

EFORWOOD  
Tools for Sustainability Impact Assessment

**Forest Resource Databases - a concept for product-oriented  
mapping of properties and volumes in forest resources**

Sven-Olof Lundqvist and Thomas Grahn



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## Preface

This report is a deliverable from the EU FP6 Integrated Project EFORWOOD – Tools for Sustainability Impact Assessment of the Forestry-Wood Chain. The main objective of EFORWOOD was to develop a tool for Sustainability Impact Assessment (SIA) of Forestry-Wood Chains (FWC) at various scales of geographic area and time perspective. A FWC is determined by economic, ecological, technical, political and social factors, and consists of a number of interconnected processes, from forest regeneration to the end-of-life scenarios of wood-based products. EFORWOOD produced, as an output, a tool, which allows for analysis of sustainability impacts of existing and future FWCs.

The European Forest Institute (EFI) kindly offered the EFORWOOD project consortium to publish relevant deliverables from the project in EFI Technical Reports. The reports published here are project deliverables/results produced over time during the fifty-two months (2005–2010) project period. The reports have not always been subject to a thorough review process and many of them are in the process of, or will be reworked into journal articles, etc. for publication elsewhere. Some of them are just published as a “front-page”, the reason being that they might contain restricted information. In case you are interested in one of these reports you may contact the corresponding organisation highlighted on the cover page.

Uppsala in November 2010

*Kaj Rosén*

EFORWOOD coordinator

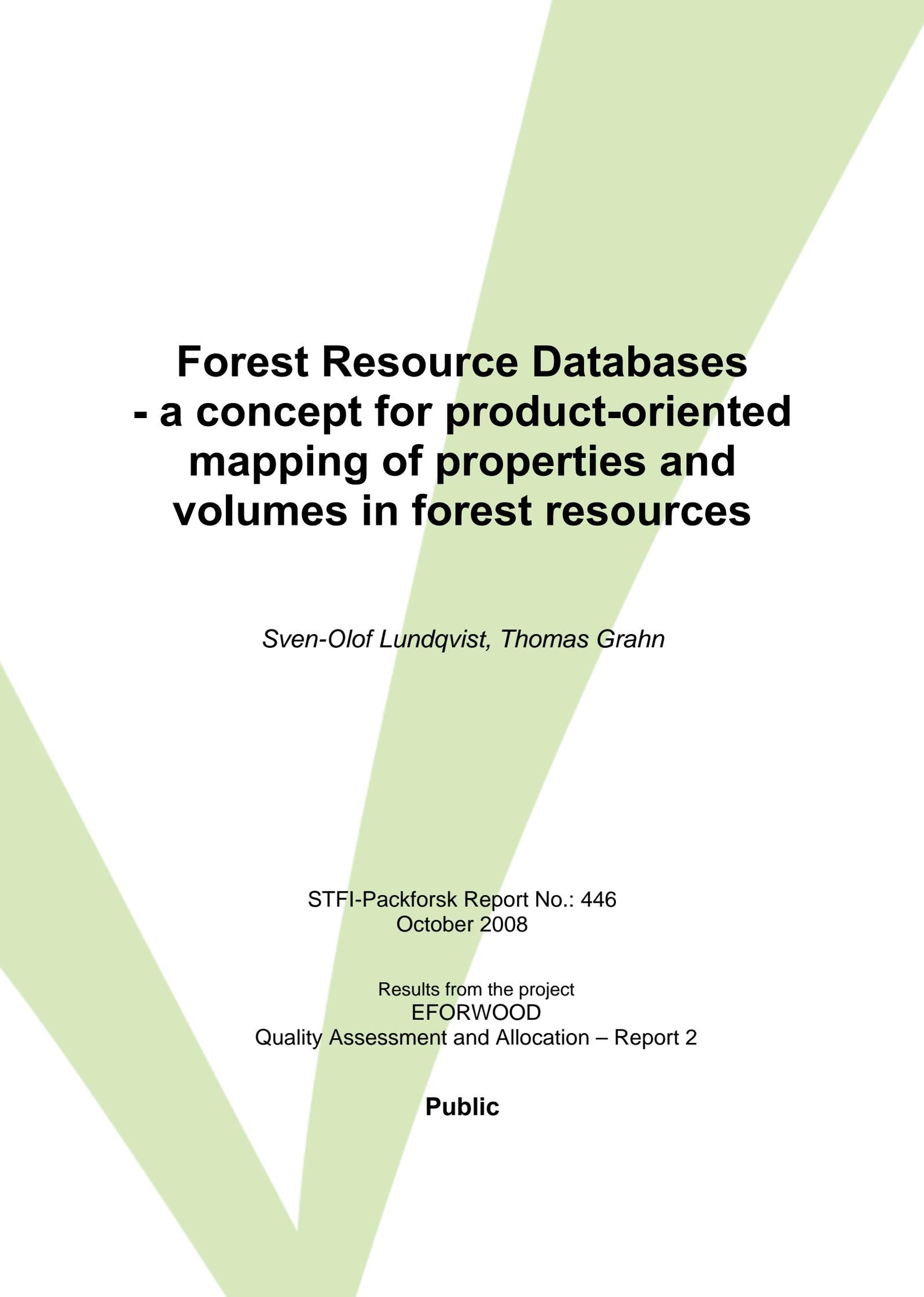
The Forestry Research Institute of Sweden (Skogforsk)

Uppsala Science Park

SE-751 83 Uppsala

E-mail: [firstname.lastname@skogforsk.se](mailto:firstname.lastname@skogforsk.se)





# **Forest Resource Databases - a concept for product-oriented mapping of properties and volumes in forest resources**

*Sven-Olof Lundqvist, Thomas Grahn*

STFI-Packforsk Report No.: 446  
October 2008

Results from the project  
EFORWOOD  
Quality Assessment and Allocation – Report 2

**Public**

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The report describes a concept called “Forest Resource Databases”. In such databases conventional forest inventory data are complemented by simulated data on properties and volumes of wood and fibres available in the resources. The concept has previously been developed by Innventias a result of long-term research and development within projects of Innventia’s “cluster research programmes”, funded by groups of pulp and paper companies, and also as a result of applications within contract work for companies.

The authors want to acknowledge all funding organisations and companies for their support to the development within EFORWOOD and in the previous projects as well as fellow researchers within EFORWOOD for inspiration and support. Special thanks are addressed to Göran Kempe, SLU, Department of Forest Resource Management, for compiling inventory data, to Lars Olsson, Innventia, for his contributions in modelling and to Barry Gardiner, Forest Research, and Hans Troëdsson for valuable comments.

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<sup>1</sup>The report is based on the EFORWOOD 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” of the workpackage “Quality Assessment and Allocation” within the project Module “Forest to Industry Interaction”.

## Table of contents

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	Page
<b>1 Summary</b> .....	<b>1</b>
<b>2 Introduction</b> .....	<b>2</b>
<b>3 Sustainability, properties and allocation</b> .....	<b>3</b>
3.1 Typical segregation of trees and allocation of materials.....	3
3.2 Mapping of resources with Forest Resource Database (task 1).....	5
3.3 Suitable production and use (Task 2).....	8
3.4 Allocation alternatives (Task 3) .....	8
3.5 Related efforts within EFORWOOD .....	9
<b>4 Building and use of Forest Resource Databases</b> .....	<b>11</b>
4.1 Sampling, measurements and modelling (Step 1).....	11
4.2 Inventory data, integrated models and simulations (Step 2) .....	12
4.3 Properties, detail and size of database depending on application .....	15
<b>5 Forest Resource Databases – The EFORWOOD version</b> .....	<b>21</b>
5.1 The forest resource and inventory data.....	21
5.2 Models used .....	22
5.3 Small-size Resource Database with log data from selected plots.....	24
5.4 Large-size Resource Database with internode data from all plots .....	27
5.5 Comments on size and detail of simulations and database .....	29
<b>6 Visualisation of property variations – One tree</b> .....	<b>30</b>
6.1 The simulated tree.....	30
6.2 Size and shape of stem .....	30
6.3 Wood properties .....	31
6.4 Fibre properties .....	32
<b>7 Examples of use</b> .....	<b>34</b>
7.1 Cross-cutting to different lengths.....	34
7.2 Properties and volumes of specific raw materials .....	35
<b>8 Conclusions and continued work</b> .....	<b>40</b>
<b>9 References</b> .....	<b>42</b>
<b>10 Invention Database information</b> .....	<b>47</b>

Public report

Forest Resource Databases - a concept for product-oriented mapping of  
properties and volumes in forest resources  
STFI-Packforsk Report No.446

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## 1 Summary

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Proper allocation of wood raw material to different mills and products is crucial for the sustainability of the forest-based sector. Poor allocation results in unnecessary use of materials, energy, chemicals and transportation, with negative effects on environment, economy and society. This report describes a concept “Forest Resource Databases” for mapping of properties and volumes of forest resources, providing a basis for optimal allocation of wood and fibres. The concept was previously developed at STFI-Packforsk, now Innventia, emphasizing properties of fibres and production of pulp and paper. Within the EFORWOOD project it has been expanded and adapted for wider applicability, with the aim to deal with all major wood-based production chains in an integrated way.

In “Forest Resource Databases”, forest inventory data about stands and trees are complemented with estimated information about properties and volumes of trees and parts of the trees: logs for various uses with different dimensions and properties, parts of logs which will become sawn products and chips, etc. These estimations result from simulation, using inventory data or data from harvesters as input data to models. The resource database offers a virtual representation of the available resource, useful in many types of applications. The size of the database, the properties included and the level of detail in the description of the trees and parts of trees are adapted to each application.

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

In the report, the general concept of Regional Resource Databases is 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. An important goal of the EFORWOOD project is to deal with all major forestry-wood chains in an integrated way, to allow not only optimization along single chains but also among different types of production chains. For this, it is necessary that the database provides information about a wide spectrum of properties of wood and fibres in the same format. The building of Forest Resource Databases and their contents are illustrated with two examples: a small-size and a large-size database for the forest resource of Västerbotten in the north of Sweden, 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 constraints set by availability, logistics, economics, etc.

## 2 Introduction

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Wood shows a large variation in properties; among tree species and types of stands, due to differences in growth conditions and between 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 report illustrates how this can be supported by using models and simulations, and more specifically through the application of the concept Forest 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 useful both in research about optimal wood and fibre utilisation and for applications.

The concept has previously been developed by Innventia to support optimization of the allocation and processing of wood raw materials into various types of products. It is a result of long-term research and development within projects of Innventia's "cluster research programmes", funded by groups of pulp and paper companies, and of applications in contract work for companies. In this previous work, fibre properties and pulp and paper issues were emphasized, but some properties of wood and knot primarily relevant for sawmills were also included. Within the EFORWOOD project, the concept has been expanded and adapted for more general applicability, in order to improve its usefulness regarding sawlogs and sawn products and for optimization also among the different chains for production of paper products, sawn products or bio energy, which was an important issue of the EFORWOOD project.

The report describes:

- The general concept of Forest Resource Databases:
  - + how they are built
  - + different levels of detail for various applications
  - + size of geographic area: from local to national databases, depending on use
- The type of database for mapping of regional resources specifically designed for the EFORWOOD project:
  - + 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.

Mapping of properties in forest resources have been applied in four EFORWOOD case studies. Results and models used are presented in (Lundqvist et al 2009). The work has been done within the EFORWOOD work package "Quality Assessment and Allocation".

### 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, economy 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 results in 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*, different steps of allocation from the forest to different types of products are illustrated. There are a number of silvicultural or harvesting operations providing wood raw materials: pre-commercial thinning, first and second thinning, final cutting. The operations are performed at different stand ages, or rather when the trees have reached suitable sizes (large enough for sawing, etc.). These sources of wood raw materials are represented with groups of trees of various sizes at the top of the figure. Also harvesting of stumps is visualized at the far right.

