EFORWOOD
Tools for Sustainability Impact Assessment

Mapping of properties in forest resources and models used – Results from EFORWOOD Case Studies in Västerbotten (North Sweden), Baden-Württemberg (Germany) and South Scotland

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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

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PU	Public	X
PP	Restricted to other programme participants (including the Commission	
RE	Restricted to a group specified by the consortium (including the Commission	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Mapping of properties in forest resources and models used

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Acknowledgements

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The immediate results presented in this report have been achieved within the project EFORWOOD, funded by the 6th Framework Programme of the European Commission and by companies and organisations in many European countries. The funding parties are acknowledged for this.

The authors also want to thank colleagues within the EFORWOOD project for inspiration and contributions, as well as co-workers who have made crucial efforts to achieve the results presented.

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1 Summary

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 input material is allocated to a process, this will normally lead to increased use of material, energy, chemicals etc. per unit product produced. In addition the product quality i.e. functionality, durability and customer satisfaction may be compromised.

Important prerequisites for successful allocation are:

1. Information about the volumes and properties of the wood raw materials available in the forest resource
2. Knowledge about raw material properties needed or preferred for production of various products in industry and costs involved in using non-preferred materials
3. Tools to match what the mill wants with what the forest is offering.
4. Knowledge of market prices, competing industry branches and competitors.

This report relates to issue 1: Mapping of properties in forest resources to support optimal allocation of wood to various products and also efficient processing. The mapping is achieved through simulation with models for properties of wood, fibres and branches/knots. Four examples are given, based on regional case studies within EFORWOOD, illustrating a number of approaches designed for different applications:

The first two examples are built on data from Västerbotten in the north of Sweden, the other two from studies in Germany and Great Britain:

1. STFI-Packforsk (now Innventia) has built “Regional Resource Databases” for the forest resource of Västerbotten. In these databases, conventional inventory data are complemented with estimated properties of trees and parts of trees related to products. A virtual representation of the available forest resource is provided, including also property and product perspectives, useful in planning but also in operational applications. Volumes and properties of wood and fibres obtained when applying different selection approaches on the Västerbotten forest have been analysed.
2. Skogforsk has applied software for bucking simulation and log characterisation on stands selected for “Eforwood Västerbotten case”. The bucking simulation mimics ordinary cut-to-length harvesting including market pricing of different sawlogs, pulpwood and energy wood when applicable. It also includes common downgrading of logs caused by stem faults. Finally the properties of different logs have been characterised by models for predicting some stem, wood and fibre properties.
3. FVA has matched inventory data and quality classes of Baden-Württemberg, to estimate grades of saw logs from spruce in the resource. Available volumes of

sawlogs are derived for conventional bucking to stem length or standard length 5 m. The simulation aimed at detailed grading of logs according to threshold values for stem taper. Grading standard EN 1927-1 (2008) was applied to set the threshold values for 4 quality grades A (highest grade) to D (lowest grade) for each of the 9 German standard mid-diameter stem classes according L0 to L6.

4. Forest Research has made a case study in Craik Forest in South Scotland. The growth of Sitka spruce under different management regimes and the volume of timber to be cut between 2005 and 2030 have been forecast. In addition predictions have been made of the stem form and wood stiffness of the trees within the stands to be harvested. These predictions are based on empirical models of tree growth and properties based on extensive surveys of growth, straightness and wood stiffness across the UK. The final result is a prediction of the volumes of logs that will become available for different end uses (structural timber, pallet wood, and biomass).

Mapping of properties in forest resources with the use of models and simulation has previously been done for some regions and wood species. The results from the current case studies show its usefulness also in other regions and for a wider variety of applications, linked to optimal use of forest resources and improved sustainability in different forestry-wood chains.

2 Introduction

2.1 Importance of good allocation of wood raw materials

The general objective of EFORWOOD is to develop a tool, ToSIA, for the analysis of sustainability effects in society and industry of forest related activities in a broad sense, covering effects of operations all along the chain: from the establishment of a forest to the use and recycling of the products, including wood-based and fibre-based products as well as bio-energy. Towards the end of the project, ToSIA will also be used to illustrate total sustainability effects of a number of scenarios of different natures and scales.

