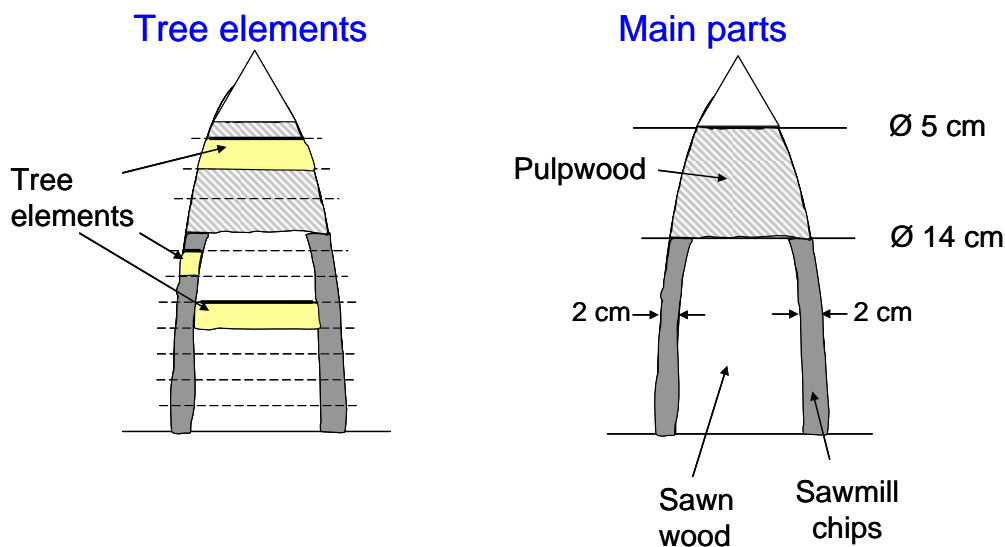
Figure 18. The tree elements are in this example longitudinally defined as an annual growth internode between two whorls and the whorl above it. For large diameter internodes, also outer elements (sawmill chips) and inner elements (sawn goods) are formed.

Figure 19. It is assumed that the stem part with a diameter smaller than 5 cm is not of interest for pulping and diameters smaller than 14 cm not interesting for sawing. An average of 2 cm from the outside of the wooden stem is assumed to become sawmill chips on sawing.

5.5 Comments on size and detail of simulations and database

This detailed description of the about 25000 simulated trees from Västerbotten results in a total of about 1.800.000 tree elements. This may be on the large side for optimal efficiency in evaluating alternatives. The ambition with showing the two examples, the small-scale and the large-scale Resource Database, is however to illustrate different possibilities when using various size of inventory data and level of detail.

When starting to build a Resource Database for a certain application, it is practical to start with a small-scale approach to get going, test the integrated model system and input data, check some basic alternatives and then plan the continued work. The test step can typically include the description of a couple of stands and some 10s of trees only, which is then expanded to 50-100 stands and a larger number of tree elements (e.g. logs of suitable length). This is in some cases enough to test different principles, for sensitivity analyses, etc. But depending on application, it may be further expanded for more detailed optimization issues, improved representation or to cover larger geographical areas.

6. Visualisation of property variations – One tree

6.1 The simulated tree

One tree has been selected to illustrate the type of information available in the database: This was a pine tree with the following characteristics as defined from the inventory data:

Data on the plot:

+ Latitude   64,8 º
+ Longitude   20,3 º
+ Altitude   180 m
+ Temperature sum   930 (estimated according to Morén et al 1994)
+ Site index   T20 (estimated height at age 100 years of the large pine trees)
+ Age   74 years (average estimated from 6 sampled trees)

Data on the tree:

+ Species: Scots pine
+ Diameter$_{BH}$ 214 mm on bark, 193 mm under bark
+ Tree height   17,9 m   (estimated by SLU)
+ Age$_{BH}$ 66 years   (estimated by SLU)

6.2 Size and shape of stem

Figure 20 shows the heights and radii of the "whole log" tree elements estimated with the procedures and models described above, that is the size and shape of the stem. Each green square indicates the height above ground of a whorl and the stem diameter at the whorl. (Local deformations at the whorl are not accounted for.) The longest internodes, the largest annual longitudinal growth, are found between 5 and 15 m above the ground. The assumed minimum pulpwood diameter and minimum sawlog diameter are indicated.
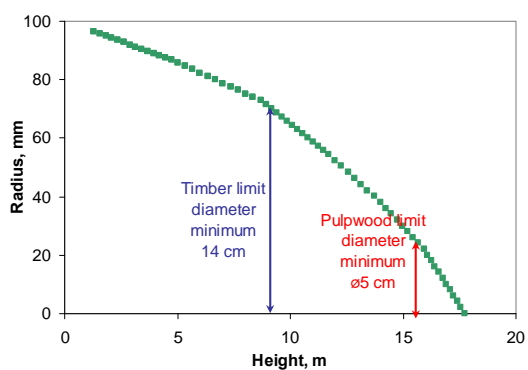
Figure 20. *The stem diameter versus the height above ground at each whorl for the selected pine tree.*
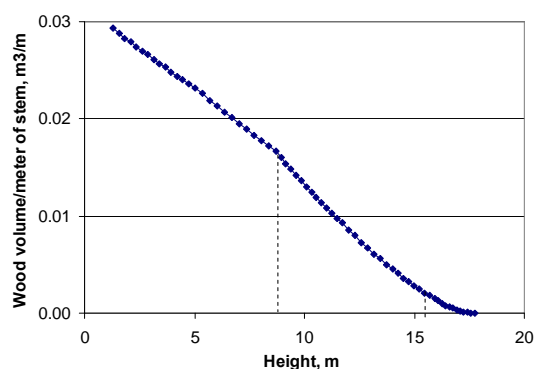
Figure 21. *The wood volume per meter of stem versus the height above ground at each whorl for the selected pine tree.*

The volume/m along the stem is shown in *figure 21*. The volume of the whole stem is 0,27 m^3. The volume/m is of course very small close to the top. To get 1 m^3 of wood for bio-fuel, low diameter material from many trees has to be collected.