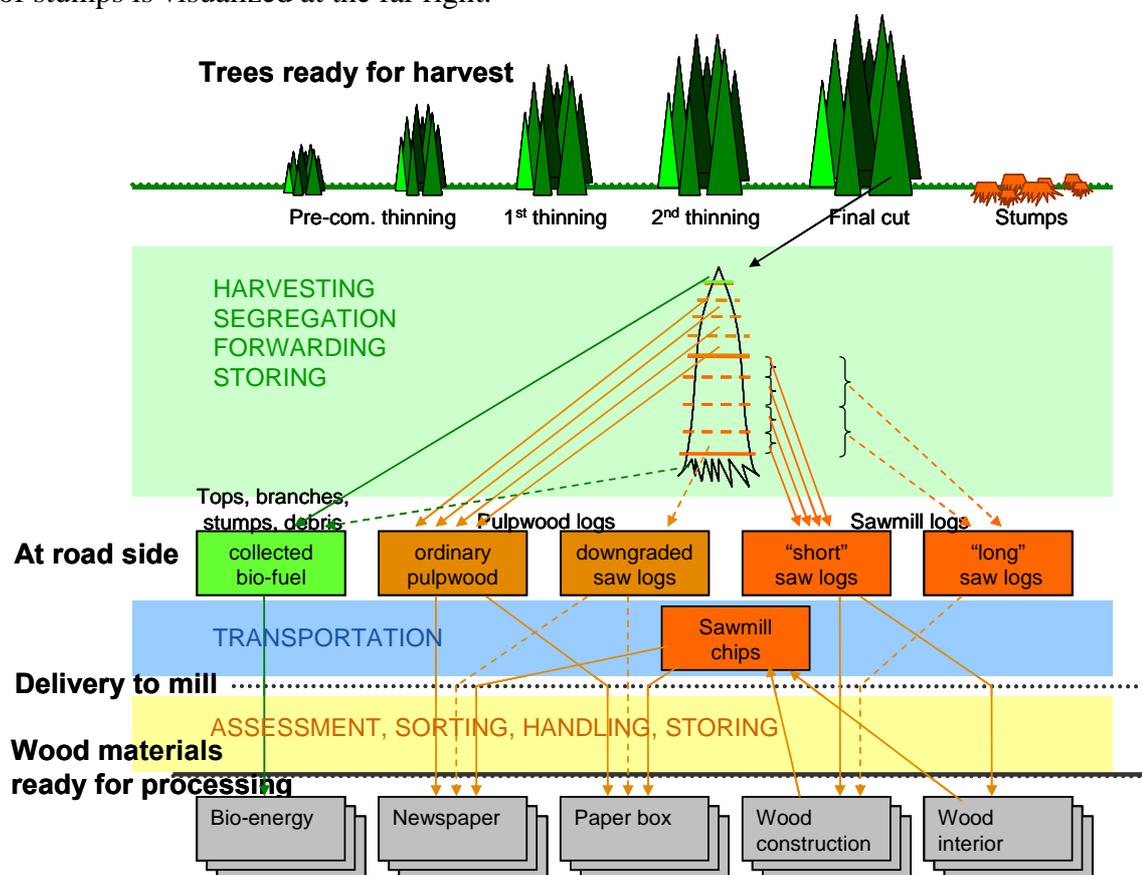
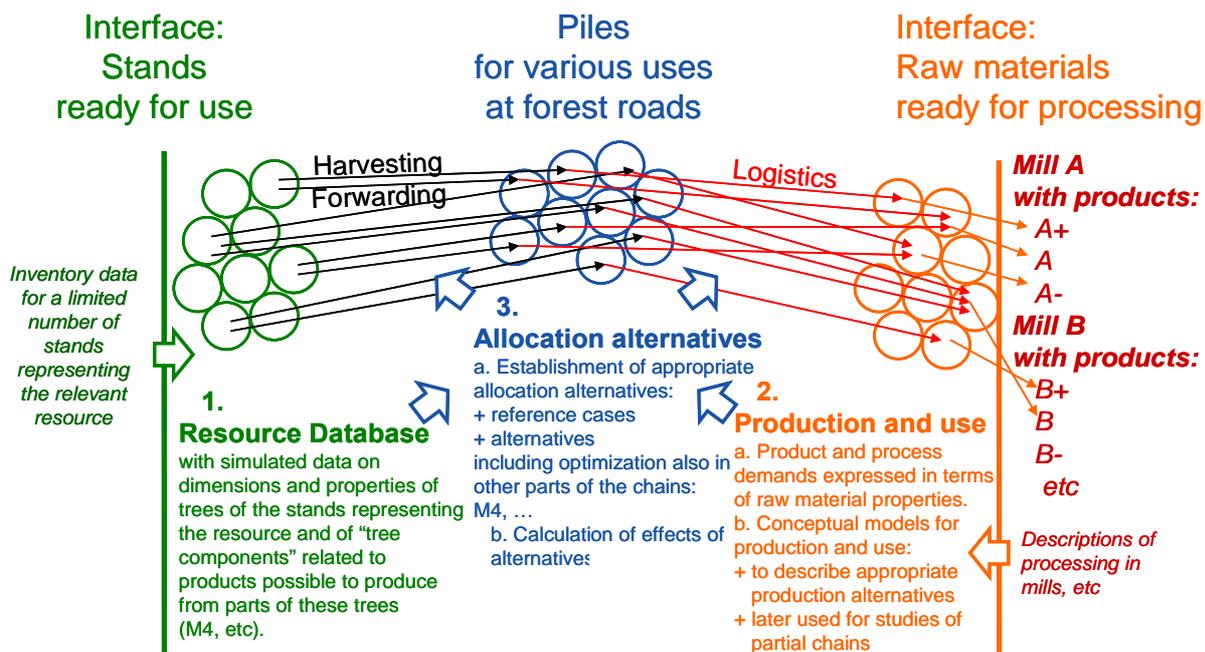


Figure 1. Typical allocation of materials from final cutting of a softwood stand.

Below this row representing different harvesting events, a typical scheme for segregation of trees and allocation of materials 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 logs large enough for sawing are cross-cut into sawlogs of different lengths, depending on what end-product is considered. Smaller dimension logs are dedicated to pulp production, together with downgraded sawlogs. Tops, branches and debris may be collected for bio-fuel. The different classes of wood raw material are forwarded to separate piles at road side. The flow chart further down in figure 1 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.

In *figure 2*, important prerequisites for and activities involved in the assessment of wood and fibre properties and suitable allocation of materials to various processes and products allocation are summarised. The figure also illustrates how allocation relates to harvesting and logistics.



**Figure 2.** Important prerequisites for and activities involved in allocation

Three main tasks are defined in the figure:

1. Mapping of the forest resource: assessment of 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.

### **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 the production of various products.

#### **General concept**

The concept of “Forest Resource Databases” was developed by Innventia (STFI-Packforsk) for this purpose. 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 elements”, longitudinal parts of the stem, which together show the variations along the stem with averages or statistical distributions related to each element.

The properties are also calculated for “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 these 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, and they may be evaluated for various aspects and perspectives.

Some prerequisites for the building of a “Resource Database” are:

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

The general concept of “Regional Resource Databases” has been used for several years at Innventia in different applications with customer companies. Databases have been built for resources of different sizes, depending on application. The first database described the resource in the wood supply area of a mill. The largest database built so far is a “National Forest 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 this work has been performed as contract work for customers and is confidential. Some examples from previous projects are, however, shown below in the description of databases designed for various purposes and how they are built. Some further examples of applications are described in (Lundqvist et al 2003b; Lundqvist et al 2007c; Grahn et al 2008; Lundqvist et al 2008).

### **Concept specially designed for EFORWOOD**

The general concept is based on data, models and tools successively developed in a number of projects. It includes many functionalities relevant for EFORWOOD. Within this project, Innventia has used a sub-set of the general functionalities to adapt a concept to the special needs of the project regarding size and detail of the Resource Databases.

The EFORWOOD project has involved 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. Due to this wide approach, it will not be possible to cover all situations which may be studied with a high level of detail. Reasons may be that detailed property models are not always 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 inventory data for large sets of stands if available or as an alternative use of inventory data from a limited set of stands/plots selected to represent the resource of the region, if large data sets are not available. The small scale alternative may also be used in a start-up phase for feasibility studies or for sensitivity analysis, which may be followed by an expansion of the database based on data from more stands.
- Use of models with less detail, only estimating averages but not statistical distributions for the properties of the tree elements. This will facilitate the development of models for properties where models do not yet exist or the adaptation of existing models to for instance new growth conditions.
- Use of small tree elements representing annual longitudinal growth (distance between whorls) to increase the flexibility in the analysis. This increased resolution for longitudinal variations in the stems offers the possibility to also compare different cross-cutting alternatives by aggregating elements to logs from arbitrary positions in stem and arbitrary lengths.

Innventia has, thus, within the EFORWOOD project designed new database structures to meet these demands and added models for further wood and fibre properties. 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 previously developed for the general concept.) Draft concepts and results were successively presented at EFORWOOD meetings in order to support the development of further sets of integrated models. One example is the general structure for such sets of models in (Lundqvist et al 2007a) and the comprehensive compilation of models in (Lundqvist et al 2009). For the simulations with the integrated models and the generation of the databases illustrated in this report, software tools previously developed at Innventia have been used.

In chapter 5 of this report, the EFORWOOD version of the concept is described in further detail. Further examples of results are presented in chapter 6 and 7 based on a case study performed for the forest resource of Västerbotten in northern Sweden.

### **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 the models match each other regarding input and output variables (interfaces), and that all of them are valid for the regional growth conditions at hand, etc. Before the models are used under new growth conditions, the models need to be checked carefully and validated. Integrated models fulfilling these demands, including properties of wood, fibres, knots, etc. are available 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.

For simulation of other species in other countries, some preparatory efforts are normally needed for the building of such sets of integrated models. Some models for growth and properties of the tree species of interest are often available. These are compiled and analysed to find out if they match each other according to the scheme designed, or if they may be adapted to match. It will probably be necessary to develop one or more complementary models and test and validation of the models will be required. Some efforts are, thus, needed before Resource Databases may be built for new species and regions, but the existence of methods and experiences from previous and ongoing development will facilitate work on new species. For initial tests, it may be possible to cut some corners and in some cases even start by partly using models for similar species.

Another comment is that the combination of calculating properties for small tree elements with simulation of large sets of stands will of course involve larger data sets, long computing time and more demanding evaluations. However, when the simulation is done and the Resource Database is at hand, the analyses are done on selected data from the database and computation time on simulation is no longer an issue. But if the database becomes extremely large, the size of it may 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 dealt with in (Lundqvist and Gardiner 2007b). Conceptual models are also needed for how the products are produced and used, in order to describe appropriate production alternatives. Examples of this are given in an EFORWOOD report on sustainability effects from wood allocation (Lundqvist et al 2010).

### **3.4 Allocation alternatives (Task 3)**

The main result of the EFORWOOD project is ToSIA, a Tool for Sustainability Impact Assessment (Lindner et al 2010; Palosuo et al 2010). ToSIA provides means to build models for chains of “processes”, interpreted in a broad sense to include different types of activities: forest operations, transportation, mill processes, etc., from the forest to the used and recycled products, as well as for the calculation of sustainability indicators related to the processes of the chains, including effects on environment, economy and society. This is supported by a library of predefined standard models for a large number of processes as well as a database with parameter values for the models and the calculation of the indicators. With ToSIA, different policies and alternatives will be evaluated through the calculation and aggregation of indicators and alternatives may be compared.

However, ToSIA has no functions to check if the alternatives defined for evaluation are realistic or not. Also impossible alternatives fed into the tool may come out with 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, and that has to be secured by experts involved in the definition of the chains and alternatives.

A practical way to do this, and not the least when investigating effects of different alternatives in allocation, is to establish appropriate current or future “base cases” including effects of operations all along the production chains. During the project, a number of chains with models and data from forest to end-use have been built and tested in different regional case studies. Models and data from these exercises may be used as backbones in the building of such 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.