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

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 means more transportation. In addition the quality, product functionality and customer satisfaction may be compromised.

In EFORWOOD, the issues related to assessment of wood and fibre properties in the forest and along the production chains and suitable allocation of materials to various processes and products are mainly dealt with in workpackage 3.1 “Quality Assessment and Allocation”.

2.2 Prerequisites for good allocation

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

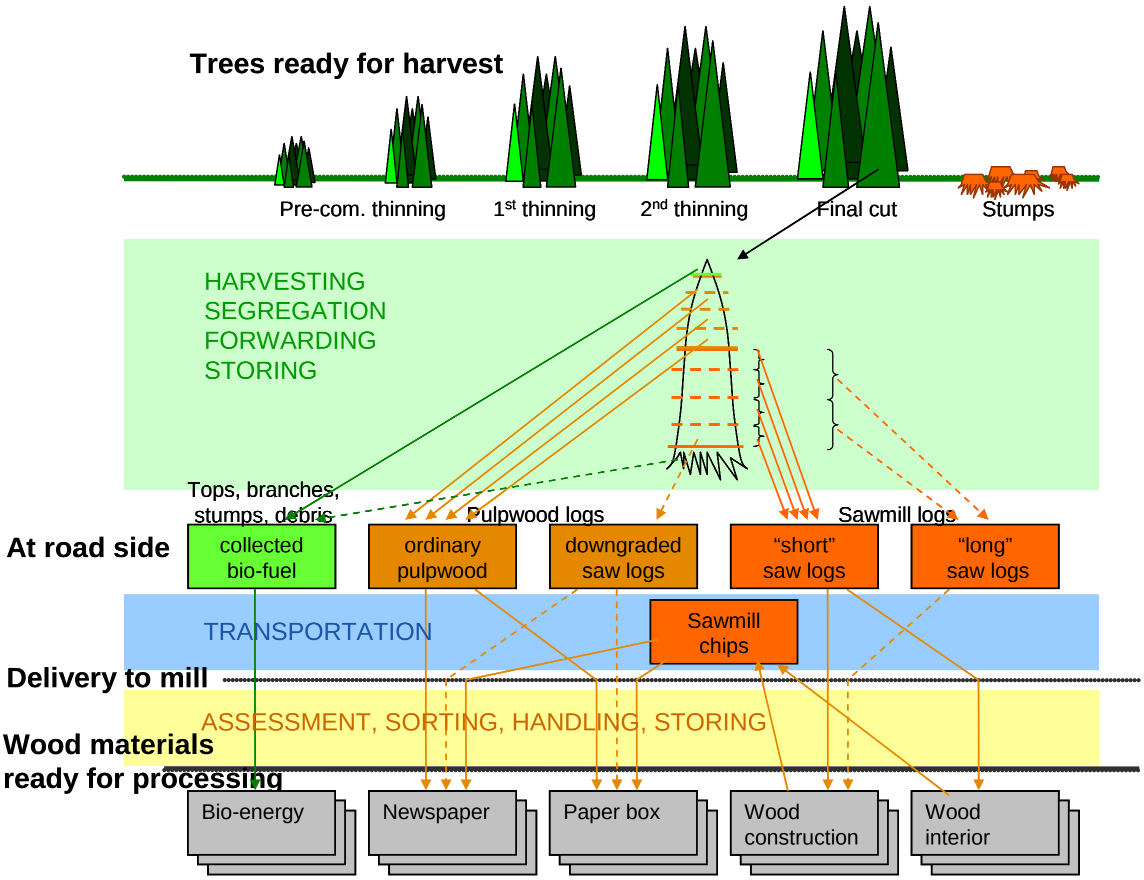

Figure 1. Typical allocation of materials from final cutting of a softwood stand.

Important prerequisites for successful allocation are:

1. Information about the volumes and properties of:
   + the wood raw materials available for harvesting in the forest resource
   + the harvested materials ready for distribution to different mills and products
2. Knowledge about industrial use:
   + raw material properties needed or preferred for production of various products in the processes of the mills
   + costs involved in using non-preferred materials
3. Procedures and tools to match what the mill want with what the forest is offering, for high quality or acceptable quality at minimal cost.