All simulated stems are at this stage straight. It would in principle also be possible to allocate crookedness at some locations along some of the stems based on statistical models, provided that the number of trees is large enough (e.g. the methodology of Macdonald et al., 2008). Such models have, however, not been applied at this stage.

6.3 Wood properties

Figure 22 shows the estimated zones with dead knots, with fresh knots and without knots in the stem as a function of height in the tree (Björklund, Moberg 1999). Models for number of knots per whorl, the diameter of the largest knot of the whorl and the knot angle are also implemented (same source).

In *figure 23* the extensions of heartwood and sapwood stem are indicated (Wilhelsson et al 2002a).

Figure 22. *The zones of dead and fresh knots and without knots versus the height above ground at each whorl. The diameters 5 and 14 cm are indicated.*
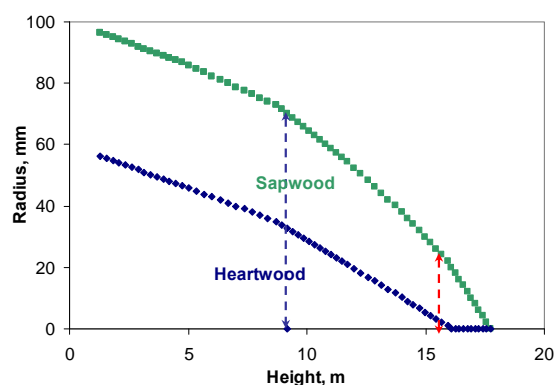
Figure 23. *The extensions of heartwood and sapwood versus the height above ground at each whorl for the selected pine tree. The diameters 5 and 14 cm are indicated*

The simulated stems are free from rot and other wood defects. If the number of trees is large enough, it would in principle be possible to allocate rot at some locations within some of the stems based on statistical models, with the highest probability at the ground and some distance upwards.

Figure 24 shows the estimated wood density for the internodes along the stem (density of air-dried wood). To the left, the density is shown versus the height above ground (forest perspective), to the right versus the diameter (industry perspective). Averages for the full stem/log cross-sections are shown for all internodes with a diameter > 5 cm, the limit below which we consider the material not useful for the fibre industries. The part of the stem with a diameter < 14 cm (red) is indicated as pulpwood, as it is assumed not to be of interest for sawing. Also thicker logs (orange) may of course be used for pulp production, if they are unsuitable for sawing or if the sawmills in the region are not equipped for the specific dimensions. For the part thicker than 14 cm, averages have been estimated also for the outer part which may become sawmill chips (blue) and the inner part which may become sawn products (brown).
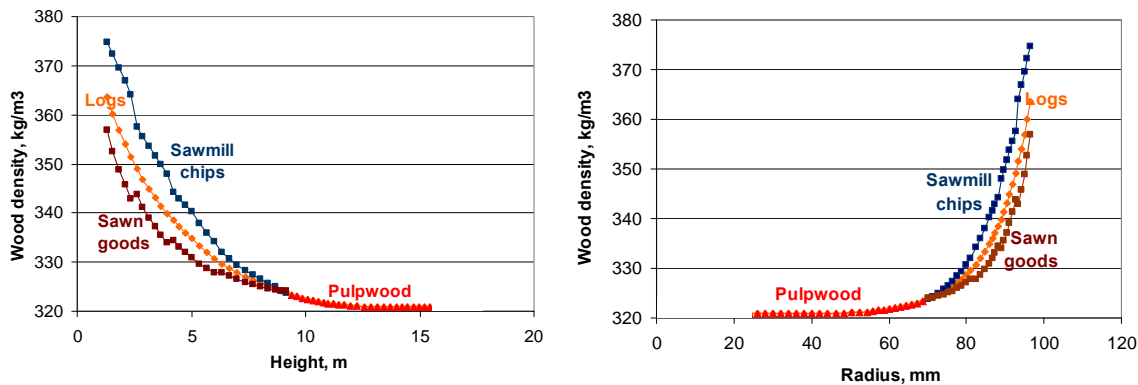
Figure 24. *The wood density (air-dried) versus height above ground (left) and radius (right) for all internodes. Graphs are shown for full cross-sections and for what may become sawn goods and sawmill chips.*

If the wood was to be used instead for bio-fuel, it is interesting to know how much energy may be obtained from use of different parts of the stem. This is close to proportional to the dry substance of the wood. The dry substance per meter along the stem, estimated as wood density (air-dried) x volume/m. is shown in *figure 25*. Graphs are shown for full cross-sections, relevant for thin parts of the stem and also for thicker logs with defects.
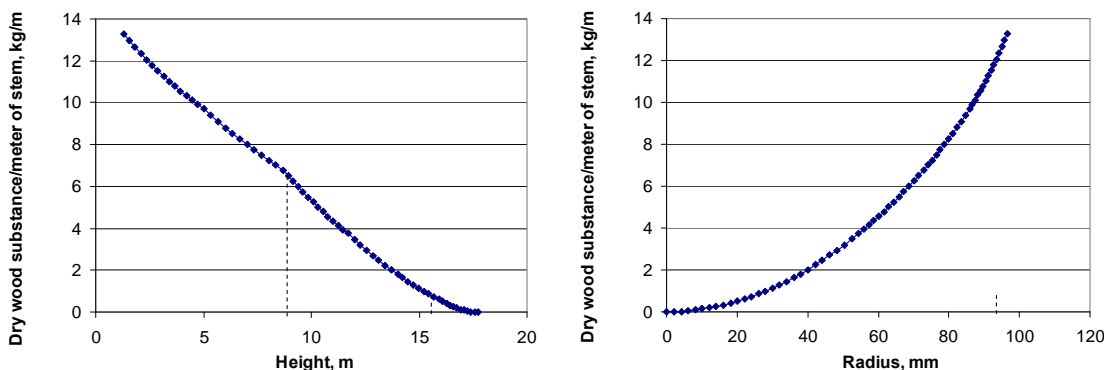
Figure 25. *The dry substance/m (air-dried) versus height above ground (left) and versus*
radius (right) for all internodes.