An example of such successive modifications: Procedures in silviculture are improved -> more favourable fibre properties are obtained -> it is possible to produce thinner/lighter paper with the same functionality -> then less material, energy and

chemicals are use per product > the 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. When it is secured that the alternatives are realistic, the effects of the alternatives are calculated with ToSIA or special versions of it. The results are expressed with indicator values which are compared. Examples of this from two case studies are presented in (Lundqvist et al 2010), including one case related to paper , packaging materials and boxes, and one case related to solid wood products and bioenergy.

### **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 products and need for efficient processing. 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: another one in Västerbotten, one in Baden-Württemberg and one in South Scotland. These are briefly presented below but are also described in further detail in (Lundqvist et al 2009), which also includes a documentation of the models used.

#### **Mapping and allocation with software for harvesters**

The other study in Västerbotten related to assessment of properties with use of models deals with mapping and allocation with software for harvesters. It has been performed by Skogforsk. 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. Prediction of properties from harvester data has previously been illustrated (Wilhelmsson et al 2000). In the case study, the application of the methods for optimal allocation of timber to a number of sawmills has been further illustrated (Wilhelmsson et al 2006; 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 two approaches of Skogforsk and Innventia are actually quite closely related. Both approaches have been applied on the forest resource of Västerbotten, 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 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

on-line allocation and operation. The approach with “Regional Resource Databases” 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.

### **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 developed 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 Baden-Württemberg 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 the quantity of wood and the 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 includes only processes from forest establishment to the mill yard. The model currently covers Sitka spruce 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

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### The general concept

Starting from scratch, two steps are involved in the building of a Forest Resource Database. The first step is to build the models, if they are not available. For this a limited size well structured sampling is performed. Many properties of the samples are measured with advanced instruments, providing data for modelling. The second step is the simulation. Then, large sets of low cost data are used as input data, 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 Innventia “Wood and Fibre Measurement Centre” has been extensively used. The Measurement Centre is equipped with unique instruments 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. Innventia has long experience in the development of measurement methods and the skill to develop and adapt methods to meet specific demands in different projects has been crucial for the measurements and modelling.

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). Instruments like STFI FiberMaster and L&W FiberTester are often used for measurements of fibre length and other dimensions of fibres and vessel elements (Karlsson et al 1999) liberated from the wood matrix, sometimes with use of own dedicated evaluation functions (Granlöf et al 2006). Other techniques which have been applied are CT-scanning for determination of cross-sectional distributions of moisture and basic density in discs (Lindgren et al 2000), and analysis of growth rings and earlywood/latewood from scanned wood discs (Olsson 2000).

With efficient measurement methods, representative sizes of sample can be analysed at reasonable cost, 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 is typically in the range of 24 to 160.

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. Models used within the EFORWOOD project are compiled in (Lundqvist et al 2009), which also provides further references.

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

This number of trees, 24 to 160, 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 data for the stands, such as site index, latitude and altitude. The simulations typically results in volumes and properties of tenths of thousands of trees, as well as for the logs obtained when cross-cutting the stems on harvesting and the chips obtained when sawing of the larger size logs. All these data are compiled in a Forest Resource Database. When using the special EFORWOOD version, the number of trees in the database is 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).

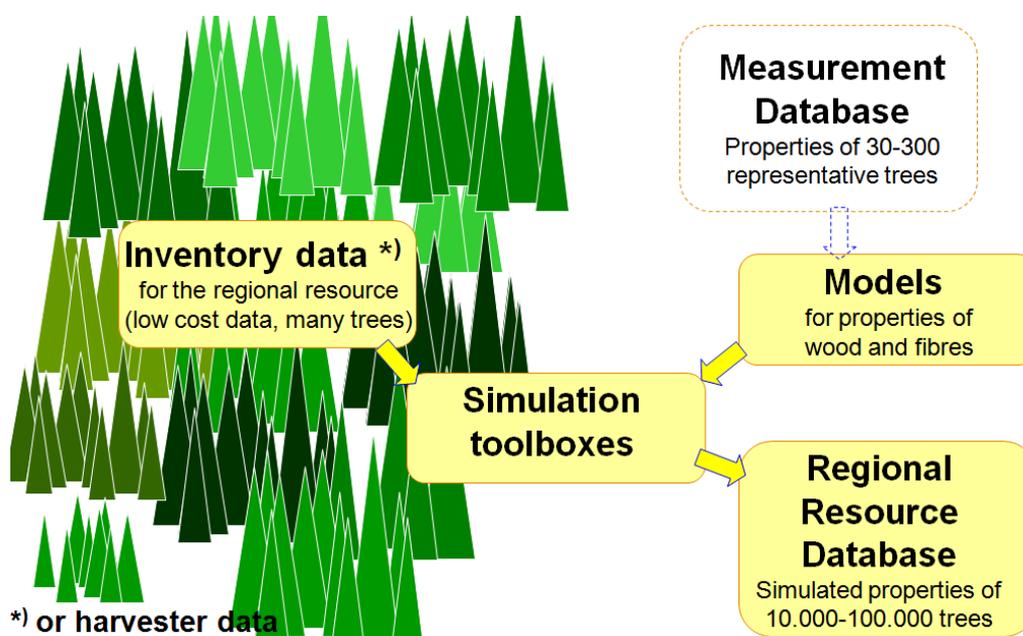
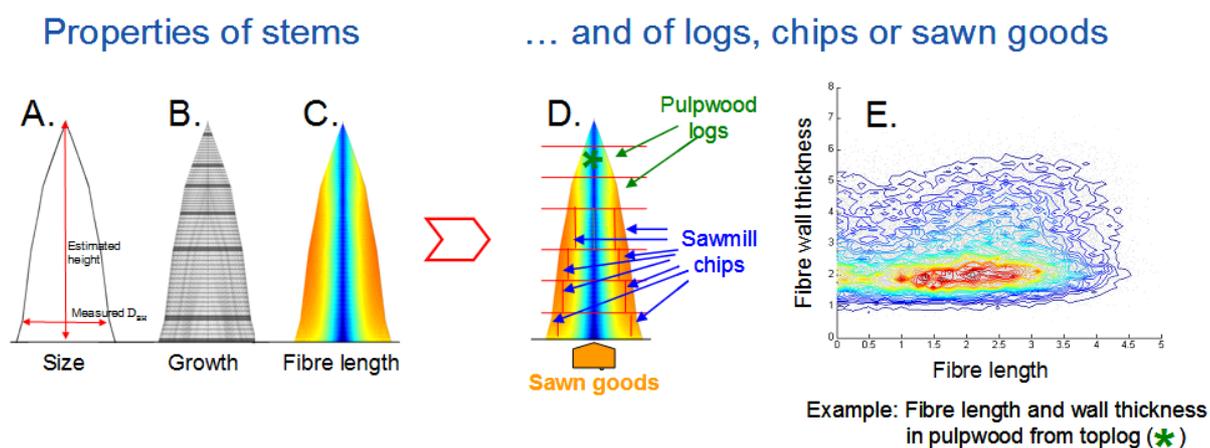


Figure 3. Illustration of the building of a Forest Resource Databases.

### 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 a model for 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 Innventia, fibre properties have been emphasised, such as fibre length (shown in the figure), fibre width and fibre wall thickness. Sometimes, however, also wood properties have been simulated, such as density, heartwood, knot properties, etc.



**Figure 4.** Stepwise simulation of wood and fibre properties of a spruce tree from Sweden and of logs and chips produced from it (Grahn and Lundqvist 2008).

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 may be generated for the parts (E). Then, several thousand fibres are typically 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 and overlap a lot among different types of logs, but the differences are still often relevant in papermaking. The distribution in the illustration relates to the top log (marked with \* in figure 4D). 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,

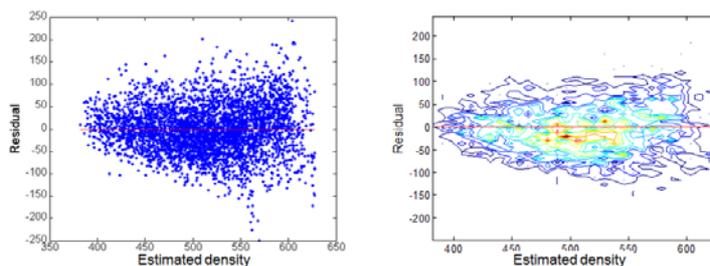
fibre dimensions and wood density. Most of the models have been developed within various cooperative projects.

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, for annual rings or parts of rings, and with different sets of independent variables are used. *Figure 5* illustrates a model developed by Innventia for wood density of Scots pine (*Pinus sylvestris*) based on data from Sweden (Grahn and Lundqvist 2008). 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.

$$\ln(\text{WD}) = 6.36 - 0.027 * \text{GRW}_n + 0.069 * \ln(n) - 0.046 * \ln(h)$$

WD = wood density (dry)  
n = ring no  
GRW<sub>n</sub> = width of growth ring n  
h = height above ground

$R^2_{\text{ring}} = 0.51$ ;  $\text{RMSE}_{\text{ring}} = 53.8 \text{ kg/m}^3$   
 $(R^2_{\text{disc}} = 0.75$ ;  $\text{RMSE}_{\text{disc}} = 30,0 \text{ kg/m}^3)$

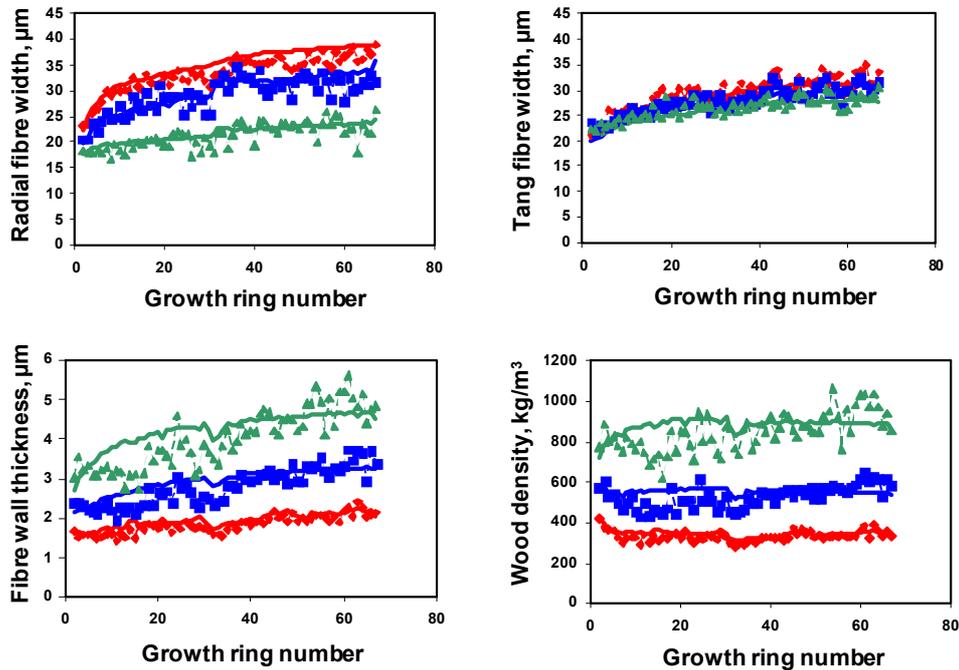


**Figure 5.** A model for the average wood density of arbitrary growth rings at arbitrary heights for Scots pine (*Pinus sylvestris*) (Grahn and Lundqvist 2008).

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).

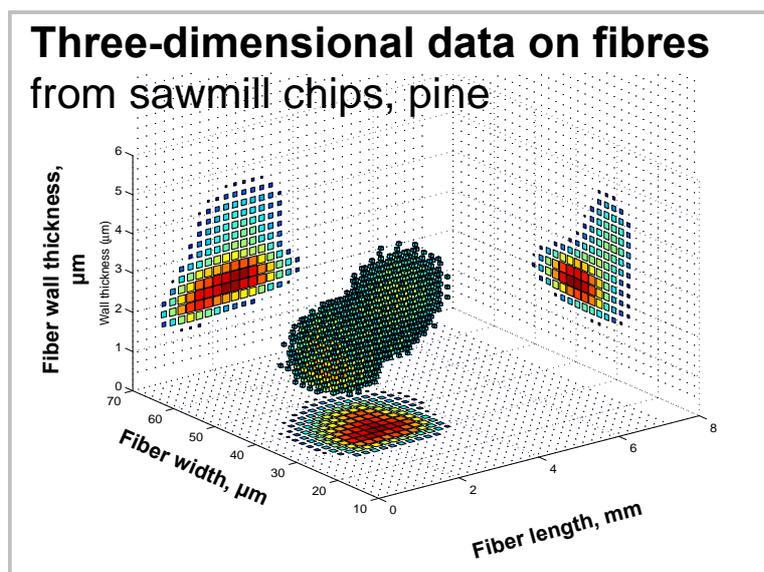
*Figure 6* illustrates how such a model is combined with a growth structure generated for the stem (left) in order to estimate the variation in the whole stem (Grahn and Lundqvist 2008). This structure is used as input data to the simulation. In the middle, graphs are shown for the estimated density 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.