This report relates to issue 1. Four examples of model-based approaches for improved property information and wood allocation are given. The examples originate from work in regional case studies of EFORWOOD within workpackage WP3.1.

Product and property demands, the second issue, have been generally described in the deliverable D3.1.2 “Key products of the forest-based industries and their demands on wood raw material properties” (Lundqvist (editor) 2007b).

2.3 Case studies and results presented in this report

The EFORWOOD project includes a number of regional case studies. Three of these studies have provided the basis for developing ToSIA and testing it from different perspectives:

- Västerbotten (Scandinavia), applying a forest resource perspective:
  The forest resources of Västerbotten are used to produce a set of key products and these products are followed all their way to users in different countries and recycling
- Iberia, applying a consumer perspective:
  A set of key products consumed in Spain and Portugal are followed back to the forest resources in different countries from which they were produced
- Baden-Württemberg, applying a regional perspective:
  Products from the forest are allocated to three different production lines with a known consumption of raw material and production of key products. Material flow in Baden-Württemberg is considered on a net-balance approach. Surplus of production from the forest which is not used in Baden-Württemberg itself is considered as export process, missing raw material for a consecutive production phase is brought into the regional system by import processes.

These studies have been complemented with further case studies. One of these has provided results to the report:

- South Scotland, applying a perspective of matching the forest resource within a single forest with the local primary processing industries. This allows testing of different allocation strategies on key economic, environmental and social indicators.

Two of the examples presented below are based on the Västerbotten case, one on the Baden-Württemberg case and one on the South Scotland case.

Figure 2. Location of the regions of the case studies on mapping of forest resources.

Approaches in allocation

Selection of wood for use in different industrial applications may be done at different steps along forestry-wood chains. Purchase of standing trees or harvested wood is definitely an important part of it. In this report, the results of physical segregation of trees and aggregation of logs into raw material flows for various uses will be emphasized and it will be demonstrated how the application of different criteria for segregation and aggregation affects volumes and properties obtained, based on different types of information.

The most selective result may be obtained by using information about the properties of individual stems already in the forest as a basis for bucking them into parts for specific purposes. The logs may then be aggregated into specific wood classes, which are channelled to the processes and products they are aimed for. Selection of individual logs for specific properties may also occur further down-stream, for instance at the woodyard of a sawmill. This log-wise approach is generally more selective but also more expensive than approaches more oriented towards selection and handling of collectives (batches) of logs with similar properties. Log-oriented selection is therefore mostly used in production chains with higher value added: commonly for sawn products but seldom for pulp and paper.

The examples presented in this report from the different case studies illustrate different types of allocation. From the Västerbotten case, log-oriented selection for sawn products is dealt with in the case study performed by Skogforsk and presented in chapter 5 and more batch-oriented selection for pulp and paper in the case performed by STFI-Packforsk, presented in chapter 4. The example from the Baden-Württemberg case, see chapter 6, describes an preliminary approach of classification of roundwood which also is oriented towards sawmill applications, while the South Scotland case includes materials for both sawn products and bio-energy, see chapter 7.

Wood allocation and sustainability

The examples on selection for better materials to pulp and paper products in chapter 4 and for sawn products and bio-energy in chapter 7 also provide bases for two other EFORWOOD case studies presented in the report “Illustration of sustainability effects of allocation” (Lundqvist et al 2009 and EFORWOOD Deliverable 3.1.9). In that report, sustainability effects are compared for different alternatives in wood allocation.

In the first case study, forest resources in Västerbotten are used to produce kraft liner, which is then exported to the European continent, used in corrugated boxes, which in turn are used and recycled. Improved allocation from the forest provides more uniform and suitable wood and fibres, which in turn results in improved kraft pulp. This offers opportunities to optimise all along the chain from tree to recycled product. Some optimised alternatives are defined and effects on sustainability indicators compared.

In the second case study, forest resources in South Scotland are mapped according to three of the key factors determining their most suitable end-use. The first segregation is by top diameter with logs needing to have minimum top diameters to be suitable for pallets (14-18 cm), or saw timber products (>18cm). Bio-energy material has no log size requirement. The second characteristic for the sawlog material is stem straightness with a designation based on whether the stem curves more than or less than1 cm in a metre length of log (“red” and “green” logs respectively). The final designation is whether the “green” logs are suitable or not for construction grade timber and this is based on the predicted stiffness of the sawlog. Only material having a mean *MOE* (Modulus of Elasticity) greater than 8 GPa, and with 95% of the material having *MOE* values greater than 5.4 GPa, being acceptable for construction timber at C16 (CEN, 2003).