6.4 Fibre properties

Figure 26 and 27 shows the fibre length and fibre wall thickness in the same way as the wood density was shown in figure 24. The figures illustrate that the fibre dimensions are quite different when comparing common low-diameter pulpwood logs, down-graded sawn timber allocated to the pulpwood and sawmill chips from pine.

Graphs for fibre width are not shown here. They would have similar appearances as those above, but show a smaller relative variation.

Also fibre properties closely related to pulp and paper properties are included in the database. As an example of this, the number of fibres/gram is presented in *figure 28*, showing that pulpwood may have more than double the number of fibres per gram as compared to sawmill chips.
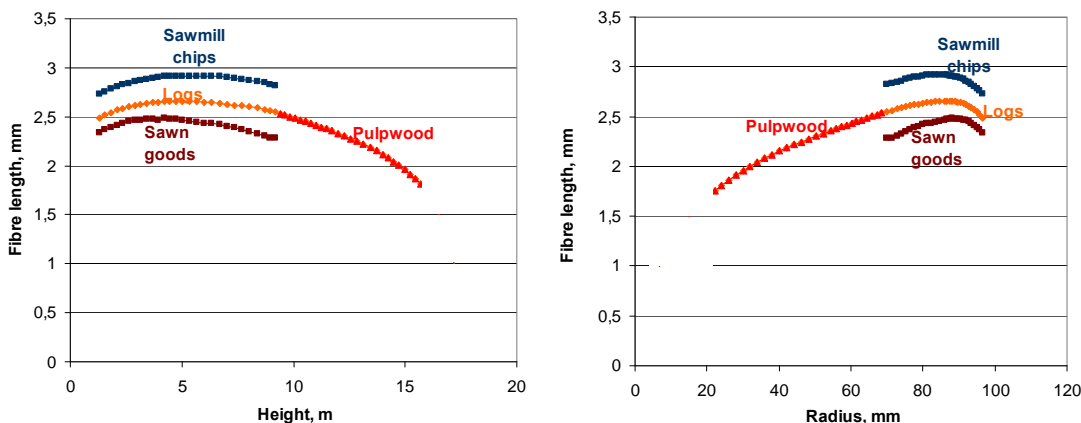
Figure 26. *Fibre length versus height above ground (left) and stem radius (right) for all*
internodes. Graphs are shown for full cross-sections and for what may become sawn goods
and sawmill chips.
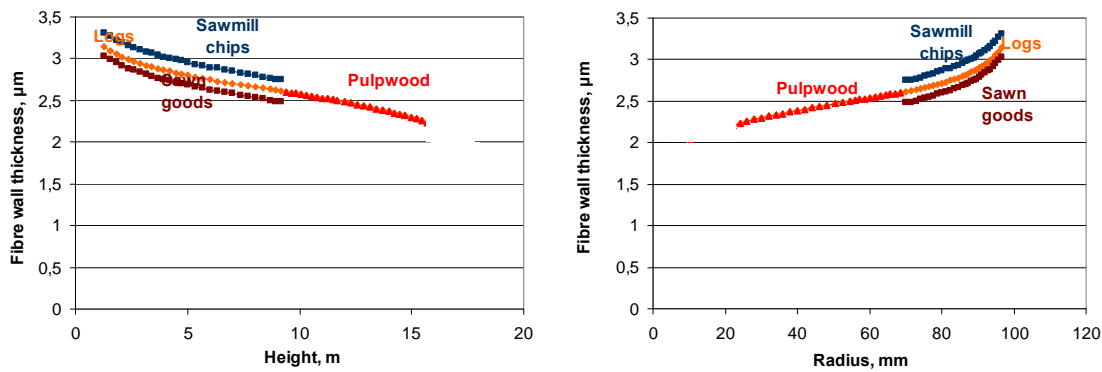
Figure 27. *Fibre wall thickness versus height above ground (left) and stem radius (right) for all internodes. Graphs are shown for full cross-sections and for what may become sawn goods and sawmill chips.*
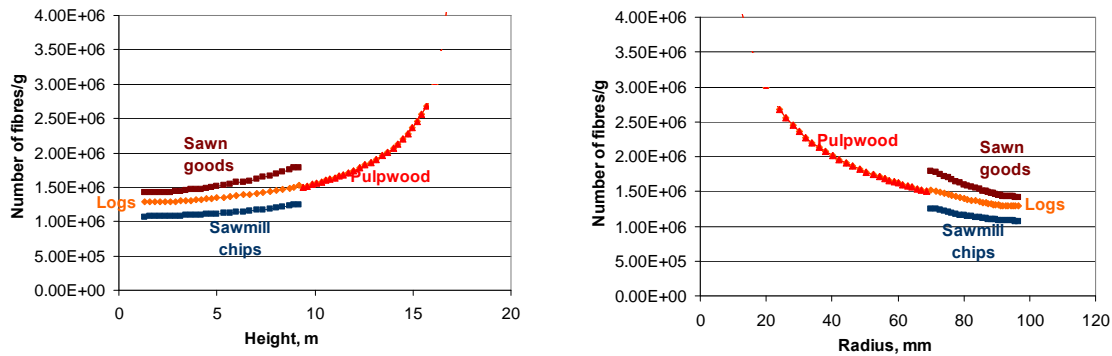
Figure 28. *Number of fibres/gram versus height above ground (left) and stem radius (right) for all internodes. Graphs are shown for full cross-sections and for what may become sawn goods and sawmill chips.*

7. Examples of use

A limited number of examples are shown to illustrate how data in the form of Forest Resource Databases resulting from mapping of resources may be used in different applications.

7.1 Cross-cutting to different lengths

The approach of describing the stems as a sequence of trees elements (internode+whorl) allows comparison of different cross-cutting alternatives. For some properties the comparison may be done as precisely as the uncertainty in the estimates allow; for some other properties the comparison will be approximate. One reason is the simplification that sawmill chips are produced from the outermost 2 cm of wood all along the sawlog part of the stem. In reality, the longer the logs are, the more material will become sawmill chips in the larger diameter end of the log.