**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).

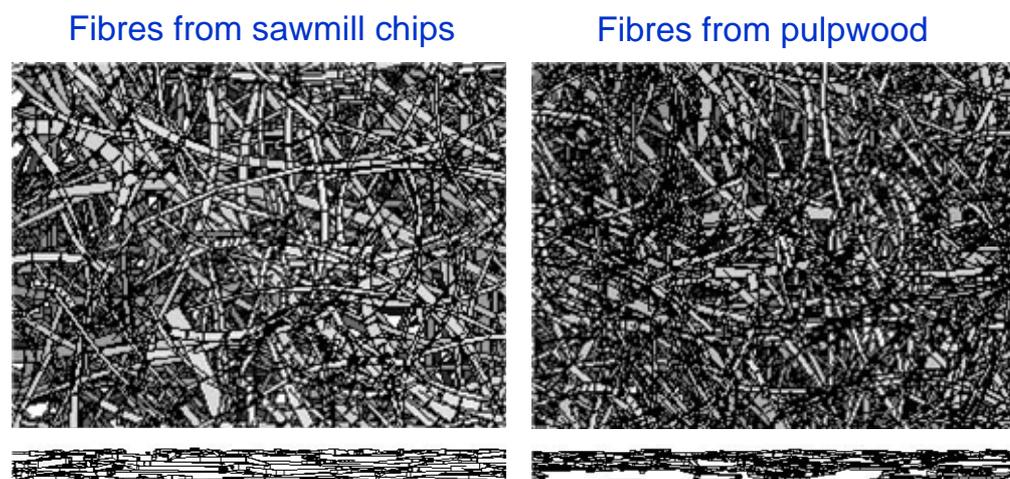
In *figure 8*, such a distribution is shown for sawmill chips from pine. The “combined properties” of relevance for pulp and paper mentioned above may be calculated from such tree-dimensional distributions. When searching for efficient allocation alternatives, different selection and aggregation criteria may be compared from a pulp and paper perspective based on such information.



**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. The concept of Forest Resource Databases is actually designed to support simulation along the value chain, especially for pulp and paper. Related tools have been developed to interface with the multidimensional distributions as shown in figure 8 and use them as input data for simulation of the forming of paper-like fibre networks (Thomsson et al 2006). Networks formed from fibres of different origins may be built. Effects of such differences in origin and fibre properties are illustrated in *figure 9* (Lundqvist et al 2008).



**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,  $\text{g/m}^2$ , and the same sheet density,  $\text{kg/m}^3$  (Lundqvist et al 2008a).

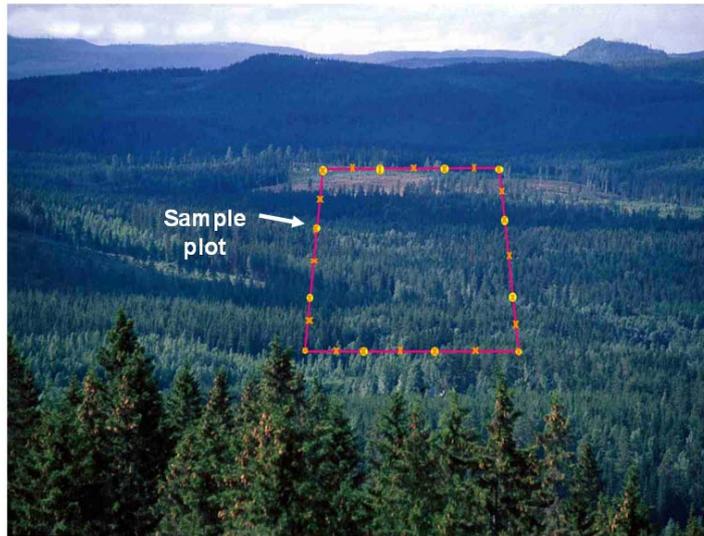
The figure show one fibre network formed from fibres of sawmill chips (left) and one formed from fibres from pulpwood. Both fibre networks have the same grammage,  $\text{g/m}^2$ , and sheet density,  $\text{kg/m}^3$ . For each fibre, the location, bonds and state of collapse are known all along its extension and different structural properties of the network may be calculated and compared. In the upper images of the figure, the networks are visualised seen from the top. The lower images show thin network cross-section. 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 built for different applications. The largest database built so is a National Resource Database for all Sweden. *Figure 10* shows the distribution of the sample plots. 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 selected regions, as well as what benefits can be reached with a more selective use of the available wood.



Source: Riksskogstaxeringen

Photo: Mats Gerentz, SLU

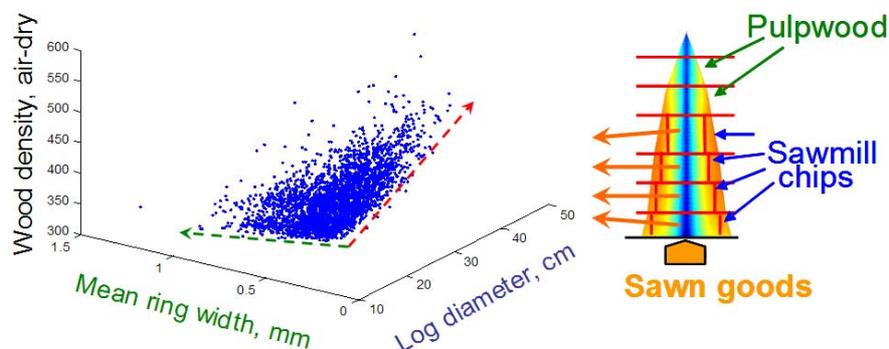
**Figure 10.** Locations of inventory plots included in the Swedish National Resource Database.

Similar databases are also being built for parts of other countries. In some cases, existing models can be reused, 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 information about a variety of potential product related raw materials from the forest. There are many potential applications of this. Two examples will now be 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. The densities are related 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 in the plot 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.

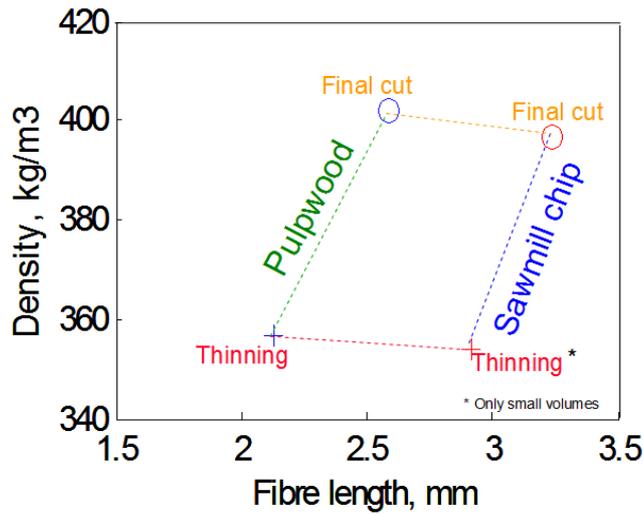


**Figure 11.** Wood density estimated for the inner parts of sawlogs (the sawn goods) plotted against log diameter and mean ring width. Data extracted for pine in a specific county from the Swedish Resource database.

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. 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. Data for these types of materials available in the specific region are extracted from the National Resource Database. Averages of each wood class are calculated for a number of important wood and fibre properties, also for “indicators” closely related to pulp and paper properties as mentioned above (coarseness, etc.).

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 the pulpwood on average provides wood with shorter fibres than the 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 not exist as a separate commercial raw material but would be mixed into the chips from final cutting sawlogs.)

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, which will also influence the properties of the pulp.



**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.

The scope of the presentation above of results from previous work at Innventia with the general concept of “Forest Resource Databases” is to present 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 version

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

- which covers a wider spectrum of wood and fibre properties
- which may be applied also when large-scale inventory data are missing
- which is easier to implement on different wood species or growth conditions in new countries
- which allows comparisons of different cross-cutting strategies and more selective use of tree parts for various products

Two alternative approaches in use of inventory data may be applied to achieve representativity: The one described above, using data on many stands representative due to the large number, or one using inventory data from only a limited number of stands selected to represent the resource. (This approach has been used also with the pre-EFORWOOD version, see (Lundqvist et al 2003b), but the procedures are now more elaborated and tested.) The number of stands needed in this case will depend on the heterogeneity of the resource. Further, the models used have less detail to facilitate implementation and simulation, but the simulation may provide more detail in the estimation of property variations along the stem, in order to allow comparison of more fine-tuned allocation alternatives.

In the report, this flexibility is illustrated through the simulation of two databases with different sizes and levels of detail:

1. Small-size Forest Resource Database  
in this chapter, based on simulation of:
  - + a limited set of stands/plots selected to represent the resource of the region.
  - + average properties of fix length logs of 4 m and for large diameter logs their inner part (sawn goods) and outer part (sawmill chips)
2. Large-size Forest Resource Database  
in chapter 6 and 7, based on simulation of:
  - + all callipered trees from all inventoried stands/plots in the region
  - + average properties for longitudinal growth units (between whorls) and for large diameter logs their inner (sawn goods) and outer parts (sawmill chips)

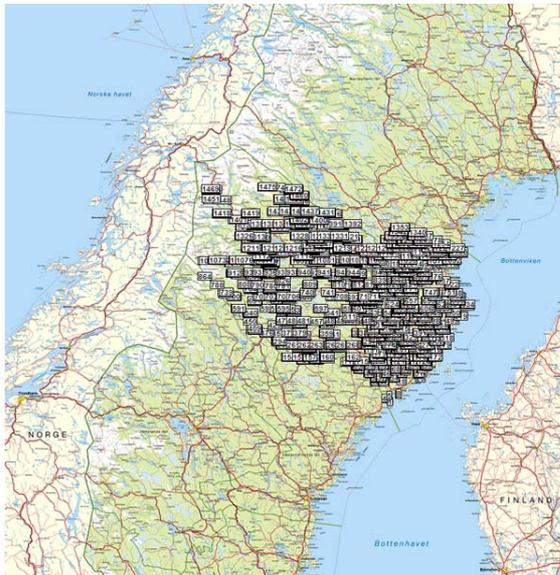
### 5.1 The forest resource and inventory data

All examples shown are based on data from Västerbotten in the north of Sweden, the region of a Scandinavian regional EFORWOOD case study, see above and (Valinger et al 2008). The data cover the administrative unit “Västerbottens län”, which includes the county of Västerbotten and the southern half of 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 inventory data used for the illustrations in this report are excerpt of data from the Swedish National Forest Inventory Database, previously compiled by the Swedish University of Agricultural Sciences (SLU) (see acknowledgement) for the building at Innventia of the "National Resource Database" for all Sweden, see above. The excerpts match geographically the region studied in the EFORWOOD case study and totally include plots inventoried during 5 consecutive years, distributed according to *figure 13*. Only Norway spruce and Scots pine trees have been simulated. Approximate numbers:

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



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

## 5.2 Models used

Many of the models used in the simulations of the Västerbotten resource originate from projects which have been run in cooperation between Innventia (then STFI-Packforsk) and Skogforsk or from further work based on data from such projects (Lundqvist et al 2003a). Examples are 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. Other examples are models for wood properties (Wilhelmsson et al 2002a) and fibre properties (Lundqvist et al 2005). Models for knots from the literature (Björklund and Moberg 1999) are also implemented. The models are based on data from Swedish conditions.