3 Case Västerbotten, approaches applied and models used

3.1 The Västerbotten Case

The Västerbotten case study is designed to represent the boreal forests of Europe and their typical forestry-wood-chains (Valinger et al 2008). Västerbotten is situated in the north of Sweden, see *figure 3*. The region ranges between the latitudes 63.6 and 66.4, close to the polar circle. It spans across Sweden from the Baltic Sea to the mountains at the border towards Norway, reaching and passing the altitude of the tree limit. The total forest area of Västerbotten comprises 3179000 ha.

Figure 3. Location of Västerbotten within Sweden

The forest is characterized by stands dominated of pine (*Pinus sylvestris* L.), spruce (*Picea abies* (L.) Karst.), or of mixtures of the two species. Many stands include some broadleaved species, most commonly birch (*Betula spp*.). 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). The stands in the region are mainly even-aged and the dominating harvesting schemes are using the highest technology available at present, i.e. harvesters and forwarders.

The total annual increment of Scots pine is 4 610 000 m^3, of Norway spruce 3 310 000 m^3, and of birch 2 000 000 m^3. The mean annual increment is 3,0 m^3/ha. The annual cutting area on forest land is 112 000 ha with a mean cut of 70 m^3/ha. The mean annual cut for Västerbotten during the years 2001-2005 was 7,8 million m^3/year. Approximately two thirds of that volume is cut in the coastal region.

The proportions of forest land divided on ownership categories in 2005 were 35,3 % public forests, 21,8 % private companies, and 42,9 % nonindustrial private forest owners.

The main deliveries from forest to industry include saw logs, pulpwood and fuel wood of pine, spruce and birch, forest wood chips, and stumps. The main types of industries supplied from Västerbotten are sawmills, pulp and paper mills and CHP plants. Examples of goods produced by the forest wood chain starting in Västerbotten are kraft liner for packaging, fine paper, wooden houses, gluelam beams, windows, furniture, planed goods, particleboards, plywood, sawn wood, pellets and bio energy.

More information about the forests of the region is found in (Valinger et al 2008).

3.2 Two approaches to support optimal allocation of wood raw materials

Two approaches using models and simulation to estimate key properties of wood, fibres and knots have been worked upon based on data on the forest resource of Västerbotten:

- STFI-Packforsk has built “Regional Resource Databases” to map the properties of the resource, one large-scale based on all inventory data available, one small-scale database including representatives for all major types of forest stands in the region. In the databases, traditional inventory data have been complemented with estimated information about properties and volumes of the trees and for different parts of the trees: pulpwood and saw logs, parts of saw logs to be chipped and sawn, etc.
- Skogforsk has applied software for bucking simulation (Arlinger et al 2004) and log characterisation on the stand database (Valinger et al 2008) selected for the “Eforwood Västerbotten case” by the Swedish National Forest Inventory. The bucking simulation mimics ordinary cut-to- length harvesting including market pricing of different sawlogs and pulpwood and energy wood when applicable. It also includes common downgrading of logs caused by stem faults. Finally the properties of different logs have been characterised by models for predicting some stem, wood and fibre properties.

The two approaches have been worked upon in order to throw light on mapping and allocation from different perspectives. The bucking simulation and tools for wood flow characterisation (Skogforsk approach) have been developed to support operational wood supply by logs from CTL-(Cut-To-Length) harvesters at the present wood market in Sweden. By altering pricelists and definitions of assortments this approach can also be used for tactic and strategic analyses to meet new and flexible customer demands. The STFI-Packforsk approach was in the first place developed for off-line use in design of allocation strategies, planning, etc. For instance to support a mill producing pulp grades with different properties in finding the best way to divide wood materials available in the regional resource and imported wood for production of the different grades. Or if the wood normally used for a specific grade can be replaced by other wood with similar properties on shortage or rising costs. More operational applications are, however, now being installed for estimation of properties of wood delivered to mills, of the chip mix now fed into the process and prediction of properties of the pulp from this chip mix. The approach may be introduced in steps to facilitate applicable in different countries.