In *figure 29* the results from bucking the stem using 3 different log lengths are illustrated. The stem of the selected pine tree is assumed to be cut into logs of lengths 2,5 m, 4 m and 6 m, starting from the stump level. If log length 6 m is needed, only one log with large enough diameter can be cut from the stem, while three 2,5 m logs may be obtained. In reality, different lengths are of course combined, but it is often possible to reach a better yield and to better benefit from special features along the stem if shorter logs are used. Property and volume data of the type shown in *figure 20-28*, including more properties and large numbers of trees may be extracted from the Resource Database and used to evaluate different cross-cutting strategies within a region with specific mills and products and for optimisation of allocation.
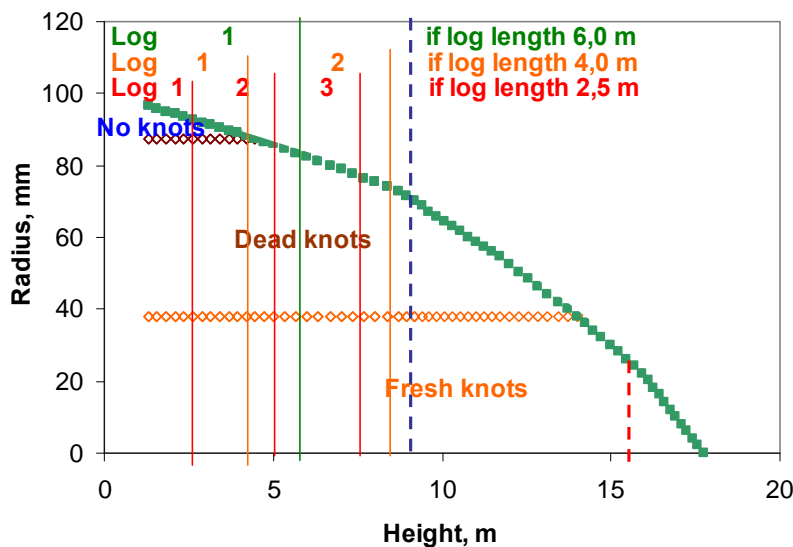
Figure 29: *Illustration of cross-cutting the stem of the selected pine tree into logs of different lengths.*

7.2 Properties and volumes of specific raw materials

There are many types of software commercially available for use of databases, offering a broad spectrum of functionalities. Data from different types of materials may be selected according to various criteria, for instance in this case logs of certain diameters from trees of certain species, ages, growth rates and locations. Averages and statistical distributions may be calculated for the sub-sets and compared. Materials with similar properties may be merged to mimic a larger volume flow of suitable raw material to a specific product at a regional mill. Three examples are given below.

Figure 30 shows the wood density and fibre length for pulpwood logs above the timber limit (timber height), for sawmill chips and for sawn products calculated for the pine resources in Västerbotten. The idea with the figure is not to provide data for technical use, but rather to illustrate how it is possible to work with this type of Resource Databases. Therefore, we have allowed some simplifications. All pine trees ready for final cutting were selected, according to the classification of the stands in cutting classes. The data on the tree elements were used to calculate statistical distributions for pulpwood, defined as the part of the stem with a diameter of 5-14 cm, and for sawn goods and sawmill chips,

from the part with a diameter larger than 14 cm. The distributions are weighted so that the area below each graph is proportional to the total volume of wood belonging to the class available in the specified types of stands. The distributions for wood density are shown to the left and those for fibre length to the right.
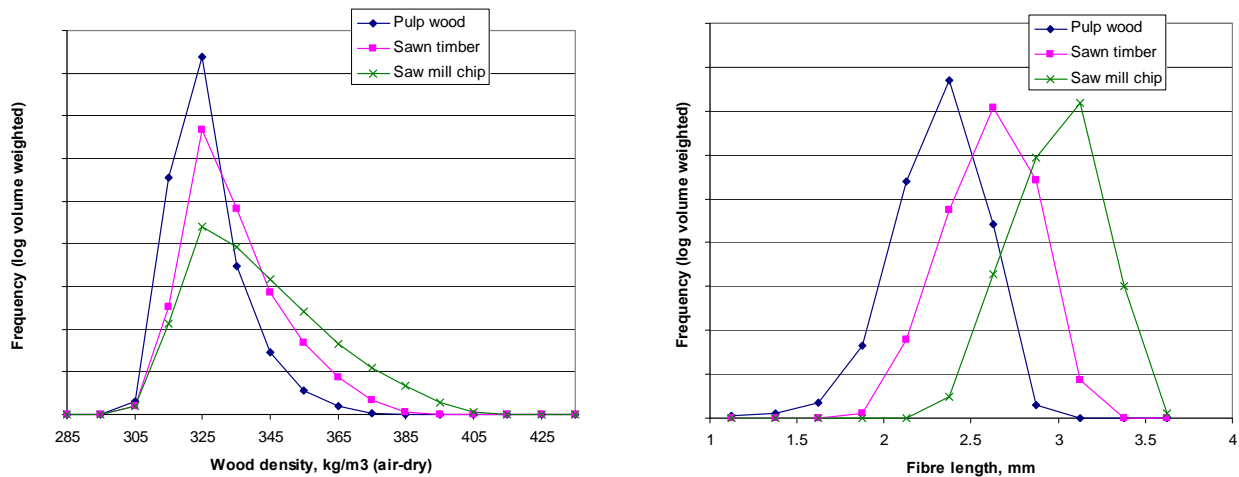
Figure 30. *Statistical distributions for wood density (left) and fibre length (right) for pulpwood, sawn goods and sawmill chips. Timber limit 14 cm. The areas below the graphs represent the relative volumes of the different wood classes, estimated from the simulated trees.*

The pulpwood may be divided into wood classes with different properties. It can be done by species (but in the figure only Scots pine is included), age of stand, growth rate, etc., if economically feasible. A sometimes useful way to do this is to distinguish between the pulpwood from thinning and from final cutting. All pulpwood from a thinning goes into the same class and all pulpwood from final cuttings into another class. This way segregation of logs in the forest or elsewhere is avoided.