A set of models used for simulation of cross-sectional property 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).

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

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

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

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

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

Table illustrates properties included in the Västerbotten Resource Database inventory data from measurements in the forest and estimated data from simulations using models of different origins. A more detailed description is given in (Lundqvist et al 2009).

**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	
		▪ ...	

The cutting class tells the state of the stand, for instance if it is ready for thinning, final cutting or shall not be harvested. This information is used to identify what raw materials in the forest resource are currently available for use in industry, for energy, etc. It is thus very useful when applying the Resource Database for studies of allocation alternatives.

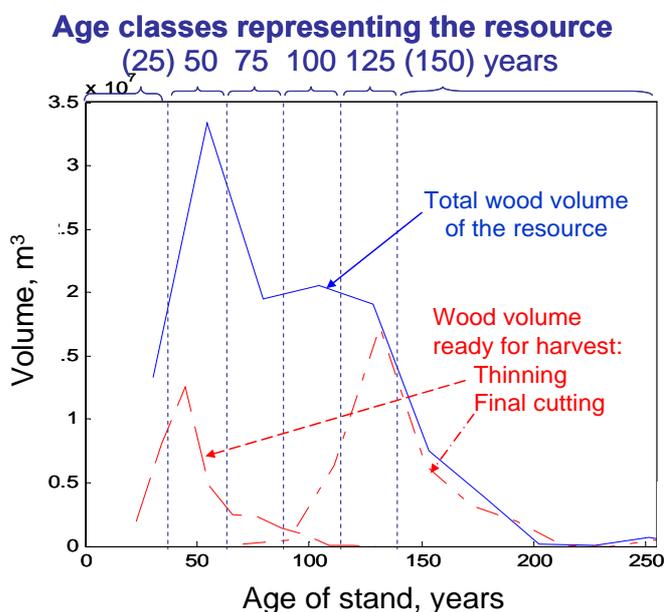
### 5.3 Small-size Resource Database with log data from selected plots

#### Selection of stands/plots to represent the regional resource

A limited number of variables with strong influence on the most important wood and fibre properties are identified. For Västerbotten, the following variables were selected:

- stand/tree age
- altitude
- site index<sup>2</sup>

Based on the variations of these variables in the local resource, a limited number of classes (intervals) are defined for each variable. 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 were defined: close to 200 m and close to 350 m, and two classes for two site index: close to P16 and close to P20. In this way,  $4 \times 2 \times 2 = 16$  types of stands were defined to represent the pine resource of the region.

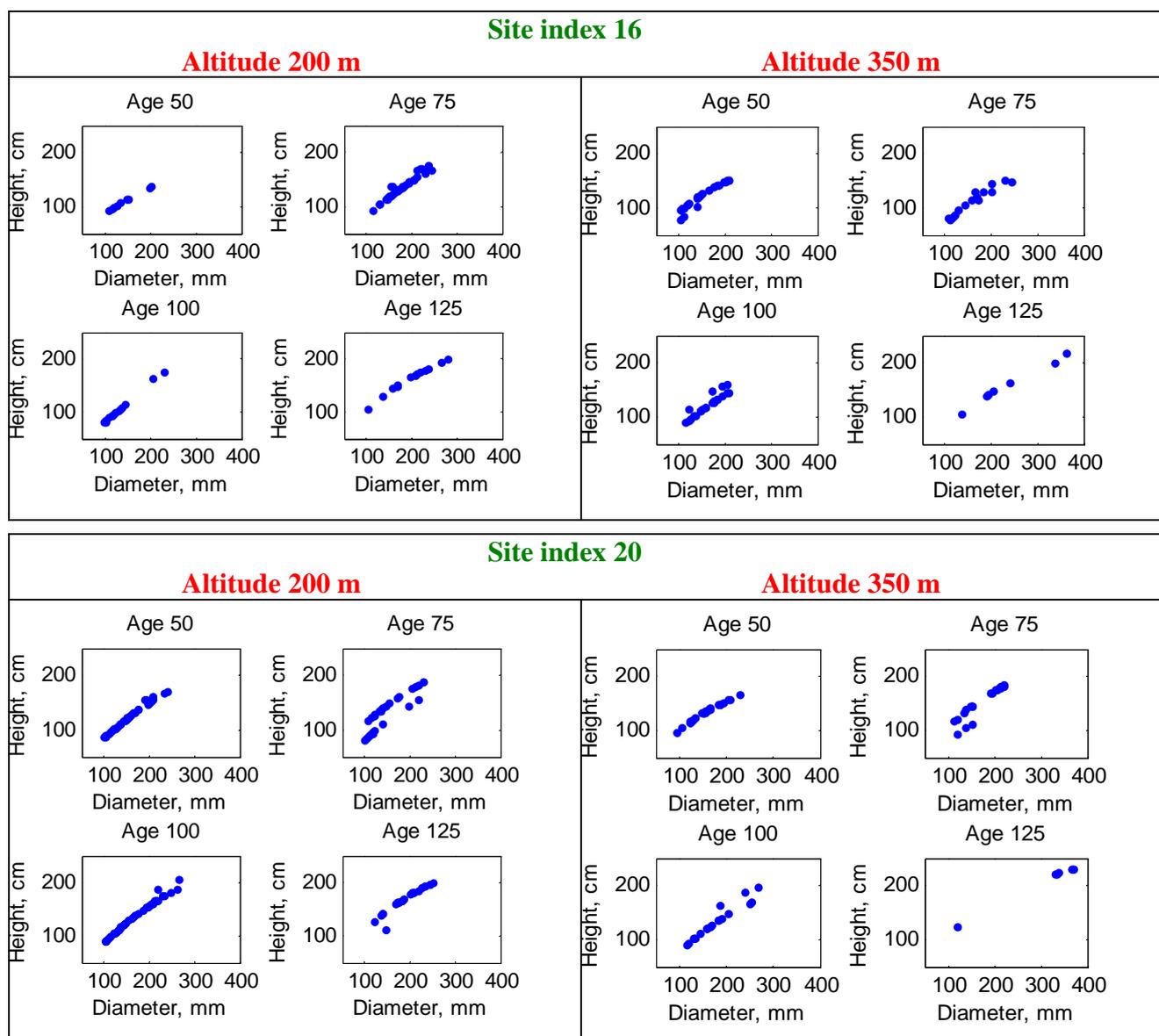


**Figure 14.** Age distribution for the total volume of wood in the region of Västerbotten in the north of Sweden, as well as for wood ready to harvest in thinning and final cutting. Age classes centred around 50, 75, 100 and 125 years of age were defined to represent the resource and the wood possible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

<sup>2</sup> The estimated height for large trees in a 100 years old stand of pine (P).

When applying this approach to other regions, similar analyses should be done to identify the major sources of property variations. It may then 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, in order to illustrate how it is possible to get started in small scale. The number of selected stands may, however, easily be increased. Data on these stands and trees were compiled for the simulation of a small-size Regional Resource Database, including a total of 363 pine trees. Figure 15 illustrates the sizes of the pine trees of various ages and growth conditions to be simulated: their breast height diameters (callipered) and tree heights (estimated by SLU (Söderberg 1992)).

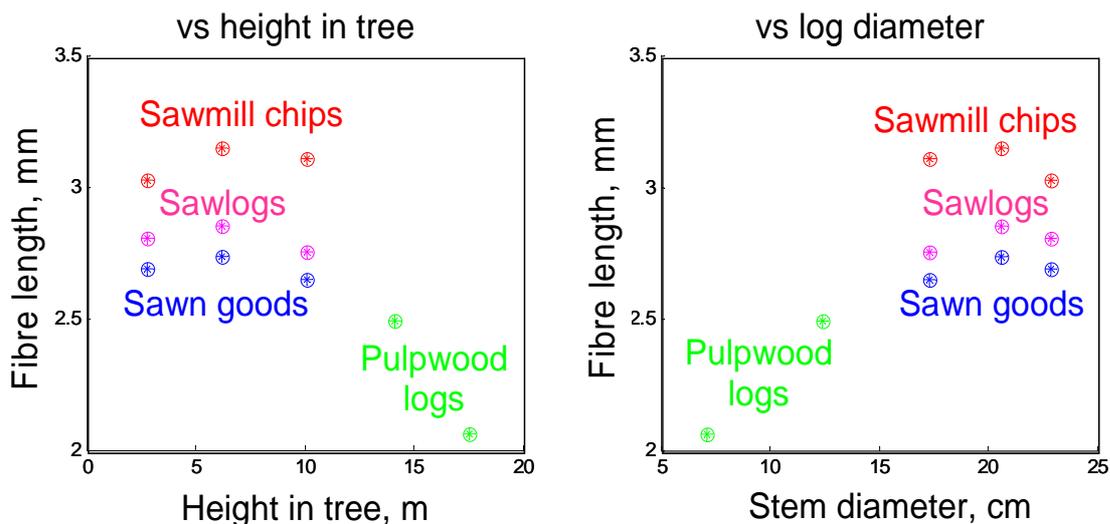


**Figure 15.** Breast height diameter (callipered) and tree height (estimated by SLU) of the trees from the 16 stands selected to represent the pine resource of Västerbotten in the north of Sweden.

### Tree elements

The properties of the trees were simulated and the stems were divided into parts: tree elements. For this example of a small-size database, the tree elements were defined as 4 m logs. Logs with a top diameter of 14 cm or more were classified as sawlogs and those with a smaller diameter as pulpwood logs. For the sawlogs, the 2 cm outermost part of the logs was defined as to become sawmill chips and the inner part as to become sawn goods. Averages are calculated for each part.

In *figure 16*, property differences between logs and sawn goods/sawmill chips are illustrated 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 close to the top of the tree is estimated to about 2.1 mm. The fibre length of the sawmill chips from the sawlogs is estimated to about 3,1 mm. To the left, the data are presented from a forest perspective versus the height position of the logs in the tree. To the right, the data are presented from a mill perspective as a function of log diameter.



**Figure 16.** Average fibre lengths of pulpwood logs and sawlogs from a pine tree. The sawlogs are also further divided into the parts which will become sawn goods and sawmill chips. To the left, the fibre lengths are presented from a forest perspective versus the height positions of the logs in the tree, to the right from a mill perspective as a function of the diameter of the log.

The small-size database will, thus, for this tree, include averages calculated for 11 tree parts, representing various uses in the industry:

- 2 pulpwood logs
- 3 sawlogs, for which also data on 3 components of sawn goods and 3 batches of sawmill chips are included.

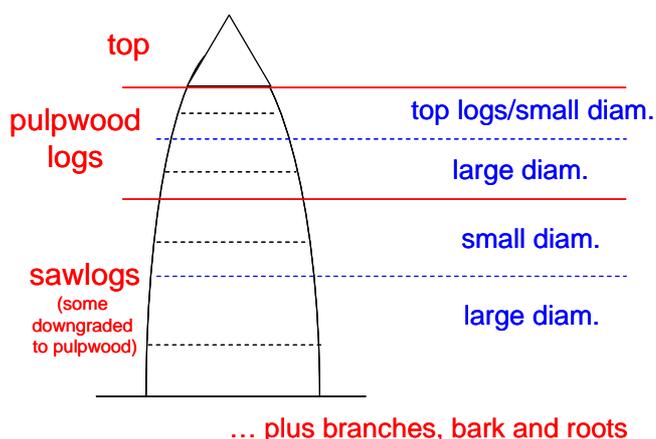
## 5.4 Large-size Resource Database with internode data from all plots

### The stands and trees

For the simulation of the large-scale Västerbotten Resource Database, no identification of most influential variables and selection of representative stands were made. A limited number of insignificant or untypical plots and trees were, however, removed. 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

A tree consists of root, stem (wood and bark), branches and leaves/needles. To the left in *figure 17*, the woody part of the stem is divided into top (often left in the forest), pulpwood logs and sawlogs, according to their main current use. To the right, these current typical log classes are further divided into sub-parts, such as small and large diameter sawlogs, as a basis for a discussion on possible alternative use.