The two approaches in Västerbotten are built on similar base facts thereby providing a basis for more efficient communication between industry and forestry. The inventory data used originate from a common source (see 3.3) and many of the models used for prediction of material properties are similar.

3.3 Inventory data used

Data on the forest resource of Västerbotten has been obtained from the Swedish National Forest Inventory (NFI) managed by SLU. The data material is based upon annual stratified sampling of plots. The sample plots are clustered in rectangular tracts. There are two types of tracts; temporary tracts which are only inventoried once, and permanent tracts which are re-inventoried with 5-10 years interval. The sampling mean error for the reference area is 2.7 % for forest area (ha) calculations and 2.2 % for growing stock (m^3) calculations for Västerbotten.

3.4 Models used

Many of the models used were developed within a joint project of STFI and Skogforsk called “Forest-pulp-paper” (Lundqvist et al 2003a). STFI had developed methods to sample and analyse detailed variations in wood and fibre property within and between trees and stands together with a group of pulp and paper companies (Hedenberg et al 1997; Hedenberg et al 1998) and the methods had been validated on stands from different regions. Skogforsk had similar experiences of detailed tree sampling and wood and fibre analyses together with SLU and AssiDomän Frövi (Duchesne et al. 1997; Wilhelmsson et al. 2000) and a good overview of the Swedish forest resource. The organisations joined forces to describe the properties and their variations in the Swedish forest, in order to create a basis to support more property and product oriented utilisation of the wood available in the industry.
In the project, 252 trees of Norway spruce and 120 trees of Scots pine were sampled from 42 spruce-dominated and 20 pine-dominated stands, representing latitudinal, site fertility and tree age variation of forest stands in Sweden. The STFI and Skogforsk routines were amalgamated into common instructions to secure compatibility and data quality (Arlinger et al 2001). Stand and plot descriptions, tree measurements, wood sampling and bark measurements were performed in the forest by Skogforsk. STFI managed the measurements of wood and fibre properties from the samples, including characterisation of growth ring patterns and contents of juvenile wood and latewood with image analysis (Olsson 2000), heartwood and basic density with X-ray tomography (Lindgren & Lundqvist 2000), fibre dimensions with STFI FiberMaster (Karlsson & Fransson 1999) and detailed radial variations of several wood and fibre properties with SilviScan (Evans et al 1995; Evans 2006). STFI and Skogforsk also compiled a joint database comprising all information from the stands, tree and wood samples, forming a statistic basis for development of models for predicting wood and fibre properties.

From these data, the variations were analysed and models developed in cooperation, in which work on wood properties were emphasized by Skogforsk (Wilhelmsson 2001; 2006, Wilhelmsson et al 2002) and fibre properties by STFI (Ekenstedt et al 2003; Lundqvist et al 2005). The common level of detail of these predictions of wood and fibre properties is cross-sectional averages along stems and logs. Later, more stands have been investigated in different countries and some models have been improved, i.e. for fibre dimensions (Lundqvist et al 2005), further detail has been added for industry applications (Lundqvist et al 2008) and models have been developed for further wood species. The different predictions of knot properties refer to (Björklund & Moberg, 1999, Moberg 2000, 2001 and 2006 and Moberg et al 2006).

For this type of simulation of property variations within trees, integrated sets of models are needed (Wilhelmsson et al 2004; Lundqvist et al 2005). Early in the EFORWOOD project, a workshop was arranged on mapping of properties in forest resources and to boost this work, STFI compiled a general scheme for such integrated models and simulations (Lundqvist et al 2007a). It is a generalisation of the integrated models used in the previously developed simulation systems STFI WoodSim and FiberSim (Grahn& Lundqvist 2008) mainly used for the paper industry but now expanded for simulation also of properties of wood and knots. A consistent set of variable names was also proposed, partly shown in *table 1*.