Figure 31 illustrates the estimated difference in fibre length obtained in Västerbotten between pine pulpwood from first thinning and final cutting, with an average of about 0,35 mm. If the information about fibre length is complemented with data for other properties, it is possible to judge on the expected effects on pulp and paper if this segregation, or other allocation strategies are applied.
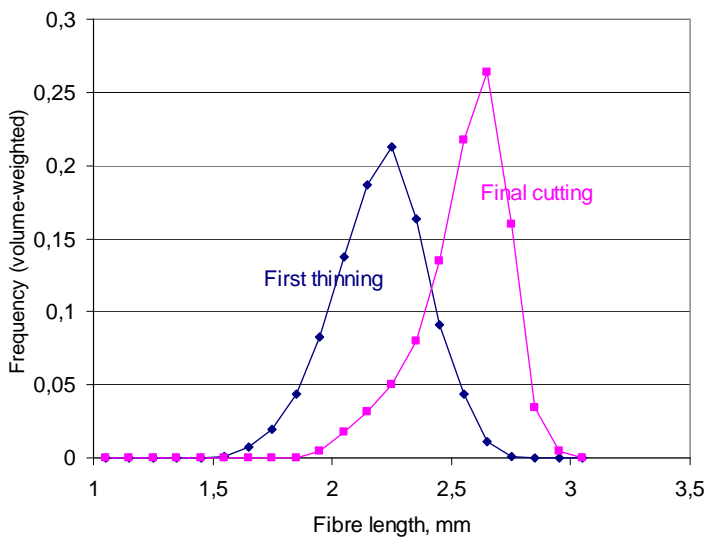
Figure 31. *Estimated difference in fibre length obtained in Västerbotten between pine pulpwood from first thinning and final cutting, in average about 0,35 mm*

The fibre and the solid wood industries are obviously closely linked to each other and the properties of wood and fibres in both industries are affected by how they divide the raw material between themselves into pulpwood and sawn timber. In *figure 32*, the statistical distributions are shown for the fibre length of the pulpwood from first thinning and final cutting of pine, assuming two different timber limits: 14 and 18 cm. Area factors for each stand (plot) have been used to calculate the contribution of the stands to the total volume. To match these calculated volumes, the fibre length distributions have been calculated from averages for each stand (plot). This is the reason why they are not as broad as those in *figure 31*.

Final cutting and first thinning- Pulpwood (above timber limit)
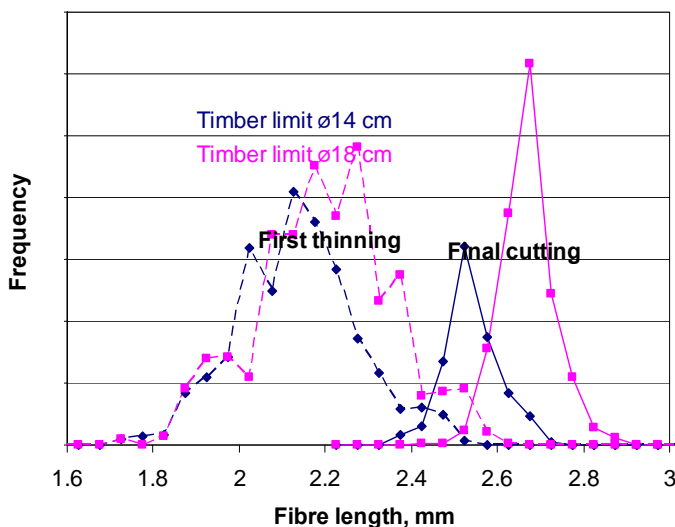
Figure 32. *Statistical distributions for the fibre length of the pulpwood from first thinning and final cutting, assuming two different timber limits: 14 and 18 cm, in the resource of Västerbotten. The areas below the graphs represent the wood volumes of the logs.*

The figure illustrates that if the sawmills are using less of the trees (less of the mid-diameter logs) then the pulp and paper mills will not only get a larger volume of pulpwood decrease, but the fibres of the pulpwood will also become longer. The figure also illustrates that the volume of pulpwood with short fibres from first thinning of this resource is larger than that of pulpwood with longer fibres from final cutting, but the difference is reduced if the timber limit is increased.

In *figure 33* the corresponding effects on the wood density of the sawn goods is illustrated. In this case, the area below each graph represents the volume obtained. The volume of sawlogs from first thinning is obviously very small, especially if larger diameter logs are requested.

Final cutting and first thinning- Sawlogs, inner part
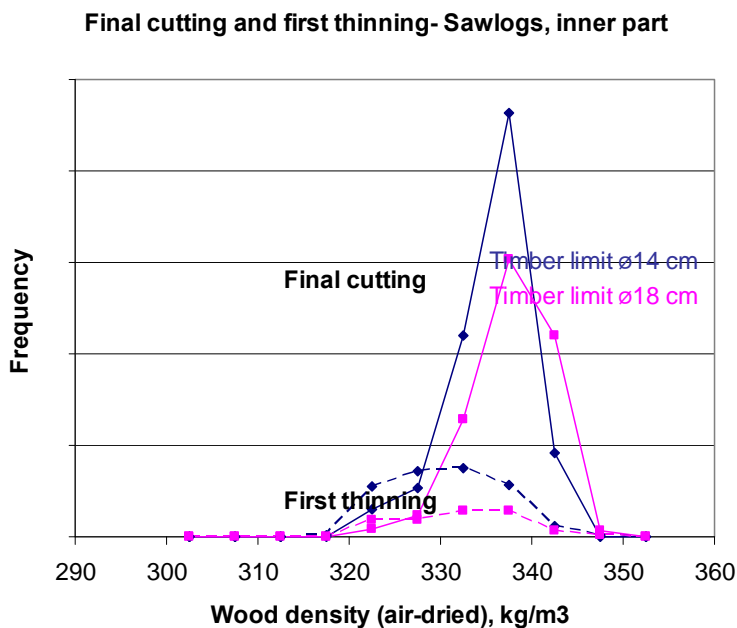
Figure 33. *Statistical distributions for the wood density of the sawn products (averages) from first thinning and final cutting, assuming two different timber limits: 14 and 18 cm, in the resource of Västerbotten. The areas below the graphs represent the wood volumes available.*

Figure 34 focuses on the sawn goods. Timber logs with diameters within three intervals: 200-300 mm, 300-400 mm and 400-500 mm, have been selected from the Resource Database and averages have been calculated for the wood density of the inner part of the logs; the part which will become sawn products. The figure illustrates that the log class with the smallest diameter, 200-300 mm, has the lowest average density, but it may also be seen that also this class includes some higher density wood, originating from slow-grown trees. It is of course possible to look in more depth into how to find these higher density logs and to include other property demands in the selection process. In Västerbotten, there is a shortage of large diameter logs. Therefore, the statistical distributions of the large diameter classes are a bit "noisy".