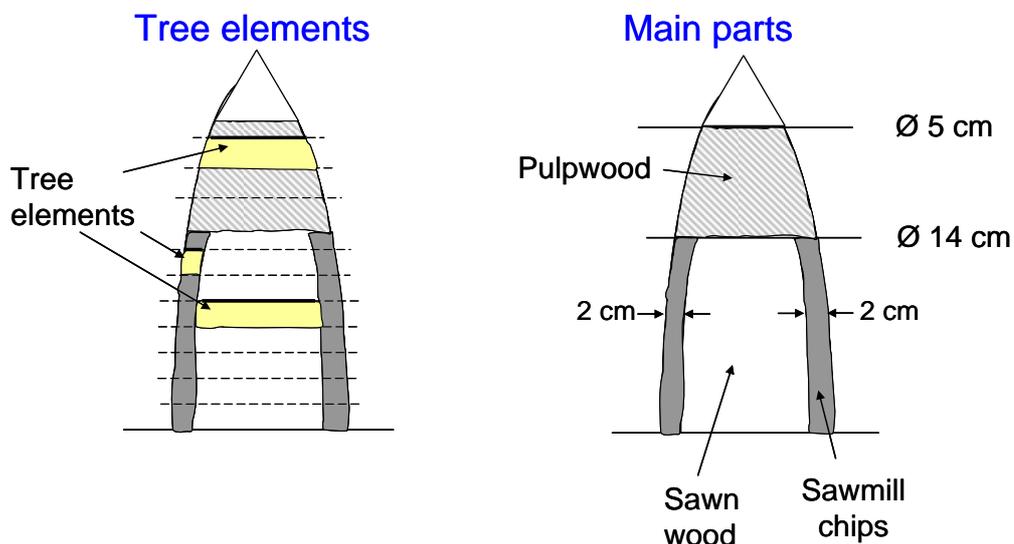
**Figure 17.** The wooden part of the stem is divided into parts according to their current main uses in the industry: Tops (often left in the forest), pulpwood logs and sawlogs of different dimensions. Allocation is, however, flexible and for analysis of current and future alternative uses, data on properties and volumes should be available also for smaller parts of the stem.

The allocation of the various parts of the trees to different products shows a high degree of flexibility. This is true already today and it may become more accentuated in the future. Downgraded sawlogs are used as pulpwood. Products and mills compete for some parts of the stems, and the outcome depends of varying price relationships, new technologies and differences in local operation costs. Logs indicated as pulpwood in the figure, especially the small diameter top logs, may be used for bio-energy, but sometimes even sawlogs are. For full flexibility in the comparison of different allocation strategies, data on properties and volumes have to be available for smaller parts of the stem than the current log sizes. In this example of a large-size Resource Database, the trees have been divided into small elements, representing internodes of annual longitudinal growth. These elements may then be “reassembled” into longitudinal stem pieces of arbitrary lengths, representing various cross-cutting and allocation alternatives.

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

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.

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.

In this example, properties are only estimated for the woody part of the stem with diameters of interest for the wood and fibre based industries. Volumes and masses may be estimated also for other parts of the tree (top, branches, bark and root), for estimation of carbon content, heating value, etc.

## **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 on evaluation. The reason to show the two examples, the small-scale and the large-scale Resource Database, is to illustrate different possibilities when using various sizes 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 tens 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, the database 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: a pine tree with the following characteristics as defined from the inventory data:

*Data on the stand/plot:*

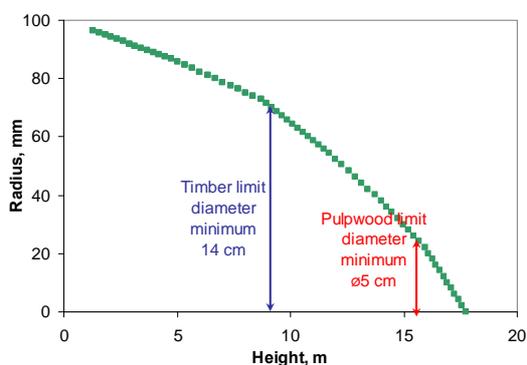
- Latitude 64,8 °
- Longitude 20,3 °
- Altitude 180 m
- Temperature sum 930 (estimated according to Morén et al 1994)
- Site index P20
- Age 74 years (average estimated from 6 sampled trees)

*Data on the tree:*

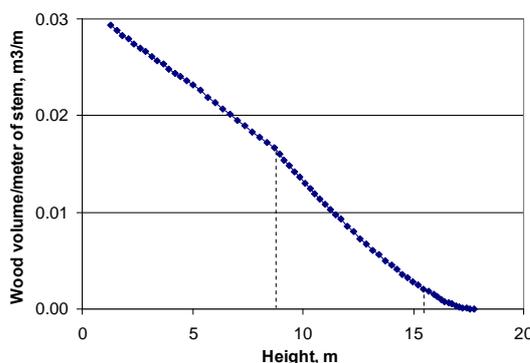
- Species: Scots pine
- Diameter<sub>BH</sub> 214 mm on bark, 193 mm under bark
- Tree height 17,9 m (estimated by SLU)
- Age<sub>BH</sub> 66 years (estimated by SLU)

### 6.2 Size and shape of stem

Figure 20 shows the estimated total height and taper of the stem of the pine tree selected for illustration, as estimated with the procedures and models described above. Each green point indicates the height above ground of a whorl and the radius of the stem at the whorl. (Local deformations at the whorl are not accounted for.) The longest internodes are found between 5 and 15 m above the ground. The assumed minimum pulpwood diameter and minimum sawlog diameter are also indicated.



**Figure 20.** The stem radius versus the height above ground at each whorl for the selected pine tree. The timber and pulpwood limits of Ø14 cm and Ø5 cm are indicated.



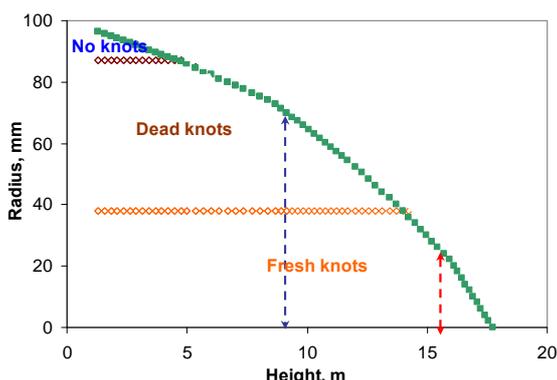
**Figure 21.** The wood volume per meter of stem versus the height above ground at each whorl for the selected pine tree. The timber and pulpwood limits are indicated.

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

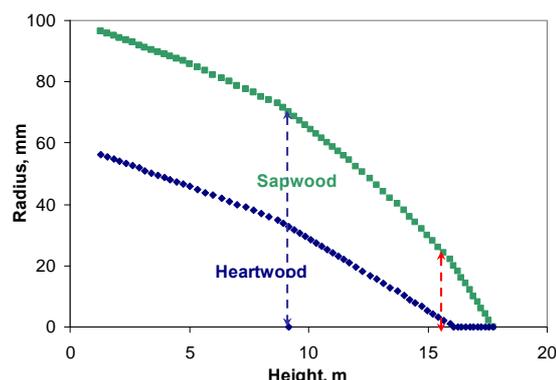
The straightness of the stem is not simulated at this stage. It would in principle be possible to allocate some crookedness at certain locations along part of the stems based on statistical models, provided that the number of trees is large enough, using for instance the methodology of Macdonald et al., 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, using models of (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 (not shown). In *figure 23* the extensions of heartwood and sapwood stem are indicated (Wilhelmsson 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.

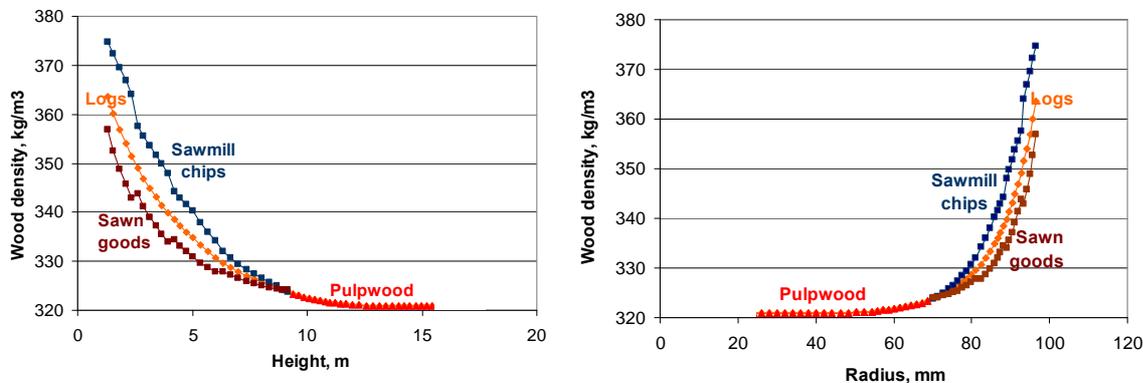


**Figure 23.** The extensions of heartwood and sapwood versus the height above ground at each whorl for the selected pine tree. The diameters 5 and 14 cm are indicated

Rot and other wood defects are not simulated. If the number of trees is large enough, it would in principle be possible to allocate rot in some of the stems based on statistical models, with the highest probability close to the ground.

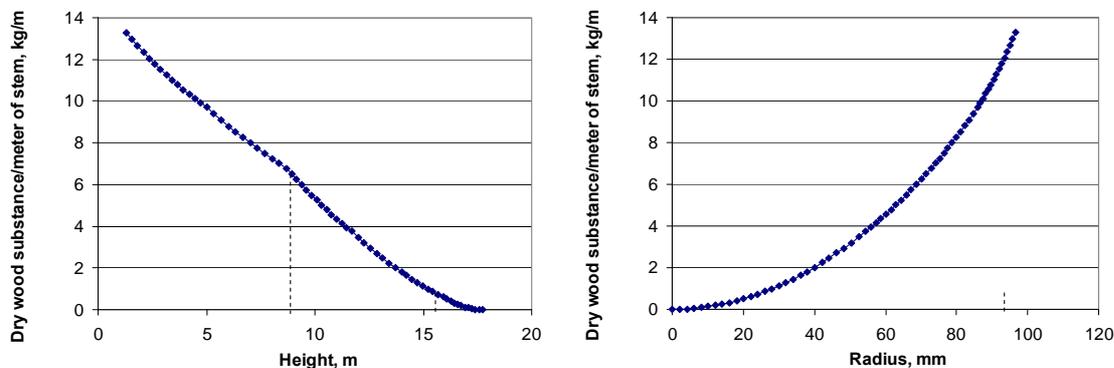
*Figure 24* shows the estimated wood density for the internodes along the stem (density of air-dried wood). To the left, the density is shown versus the height above ground (forest perspective), to the right versus the diameter (industry perspective). Averages for the full stem/log cross-sections are shown for all internodes with a diameter  $> 5 \text{ cm}$ , the limit below which we consider the material not useful for the fibre industries. The part of the stem with a diameter  $< 14 \text{ cm}$  (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 instead was to be used 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.



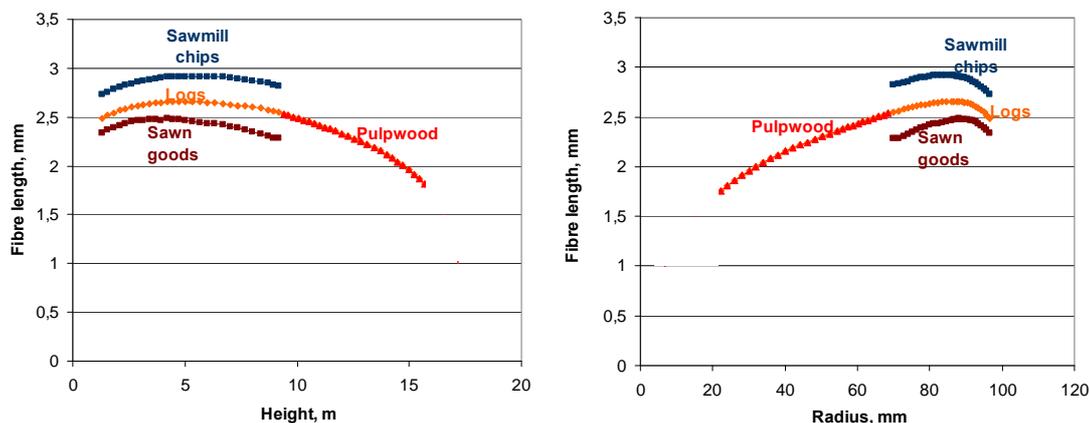
**Figure 25.** The dry substance/m (air-dried) versus height above ground (left) and versus radius (right) for all internodes.