Skogforsk has developed a system for bucking simulation of stems and logs by CTL-harvesters including characterisation of stem, wood and fibre properties (Arlinger et al 2004). The bucking simulation software consist of three main components TimAn2/Aptan, Pri-analysis and additional SAS-software. The input needed is stand location (latitude, altitude), stand age (tree ages) and tree dimensions from any source of forest inventory, and defined industrial demands expressed by alternative pricelists or apportionment requirements. A comprehensive description of the models used in Skogforsk's tools for prediction of properties (characterisation) in the bucking simulation software is given in (Lanvin et al. 2008. Models in appendix 9). Some models, like green density of wood and bark have been preliminary published (Wilhelmsson & Moberg, 2004). Some additional, tentative models, have not yet been published.

Below, some of the most important models used in the Västerbotten case for estimation of properties of Norway spruce and Scots pine are compiled, emphasizing models for wood, fibre and knot properties. The variable names are given in *table 1*. Complete descriptions of the models are given in the referred publications. A study of the references is recommended before use, to better understand the prerequisites and

Table 1. Variables and units

Response variables		*Explanatory variables*	
FL =	fibre length, mm	D_h =	Diameter over bark at height h, mm(in knot models cm)
FW =	fibre width, µm	D_{BH} =	Diameter at breast height , mm (in knot models cm)
FWT =	fibre wall thickness, µm	D_{rel} =	D_h/D_{BH} (over bark)
		d_h=	Diameter under bark at height h, mm
		d_{bh}=	Diameter under bark at breast height, mm
		d_{rel}=	d_h/d_{bh} at height h (under bark)
WD =	wood density, kg/m^3	R_h =	radius of stem cross-section at height h, mm
WHW=	heartwood diameter, mm	N_h =	number of growth rings in cross-section at height h
WJUW=	juvenile wood diam, mm	AGW_h =	average growth ring width at height h, mm
WLWC=	latewood content, %	h =	height in tree of cross-section, m
KN =	number of knots	h_{rel} =	relative height in tree of cross-section ($0<h_{rel}<1$)
KD =	diameter of knots, mm	$h_{(llb)}$ =	height in tree to lowest live branch, m
KL =	length of knots, mm	CL =	crown length, from top to lowest live branch, m
KA =	area of knot, mm^2	alt =	altitude above sea level, m
		lat =	latitude, ˚, North
Index h	= height h	tsum =	day-˚C(In Sweden and for Norway spruce in Europe)
Index k	= number of whorl	AGE	mean total stand age
		SI =	Site index

assumptions behind the development of these models to judge their strengths and limitations for different applications. Some of these models have also been used in the Baden-Württemberg case. For models describing growth, taper, etc., references are made to the literature.

3.4.1 Taper, bark and annual rings and temperature sum

Taper = Diameter at height h	(Edgren & Nylinder 1949; Spångberg et al 2001)
Bark thickness at height h	(Wilhelmsson et al 2002; Hannrup 2004)
Number of annual rings at height h	(Wilhelmsson et al 2001; 2006)
Temperature sum at latitude, altitude	(Morén & Perttu 1994)

3.4.2 Wood, fibres and knots - Norway Spruce

Fibre properties

(Lundqvist et al 2005)

Fibre length:

$$FL_h = 0.86+2.20*[1-\exp(-N_h/29.35)] -1.55*\exp(-AGW_h/0.74) – 0.70*\exp(-h_{rel}/0.14) +0.00056*tsum \quad (1)$$

Fibre width:

$$FW_h = 32.57 +11.13*[1 – \exp(-R_h/5.75)] – 19.7*\exp(-h_{rel}/0.022) + 0.5*\ln(AGW_h)– 0.12*lat \quad (2)$$

Fibre wall thickness:

$$FWT_h = 6.02 – 0.058*lat – 0.21*AGW_h + 0.75*[1 – \exp(–R_h/4.96)] – 0.28*\exp(–h/3.10) \quad (3)$$

Fibre coarseness (FC_h) and other properties are calculated

Wood properties

(Wilhelmsson et al 2002)

Wood density:

$$WD_h =304.3+10.4437*sqrt(\ln(N_h)-444.13*(d_h^{1.5}/(N_h*tsum)) +0.2957*tsum/(0.5*d_h/N_h+2.3) \quad (4)$$