All these examples emphasizing various properties and products are based on the application of different selection criteria on the same Regional Resource Database for Västerbotten, followed by calculations of averages, statistical distributions, etc. Hopefully, the examples may inspire new ideas about how to apply the concept within EFORWOOD and in other projects.
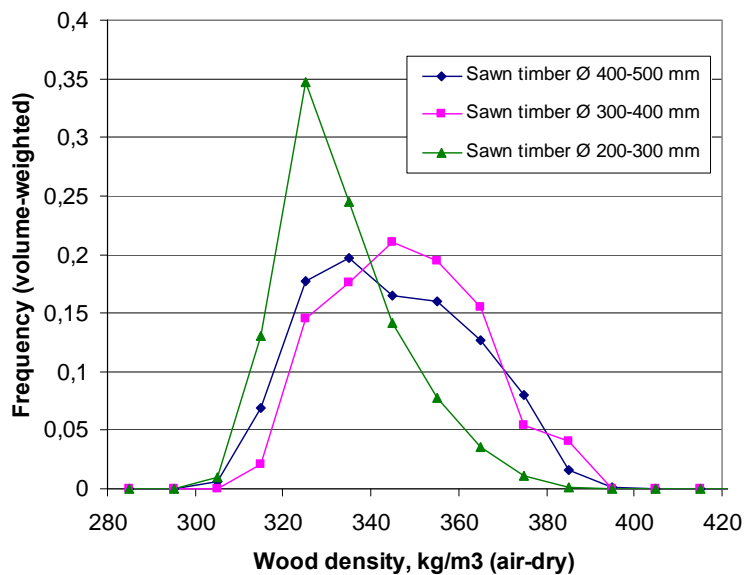
Figure 34. *Statistical distributions for wood density of the inner parts of logs, what will become sawn products, from different log diameter classes, in the resource of Västerbotten.*

8. Conclusions and continued work

Conclusions

Proper allocation of wood raw materials to different products and processes has a strong impact on sustainability. It is relevant from both a policy and technology perspective, on regional level and for individual growers and producers. Prerequisites for good allocation are knowledge about volumes and properties of available materials in the forest (mapping) and about the property demands of various products and processes on the raw materials.

Forest Resource Databases offer a very versatile way to map existing resources in the forest. A broad spectrum of wood and fibre properties relevant for different forest-based products may are described in an integrated way for entities of interest for mills and forest owners: pulpwood logs, sawlogs, sawmill chips, materials from a stand ready to harvest, aggregated flows to mills, etc. The Resource Databases designed for EFORWOOD provide integrated information about the properties of wood, knots and fibres in the same formats, in order to offer opportunities to optimize allocation not only in single chains for pulp and paper mills or sawmills but also among fibre chains, solid wood chains and bio-energy chains. Data may also be estimated for individual growth internodes to allow the analysis of cross-cutting alternatives.

Resource Databases are built through simulation, using sets of integrated models and low-cost forest inventory or harvester data. They may be built with different levels of detail for various applications, as has been proven in previous work with the general concept at STFI-Packforsk. Models are available for some species and regions, but additional work has to be done to cover more of the total European

resource. Routines for sampling, measurements and modelling are, however, established, which facilitates further development.

Resource Databases may also be built based on large scale or limited scale sets of data, useful for different purposes. The versions designed for the EFORWOOD project offers different approaches, depending on data available and issues to study. The experience of STFI-Packforsk is that it is normally possible to transfer existing data to useful formats, at least of acceptable size to illustrate basic effects of different strategies in allocation and processing.

Continued work within EFORWOOD. Further needs and possibilities

It would be fruitful during the last year of EFORWOOD to investigate a number of allocation strategies within ToSIA, including both policy and technology driven issues on different levels of detail, from regions to individual mills, in different European regions. Such a large-scale effort is not possible, but the methods to map resources and optimize allocation will be further tested and illustrated in module specific activities. According to the current plans, this will be achieved through a more detailed study based on the Västerbotten data, emphasizing allocation alternatives for fibre chains to the paper industry. A similar study is planned for Baden-Württemberg, focusing on the solid wood and bio-energy chains. A third study will be performed in Scotland addressing issues important for sawing of Sitka spruce and the impact of different silvicultural strategies.

It would also be fruitful to analyse in further detail the applicability of the concept of Resource Databases in a wider selection of European regions with further wood species. Such a study should also include the analysis of what additional models and data would be needed to build the sets of integrated models and to simulate the databases. This work should obviously be done in cooperation with experts in the different regions, to fully benefit from previous work.

STFI-Packforsk is building Regional Resource Databases and is using them in different research projects and in contract work together with research groups and companies and functionalities developed in the EFORWOOD project are currently being applied. Databases are now being built for parts of another country, using existing models for Norway spruce and Scots pine. It would be very interesting to apply the EFORWOOD approach in similar projects for resources of one or two other important wood species in other regions, such as Sitka spruce or a hardwood species, or for the same species but growing under other growth conditions, such as temporary drought, in cooperation with researchers in the regions. It would also be very valuable to use forest data from new assessment methods, such as remote sensing, as input data for the simulations.

Some applications have already been studied and developed, but it would be good to use the methods in some more cases. It would particularly be extremely valuable to apply the EFORWOOD approach in optimization including allocation along the fibre, wood and bio-energy chains, in order to improve the methods and widen the experiences from their use.

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This report will be modified by STFI-Packforsk into two publications. A more comprehensive state of the art description will then be added, putting this work into the context of other integrated systems of models for simulation of properties of wood and fibres. The reference list above will then be reduced to include only a selection of these references, while others related to the state of the art will be added.