### 6.4 Fibre properties

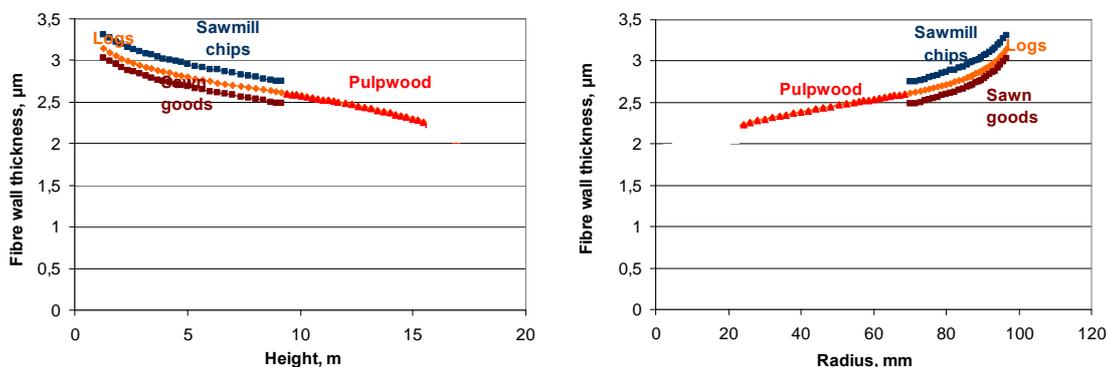
*Figure 26 and 27* shows the fibre length and fibre wall thickness in the same way as the wood density was shown in *figure 24*, using models of (Lundqvist et al 2002; Lundqvist et al 2005). The figures illustrate that the fibre dimensions are quite different among wood used for pulp production: common 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.

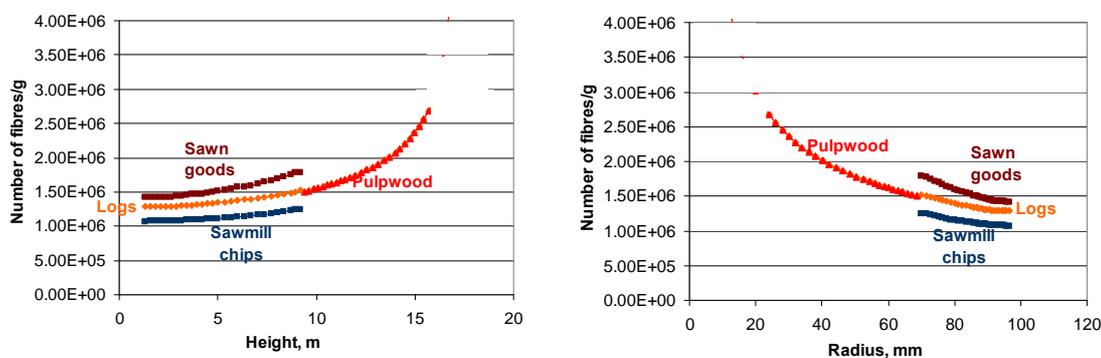
Also fibre properties closely related to pulp and paper properties are included in the database. As an example, the number of fibres/gram is presented in *figure 28*, showing that pulpwood may have more than double the number of fibres per gram as compared to sawmill chips.



**Figure 26.** Fibre length versus height above ground (left) and stem radius (right) for all internodes. Graphs are shown for full cross-sections representing pulpwood logs and sawlogs, as well as 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 representing pulpwood logs and sawlogs, as well as 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 representing pulpwood logs and sawlogs, as well as for what may become sawn goods and sawmill chips.

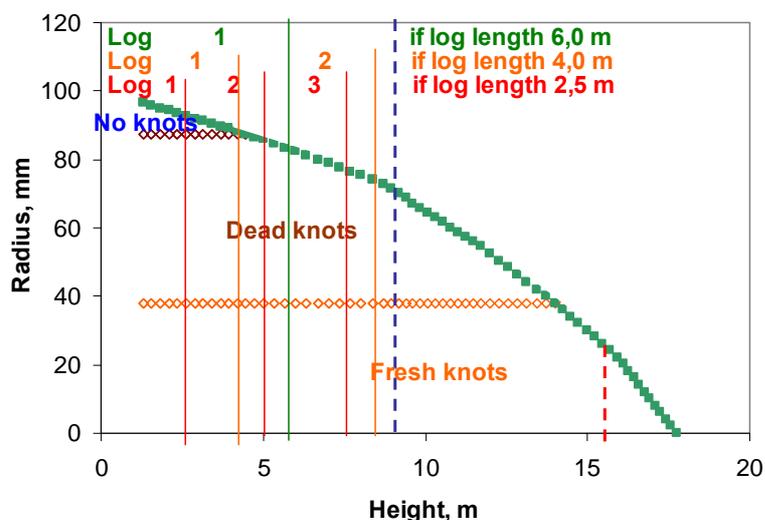
## 7 Examples of use

Some examples are shown to illustrate how data from mapping of resources with Forest Resource Databases 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 product oriented tree components including full cross-sections, such as poles, the fibres in pulpwood logs, etc., the estimate for the full component will be as good as the property estimation. For other product oriented components, such as sawn products and sawmill chips, the comparison will be approximate. One reason is the simplification that sawmill chips are produced from the outermost 2 cm of wood all along each sawn log. In reality, the longer the logs are, the more material in the larger diameter end of the log will become sawmill chips, as the sawing pattern is governed by the small diameter end.

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 types shown in *figure 20-28*, but for more properties, may be extracted from the Forest Resource Database. Data may be extracted for large numbers of trees and logs and used to evaluate different cross-cutting strategies within a region, addressing needs of specific mills and products in the optimisation of wood and fibre allocation.



**Figure 29:** Illustration of cross-cutting of the stem of the pine tree into logs of different lengths.

Tools for optimization of cross-cutting based on other approaches have been developed for instance by Skogforsk and are commercially available for planning and harvester operation.

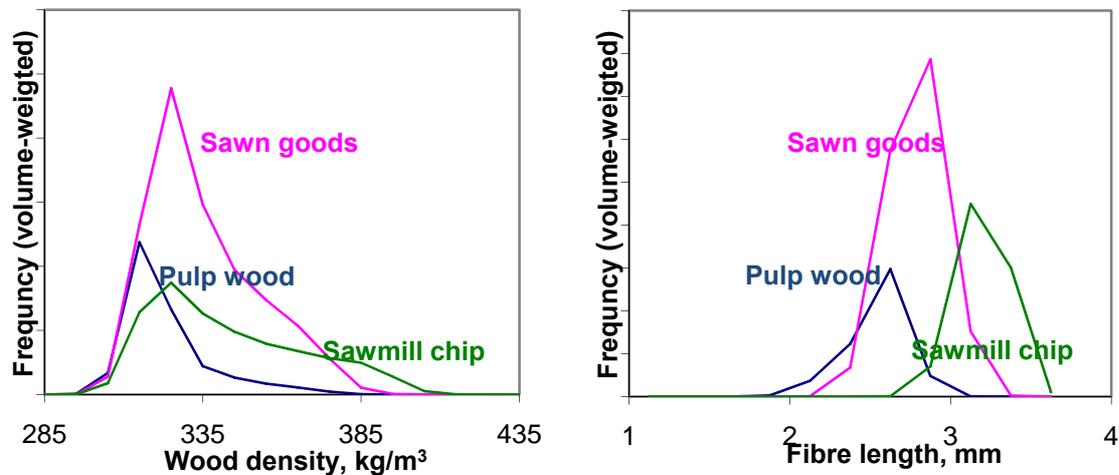
## 7.2 Properties and volumes of specific raw materials

A first issue in the selection of raw materials for production of specific products is often the wood species, due to differences in properties of wood and fibres, appearance, processability or other factors. In this example, only wood and fibres from pine will be dealt with, to reduce the complexity of the illustration, emphasizing fibre length for materials used for pulping and wood density of timber for sawing.

The data in the Forest Resource Database may be refined and turned into applicable information with use of standard database software. Materials of different origins and properties may be identified through the application on the database of different sets of selection criteria. Data on volumes and properties of these very materials can then be extracted from the database and used for various calculations and comparisons. Several commercial database softwares are available for this, offering a broad spectrum of functionalities. Practical examples of selection criteria relevant for the allocation to specific mills and products are related to log diameter, tree species, ages, growth rates, location in tree, etc. and various combinations of these. When materials fulfilling the different criteria have been identified, averages and statistical distributions for properties may be calculated, as well as volumes. The results may be compared by statistical means as well as with visual illustrations. Materials with similar properties may be merged to achieve larger volume flows of suitable raw materials to specific products at regional mills. This can be done for all the existing materials of the forest or, by looking at the cutting classes of each stand/plot in the database, for the material available for harvesting only. Four examples are given below.

### Wood in stands ready for final cutting

*Figure 30* shows the wood density and fibre length distributions estimated for all stands ready for final cutting in the Västerbotten pine resource, but divided into 1) pulpwood logs (above the timber limit/timber height), 2) sawmill chips and 3) sawn products. The figure is not produced 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. The pine trees ready for final cutting were selected by application of selection criteria for tree species and cutting class. The data on the tree elements were used to calculate statistical distributions for pulpwood, identified by selection of all tree elements (internodes) of these stems with a diameter of 5-14 cm, and for sawn goods and sawmill chips from the parts 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 of the specified class available in the specified types of stands. The distributions for wood density are shown to the left and for fibre length to the right.



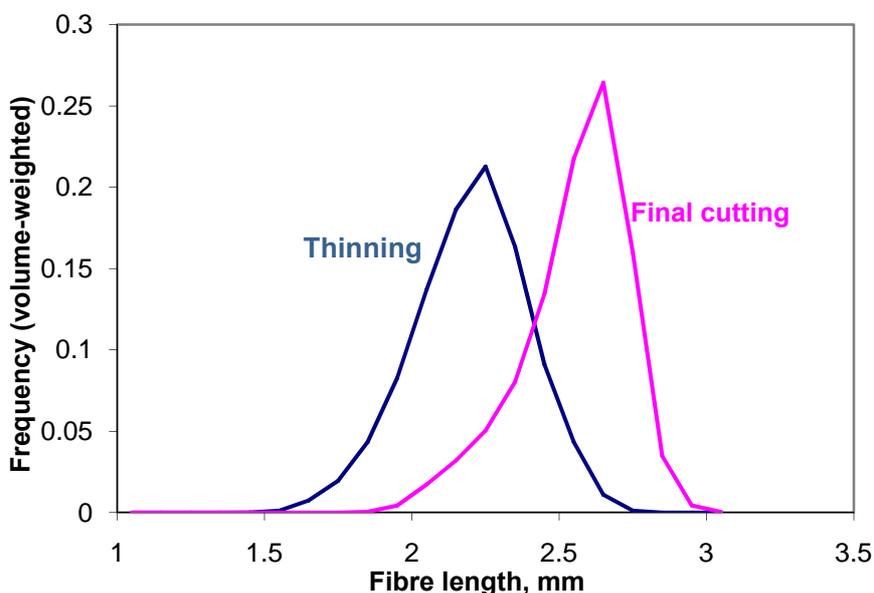
**Figure 30.** Statistical distributions for wood density (left) and fibre length (right) for pulpwood, sawn goods and sawmill chips from final cutting. Timber limit 14 cm. The areas below the graphs represent the volumes of the different wood classes, estimated from the simulated trees.