Hearthwood diameter:

$$WHW_h =-15.6 + 0.2149*d_h*\ln(N_h)-0.00124* d_h*(\ln(N_h)^3 \quad (5)$$

Juvenile wood diameter:

$$WJUW_h = 0.998*d_h*N_h^{(0.592*(\ln(\ln(u))-\ln(\ln(N_h))}$$

Where u=15 if N_h>15; and u=N_h if N_h<=15 (6)

Latewood content:

$$WLWC_h = 6.1-9.183*\ln(d_h)+28.885*(\ln(N_h)^{0.5}+0.005911*tsum \quad (7)$$

Knot properties

(Moberg 2001; Moberg 2006)

Number of knots:

$$KN_k = 0.693*SI^{0.321}*\Delta H_k^{0.707} \quad (8)$$

Equations for knot diameter: (9)
H_k is heigth at whorl k
if $H_k <= h_1$
$KD_k = a*H_k/(b0+H_k)$
if $h_1 < H_k < h_2$
$KD_k = a*H_k/(b0+H_k) + (c*((h_2-H_{total})+d*((h_2-H_{total})^2-a*H_k/(b0+H_k))*((H_k-h_1)/h_2-h_1))^2$
if $H_k >= h_2$
$KD_k = c*(H_k-H_{total})+d*(H_k-H_{total})^2$ H_{total} is total height of tree

Parameters for mean knot diameter:
$a=0.0161*tsum+3.15*D_{BH}/AGE$
$c=-.206*AGE-0.00469*D_{BH}+0.0838*CL+0.00298*D_{BH}*CL$
$d=((c*(H_{total}-h_2)+a*h_1/(0.334+h_1))/(h_2-h_1)+c/2$
$d=((c*(H_{total}-h_2)+a*h_1/(0.334+h_1))/(h_2-h_1)+c/2$
$h_1=MIN(0.195*SI,0.877-1)$
$h_2=H_{total}-0.877*CL$ where CL is crown length that is: $H_{total} - H_{lowest\ live\ branch}$

Parameters for max knot diameter:
$a=0.0196*tsum+5.45*DBH/AGE$
$c=-.25*AGE-0.00397*DBH+0.11*CL+0.00282*DBH*CL$
$d=((c*(H_{total}-h_2)+a*h_1/(0.334+h_1))/(h_2-h_1)+c/2$
$h_1=MIN(0.2*SI,0.952-1)$
$h_2=H_{total}-0.952*CL$

H_k= Height above ground (m) for whorl k
ΔHk= Distance between a whorl and its adjacent lower whorl (H_k-H_{k-1})
$KDrel_k = KDmax_k/KDmean_k$;
$KLs_k = -25.9*KDrel_k+15.1*KDrel_k*sqrt(KDmean_k)+-2.73*H_k+-0.813*H_k*KDrel_k^2+0.562*H_k*KDrel_k*sqrt(KDmean_k)+1.83*D_{BH}$
$KL_{dk} = KDrel_k^{0.222}*D_{BH}^{0.986}$
KA_k = N/A

3.4.3 Wood, fibres and knots – Scots pine

Fibre properties
(Lundqvist et al 2005)

Fibre length:
$FL_h = - 0.56 + 0.69*(\ln(N_h) + 0.33*\ln(AGW_h) – 0.65*\exp(-h_{rel}/0.13) + 0.00043*tsum$ (10)

Fibre width:
$FW_h = 23.99 + 3.18*\ln(R_h) – 5.25*\exp(-AGW_h/1.87)$ (11)

Fibre wall thickness:
$FWT_h = 1.16 + 0.24*\ln(R_h) – 0.23*\ln(h_{rel}) + 0.00030*tsum$ (12)

Fibre coarseness (FC_h) and other properties are calculated

Wood properties
(Wilhelmsson et al 2002)

Wood density:
$WD_h = 364.4-17.578*(0.5*d_h/N_h)-0.607*(\ln(N_{BH})))^3+ 0.4172*((\ln(N_{BH})))^3)*(\exp(d_{rel}))^7)$
$+0.0578*tsum$ (13)

Heartwood diameter:

$WHW_h = -15.4 + 0.158*D_h*\ln(N_h)$ (14)

Juvenile wood diameter:

$WJUW_h = 0.986*d_h*N_h$^(0.5577*(0.592*(ln(ln(u))-ln(ln(N_h)))

where u=15 if $N_h > 15$, u=N_h if N_h (15)