Enclosure 1

General scheme for simulation of trees and their properties with integrated models
Part of the generation of Regional Resource Databases

Sven-Olof Lundqvist, Thomas Grahn, Lars Olsson, STFI-Packforsk

This document describes a general scheme for the stepwise calculation of size and shape of trees
and their internal properties with a chain of integrated models and input data on stands and trees.
As an example, reference are given to the models used by STFI-Packforsk for Scots pine
in the generation of Regional Resource databases.
If there are alternatives, the one used for Scots pine is indicated with black, the others shown in grey.

Variables, notations and units used are defined below.
This set of notations for integrated models may in itself be interesting to study and use in other projects.

The scheme has been developed by STFI-Packforsk in its development of the general concept
of Regional Resource databases with different levels of detail for various applications.
This version was compiled for the EFORWOOD WP3.1 workshop in Stockholm March 3, 2007.
The scheme will be part of a publication.

Input data of stands and trees
The input data needed for the simulation of the trees may differ between wood species
and regional growth conditions. Examples are:

Stand data: Latitude, longitude, altitude, site index, "tree height", age (if even-aged stands)
or age distribution, stocking, etc

Tree data: Breast height diameter, tree height, number of growth rings at breat height, etc.

Step A, providing the SIZE and SHAPE of the stem

Estimation of tree size (on or under bark)

Four alternatives may be used to obtain the diameter at breast height (DBH) and height of tree (H):
    A1   Both DBH and H estimated with growth models and taper estimated with model
    A2   DBH measured (calipered), H estimated with model, taper estimated with model
    A3   Both DBH and H measured, taper estimated with model
    A4   Diameter at different heights measured with the harvester, providing also the taper
The diameter/taper on or under bark may be estimated and the bark thickness subtracted/added.
In this example, the DBH was calipered and H estimated by SLU and supplied with the inventory data.
The stem taper under bark was estimated and the bark thickness added.

Estimation of taper (diameter on or under bark)

D(h) = $Model$ *Input: D_{BH}, h_{rel}, H*   AD(h)

Good models for simultanuous estimation of d(h,t), the taper as a function of time,
providing also the interior growth ring structure, would be very useful.

Estimation of bark thickness

			Source of model
B(h) =	$\mathcal{Model}$	*Input: D(h), lat*	AB(h)

B(h) is simulated with this models at some heights and interpolated in between

Calculation of diameters on and under **bark**

Step B, providing the GROWTH PATTERN in the stem

After this step, all independent data needed to estimate the properties aimed for are available **Source of model**

(Scheme for cross-sectional averages)

		If model for D(h) was used above	If model for d(h,t) was used above:	
t_{BH} =	$\mathcal{Model}$	Estimated by SLU and supplied with inventory data		Not published
N(h) =	$\mathcal{Model}$	*Input: N_{BH}, D_{rel}*	(growth ring number)	AN(h)
H(t) =		Determined from N(h)	(height)	
IL(h) =		Determined from H(t)	(internode length)	
GRW_{ave}(h) = D(h)/(2*N)			(average growth ring width)	

Step C, providing PROPERTIES and distributions within the stem

(In EFORWOOD related to cross-sections, that is Y(h), not Y(h,r) or Y(h,n)) **Source of model**

Fibre properties

FL(h) =	$\mathcal{Model}$	*Input: N(h), GRW_{ave}, h_{rel}, tsum*	(fibre length)	AFL(h)
FW(h) =	$\mathcal{Model}$	*Input: R, GRW_{ave}*	(fibre wall thickness)	AFW(h)
FWT(h) =	$\mathcal{Model}$	*Input: R, h_{rel}, tsum*	(fibre width)	AFWT(h)
FC(h) =		Calculated from FW(h) and FWT(h)		

Models for and calculations of further properties may be added

Wood density

WD_b(h) =	$\mathcal{Model}$	*Input: D(h), N(h), N_{BH}, D_{rel}, tsum*	AWD_b(h)

Other wood properties

WHW(h) =	$\mathcal{Model}$	*Input: D(h), N(h)*	(content of heartwood)	AWD_b(h)

Models for further properties may be added

Whorls and Knots

KN(h) =	$\mathcal{Model}$	*Input: tsum, GRW_{ave}*	(no of knots/whorl)	AKN(h)
KD(h) =	$\mathcal{Model}$	*Input: tsum, GRW_{ave}, D_{BHrel}*	(average knot diam)	AKD(h)
KLs(h) =	$\mathcal{Model}$	*Input: SI, $D_{BH\,rel}$*	(length of sound knot)	AKLs(h)
KLd(h) =	$\mathcal{Model}$	*Input: $D_{BH\,rel}$*	(length of dry knot)	AKLd(h)
KA(h) =	$\mathcal{Model}$	*Input: GRW_{ave}, D_{BHrel}*	(knot angle)	AKA(h)

Models for further properties may be added

Step D, providing Volumes or Masses of Branches and Root

Wood in stem
SWV =	Calculated from D(h)	total volume of wood in stem
SWM =	Calculated from D(h) and $WD_b(h)$	total mass of wood in stem

Bark on stem
SBV =	Calculated from B(h)	total volume of bark on stem
SBM =	Calculated from SBV and average bark density	total mass of bark on stem

Stem
SV =	Calculated from SWV and SBV	total volume of stem
SM =	Calculated from SWM and SBM	total mass of stem

Branches
BV =	Proportional to SV	total branch volume
BM =	Calculated from BV and average branch density	total branch mass

Root
RV =	Proportional to SV	total root volume
RM =	Calculated from RV and average root density	total root mass

Tree
TV =	SV+BV+RV	total tree volume
TM =	SM+BM+RM	total tree mass

Step E, integration of VOLUMES, MASSES and ENERGY VALUES for LOGS, SAWMILL CHIPS, BARK and WHOLE TREES

Volumes, masses and averages are calculated

Variables, notations and units
used in the stepwise estimation of size, shape and properties of trees
Part of the generation of Regional Resource Databases