The differences shown in the figure between pulpwood and sawmill chips regarding fibre length and in wood density, which reflects similar differences in fibre wall thickness, are already today exploited by some pulp and paper mills to improve properties of specific products. There are also other differences within each species which may be exploited, such as age of tree, growth rate, dimensions and part of stem, if economically feasible. Examples related to European spruce resources and paper from thermo-mechanical pulps are given in (Lundqvist et al 2003c) and (Persson et al 2003).

#### Wood in stands ready for thinning and final cutting

One sometimes useful and economically feasible way to do this is to distinguish between pulpwood from thinning and from final cutting: When a thinning is performed, all pulpwood from the stand is handled as one common class of wood. When making a final cutting, one class of wood is formed with all pulpwood logs. This way segregation of logs in the forest or elsewhere is avoided and the cost is kept as a minimum. *Figure 31* illustrates the estimated statistical distributions for fibre length of pine pulpwood from thinning and final cutting in Västerbotten. The difference between the averages is about 0,35 mm.

With this type of information about fibre length complemented with data for other properties in the database, it is possible to judge on the expected effects on pulp and paper, if such segregation between pulpwood from thinning and final cutting is applied, and to compare it with other allocation strategies. More detailed examples are shown in (Lundqvist et al 2009), including more fibre properties, as well as both spruce and pine and comments on volumes available.



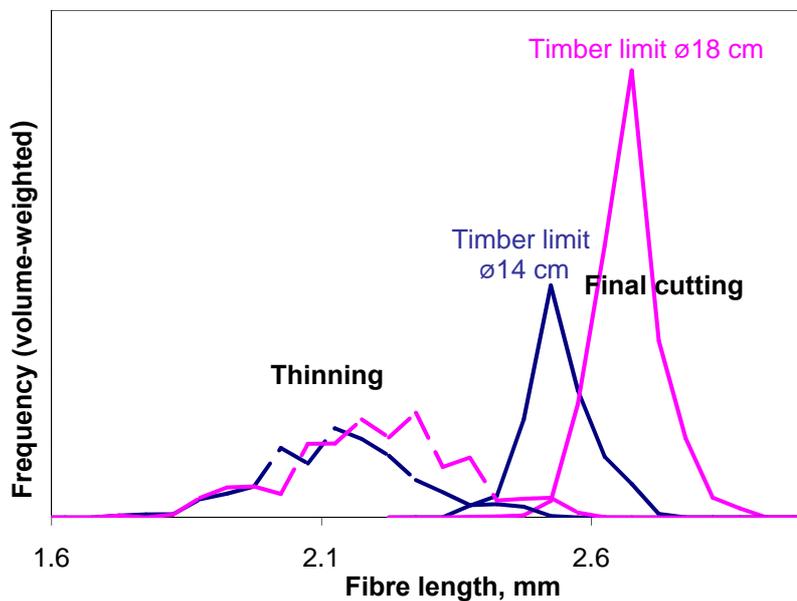
**Figure 31.** Estimated difference in fibre length in Västerbotten between pine pulpwood from thinning and final cutting, in average about 0,35 mm.

Figure 31 illustrates differences in properties between wood from thinning and final cutting, but not in volumes. Looking at volumes, it is important to consider not only the existing volumes in the resource, but also the difference that on final cutting, most trees are harvested, while on thinning only part of the trees are removed, depending on the thinning strategy. In Västerbotten, most stands are thinned only once and then about 30 % of the trees are removed, and that is valid for all size classes of trees (Nordmark 2009). When estimating the wood volumes which actually may be delivered to the industry, the graph representing thinning in figure 31 has to be scaled down to about 1/3 of the area shown in figure, while the graph representing final cutting will remain about as it is.

#### **Interdependence between pulp mills and sawmills**

The fibre and the solid wood industries are obviously closely linked to each other. The properties of wood and fibres are affected in both industries 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 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.

Further, in figure 32 now discussed, the distributions are weighted so that the area below each curve represents the volume actually available for the industry, bio-energy, etc. of each type of wood, considering the fact that only about 1/3 of the material of stands available for thinning is harvested.



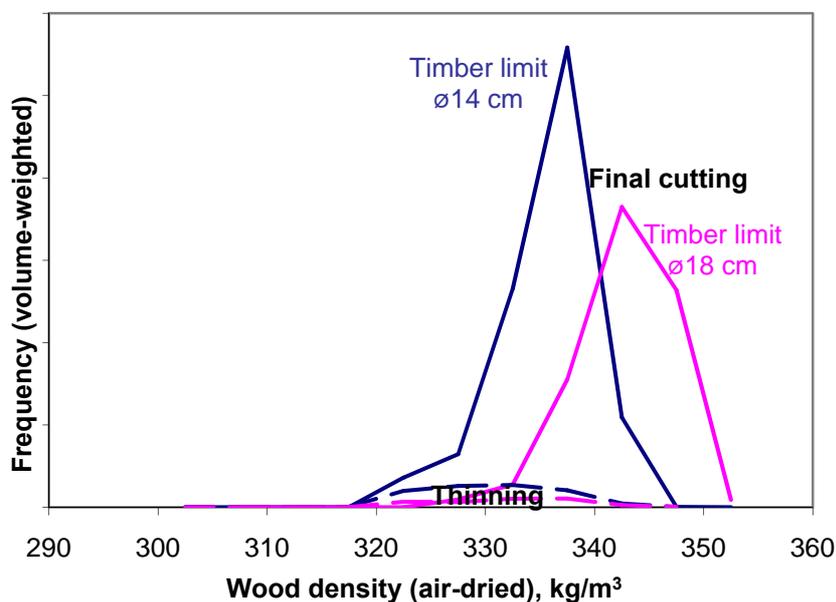
**Figure 32.** Statistical distributions for the fibre length of the pulpwood from thinning and final cutting of pine, assuming two different timber limits: 14 and 18 cm, in the resource of Västerbotten. The areas below the graphs represent the wood volumes of the logs possible to harvest with the thinning strategy to be applied.

If the timber limit is increased, the sawmills will use less of the trees (less of the mid-diameter logs). The figure illustrates that this not only means that the pulp and paper mills will get a larger volume of pulpwood, but also that the average fibre length will increase for the pulpwood. The figure also illustrates that, in the Västerbotten resource, the volume of pulpwood harvested from thinning, with short fibres, is similar to the volume of pulpwood harvested from final cutting, with longer fibres, but with somewhat larger relative volume from final cutting at larger timber limit.

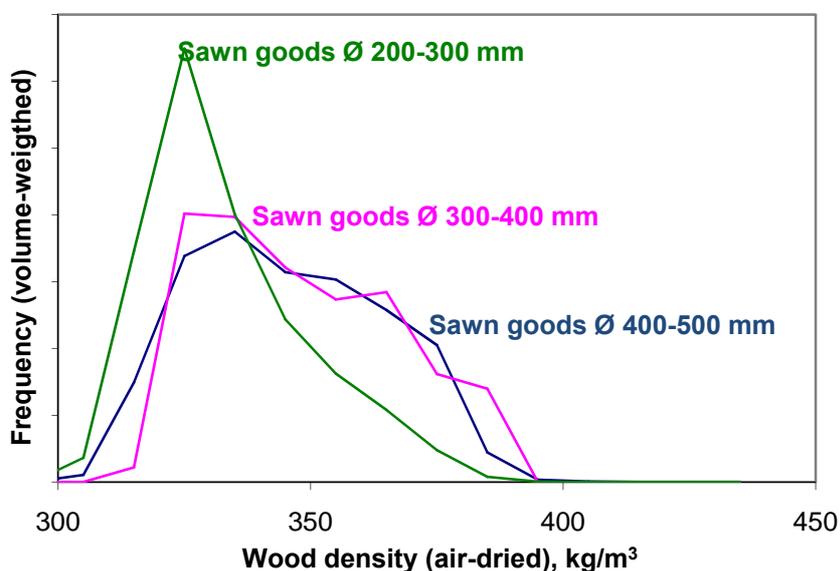
In *figure 33* the corresponding effects on the wood density of the sawn goods is illustrated. Also in this case, the area below each graph represents the volumes obtained from harvesting. The volume of sawlogs from thinning is obviously very small, especially if larger diameter logs are requested.

### Sawlogs of different diameters

*Figure 34* is addressing the properties of 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, which originate from slow-grown trees. It is of course possible to look closer into the database, applying other selection criteria, in order to identify these higher density logs and to include other property demands in the selection process.



**Figure 33.** Statistical distributions for the wood density of the sawn products (averages) from 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.** 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.

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 different projects.

## 8 Conclusions and continued work

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### Conclusions

Proper allocation of wood raw materials to different products and processes has a strong impact on sustainability, influencing environment, economy and society. It is relevant from global to regional scale as well as for individual growers and producers, and from both a policy and technology perspective. 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. The report presents a concept for Forest Resource Databases to provide such information on properties and volumes of stands, trees and product-oriented parts of trees in forest resources. Such databases have previously been built for geographic areas of different sizes depending on the application: from regional wood supply areas of mills to the softwood resource of Sweden.

The general concept of Forest Resource Databases offers a versatile way to map existing resources in the forest and to compare alternatives in allocation to mills and products. Available volumes and a broad spectrum of wood and fibre properties relevant for different forest-based products may be described in an integrated way. This may be done for entities of interest for mills and forest owners, such as for different types of pulpwood logs, sawlogs and sawmill chips. It can be done for all materials available in the forest resource as a whole or for materials from forest stands ready to harvest. Materials of similar properties may be aggregated to create flows dedicated to specific mills and products, 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 different chains: 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.

Forest 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 Innventia. 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 useful for different purposes may be built based on large scale or limited scale sets of forest inventory data. The versions designed for the EFORWOOD project offers different approaches in this, depending on data available in the region of interest and issues to study. The experience of Innventia is that it is normally possible to

transform existing inventory data to formats useful for simulating the resource, at least to illustrate basic effects of various strategies in allocation and processing.

### **Actual and possible applications of Forest Resource Databases within EFORWOOD**

It would have been 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 was not possible due to limitations in time and funding, but methods to map volumes and properties of forest resources and to optimize allocation have been tested and illustrated in regional case studies. Two product oriented case studies have also been performed to illustrate sustainability effects of allocation, starting with the forest resource and including also consequences along the production chain towards end-users and recycling.

### **Further possibilities and needs**

Innventia is building regional Forest Resource Databases and is using them in different research projects and in contract work together with research groups and companies. Databases are now being built for parts of another country, using existing models for Norway spruce and Scots pine. It should now be possible and very interesting to apply the EFORWOOD approach in similar projects for resources of other important wood species in other regions, such as Sitka spruce or hardwood species, as well as for the tree species simulated so far but growing under other growth conditions, in cooperation with researchers in the specific 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.

It would particularly be valuable to apply the approach in optimization including allocation and processing along the fibre, wood and bio-energy chains, in order to improve the methods and widen the experiences from their use.

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.

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## 10 Innventia Database information

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**Title**

Forest Resource Databases - a concept for product-oriented mapping of properties and volumes in forest resources

**Author**

Sven-Olof Lundqvist, Thomas Grahn

**Abstract**

This report presents a concept “Forest Resource Databases” for mapping of properties and volumes of forest resources. In such a database, forest inventory data about stands and trees are complemented with estimated information about properties and volumes of trees and parts of the trees: logs for various uses with different dimensions and properties, parts of logs which will become sawn products and chips, etc. These estimations result from simulation, using inventory data or data from harvesters as input data to models. The resource database offers a virtual representation of the available resource, providing a basis for optimal allocation of wood and fibres. The size of the database, the properties included and the level of detail in the description of the trees and parts of trees are adapted to each application. The report describes the general concept previously developed at STFI-Packforsk, now Innventia, as well as an expanded version for wider applicability from the EFORWOOD project, with the aim to deal with all major wood-based production chains in an integrated way. Many examples are given.

**Keywords**

Fibre properties, forest, optimisation, paper, Picea, Pinus, pulp, sawing, simulation model, simulation, wood properties

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