Notation	Variable	Unit	Comment
Time and age			
t	time from plantation of the tree	year	
T	time = age of tree at current age or simulate	year	
i(h)	time to a given height in stem (primary age)	year	
integer (i(h))	number of the internode at height h		
i_{BH}	age when the tree reached breast height	year	
i(T)	age of tree	year	
Heights			
h	height in tree	m	
H	Height to the top of the tree (from the ground	m	
h_{rel}	relative height in tree h/H		$0 \leq h_{rel} \leq 1$
h_S	height of the stump	m	
h_{BH}	breast height = 1,3 m		

Diameter, radius

D(h)	diameter of the stem cross-section at height	cm
R(h)	radius of stem cross-section at height h	cm
r(h)	radial position within the cross-section at he	cm
D_{BH}	diameter at breast height (1,3 m)	cm
D_{rel}	diameter related to diameter at breast heigh	$0 \leq D_{rel} \leq 1$
r_{BH}	radius at breast height (1,3 m)	cm
D_{BHave}	average D_{BH} in stand	cm
D_{BHrel}	D_{BH} of tree in relation to stand average	
B(h)	bark thickness at height h	mm

It is assumed that growth and properties do not vary among radii in the same cross-section

Growth rings

N(h)	number of growth rings in the stem cross-section at height h	
n(h)	number of a certain growth ring in the cross-section at height h (secondary age)	
N(i)	number of growth rings in the stem cross-section at internode i	
n(i)	number of a certain growth ring in the cross-section at internode i	
N_{BH}	number of a certain growth ring at breast height	
$GRW_{ave}(h)$	average growth ring width in cross-section a	mm

Fibre properties (cross-sectional averages)

FL(h)	fibre length at tree height h	mm
FW(h)	fibre width at tree height h	µm
FWT(h)	fibre wall thickness at tree height h	µm
FC(h)	fiber coarseness at tree height h	g/m
MFA(h)	microfibril angle at tree height h	°

Wood properties (cross-sectional averages)

$WD_d(h)$	dry wood density at tree height h	kg/m^3
$WD_b(h)$	basic density at tree height h	kg/m^3
WMOE(h)	modulus of elasticity at height h	N/m^2
WHW(h)	heartwood content	%

Whorls and knots properties

IL(h)	internode length at height h	m
KN(h)	number of knots/internode at height h	
KD(h)	average knot diameter at height h	cm
$KL_f(h)$	length of fresh knot at height h	cm
$KL_d(h)$	length of dry knot at height h	cm

Branches and root properties

SWV	total volume of wood in stem	m^3
SWM	total mass of wood in stem	kg
SBV	total volume of bark on stem	m^3
SBM	total mass of bark on stem	kg
SV	total volume of stem	m^3
SM	total mass of stem	kg
BV	total branch volume	m^3
BM	total branch mass	kg
RV	total root volume	m^3

RM	total root mass	kg
TV	total tree volume	m^3
TM	total tree mass	kg

Stand data

lat	latitude	º
long	longitude	º
alt	altitude	m
tsum	temperature sum	day-ºC
NS	number of stems per hectare	

Sorces of models: Example Scots pine

Property	Identification	Reference
H(T)	AH(T)	Söderberg, U, Functions for forest management: Height, form height and bark thickness of individual trees. SLU report 52 (In Swedish)
N(h)	AN(h)	Wilhelmsson, L., Two Models for Predicting the Number of annual Rings in Cross-sections of Stems, Skogforsk
D(h)	AD(h)	Spångberg, K., Arlinger, J., Wilhelmsson, L., Lundqvist, S-O., Hedenberg Ö., Arbetsrapport 491, Skogforsk 2001.
B(h)	AB(h)	Wilhelmsson, L., Arlinger, J., Spångberg, K., Lundqvist, S-O., Hedenberg, Ö., Olsson, L., Grahn, T., et al., Models for Predicting Wood Properties in Stems of Picea abies and Pinus sylvestris in Sweden, Scand.J.For.Res
KN(h)	AKN(h)	Björklund, L.,Moberg,L., Modelling the inter-tree variation of knot properties for Pinus sylvestris in Sweden, Studia Forestalia Suecica 1999.
KD(h)	AKD(h)	Björklund, L.,Moberg,L., Modelling the inter-tree variation of knot properties for Pinus sylvestris in Sweden, Studia Forestalia Suecica 1999.
KL$_s$(h)	AKL$_s$(h)	Björklund, L.,Moberg,L., Modelling the inter-tree variation of knot properties for Pinus sylvestris in Sweden, Studia Forestalia Suecica 1999.
KL$_d$(h)	AKL$_d$(h)	Björklund, L.,Moberg,L., Modelling the inter-tree variation of knot properties for Pinus sylvestris in Sweden, Studia Forestalia Suecica 1999.
KA(h)	AKA(h)	Björklund, L.,Moberg,L., Modelling the inter-tree variation of knot properties for Pinus sylvestris in Sweden, Studia Forestalia Suecica 1999.
FL(h)	AFL(h)	Lundqvist, S-O, Grahn, T, Hedenberg, Ö, Models for fibre dimensions in different wood species. Simulations and comparisions of within and between tree variations for Norway and Sitka spruce, Scots and Loblolly pine, IUFRO NZ, 2005.
FW(h)	AFW(h)	Lundqvist, S-O, Grahn, T, Hedenberg, Ö, Models for fibre dimensions in different wood species. Simulations and comparisions of within and between tree variations for Norway and Sitka spruce, Scots and Loblolly pine, IUFRO NZ, 2005.
FWT(h)	AFWT(h)	Lundqvist, S-O, Grahn, T, Hedenberg, Ö, Models for fibre dimensions in different wood species. Simulations and comparisions of within and between tree variations for Norway and Sitka spruce, Scots and Loblolly pine, IUFRO NZ, 2005.
WD$_b$(h)	AWD$_b$(h)	Wilhelmsson, L., Arlinger, J., Spångberg, K., Lundqvist, S-O., Hedenberg, Ö., Olsson, L., Grahn, T., et al., Models for Predicting Wood Properties in Stems of Picea abies and Pinus sylvestris in Sweden, Scand.J.For.Res