Latewood content:

$WLWC_h = 91.7-31.7*\ln(0.5*d_h/N_h)- 224.9*1/((0.5*d_h/N_h)+2)$

+2.09*(e^(d_{rel})^7 +0.00517*tsum (16)

Knot properties (Björklund & Moberg 1999; (Moberg 2001; Moberg 2006)

$KN_h = 2.0+0.0013*tsum+1.08*GRW_{ave}$ (17)

$KD_h = -0.48+0.0065*tsum+2.85*GRW_{ave}+5.94*D_{BHrel}$ (18)

$KLs_h = 23.8+1.42*SI+46.5*D_{BHrel}$ (19)

$KL_{dh} = 1.92 + 37.8*D_{BHrel}$ (20)

$KA_h = 51.4 - 7.07*GRW_{ave}+22.2*D_{BHrel}$ (21)

$D_{BHrel} = D_{BH}$/(stand sample mean D_{BH}) Relative D_{BH} (22)

4 Mapping and allocation with a Regional Resource Database

4.1 Objectives and methods

"Forest Resource Databases" is a new concept providing a basis for improved use of forest resources: for improved allocation of wood materials to specific mills and products and for more efficient processing. In these databases, forest inventory data are complemented with information about properties of the trees and product related parts of the trees. "Forest Resource Databases" are built through simulation, illustrated in *figure 4*. Forest inventory data or harvester data are used as input data to sets of integrated models. With these models, the size and shape of the stem (A), interior growth structure (B) and property variations within the stem (C) are successively simulated for large numbers of trees. In this way, a virtual representation of the forest resource is created. In the next step, the simulated stems are segregated into parts of technical interest, related to different types of products (D). For all these parts, properties and volumes are calculated and compiled in the database, sometimes also statistical property distributions for the parts (E). Common database tools may then be used to select information about various types of materials based on origin, properties, dimensions, etc. Materials can be aggregated to represent material flows of interest for mills and products. Mills and companies may analyse and compare alternatives in allocation and processing of the available raw materials.

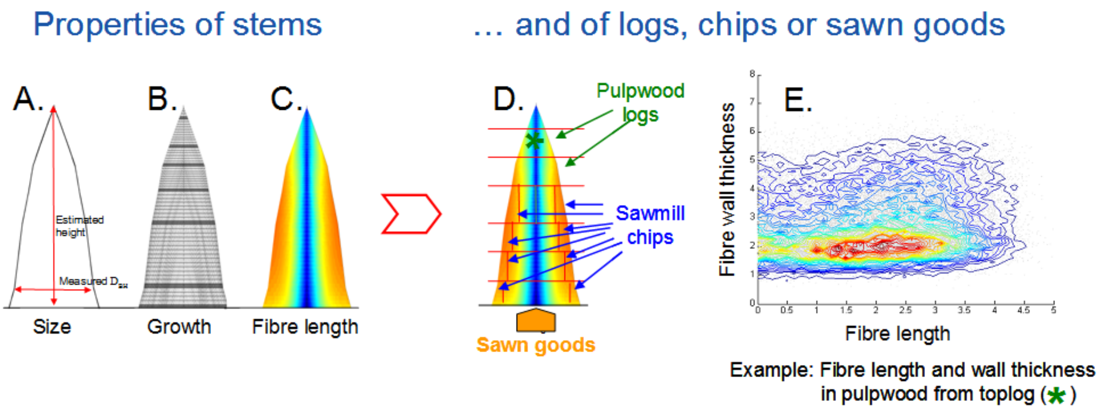

Figure 4. Building of a Forest Resource Database through stepwise simulation of the size, shape, interior structure and wood and fibre properties of a tree, followed by its segregation into logs and chips representing parts of industrial interest and calculation of their properties and volumes.

Tools have been developed, see *figure 5*, to support the simulation of such databases adapted to various applications: with different regional sizes, properties and levels of detail. From data on small sets of stands and trees for initial studies to very large databases with representative data for forest resources over large geographical areas. A broad spectrum of properties may be estimated for stands and trees, logs, pulpwood, sawmill chips, wood, knots, fibres, including also properties more closely related to products from the relevant parts of the trees, aggregated flows of raw materials, etc.

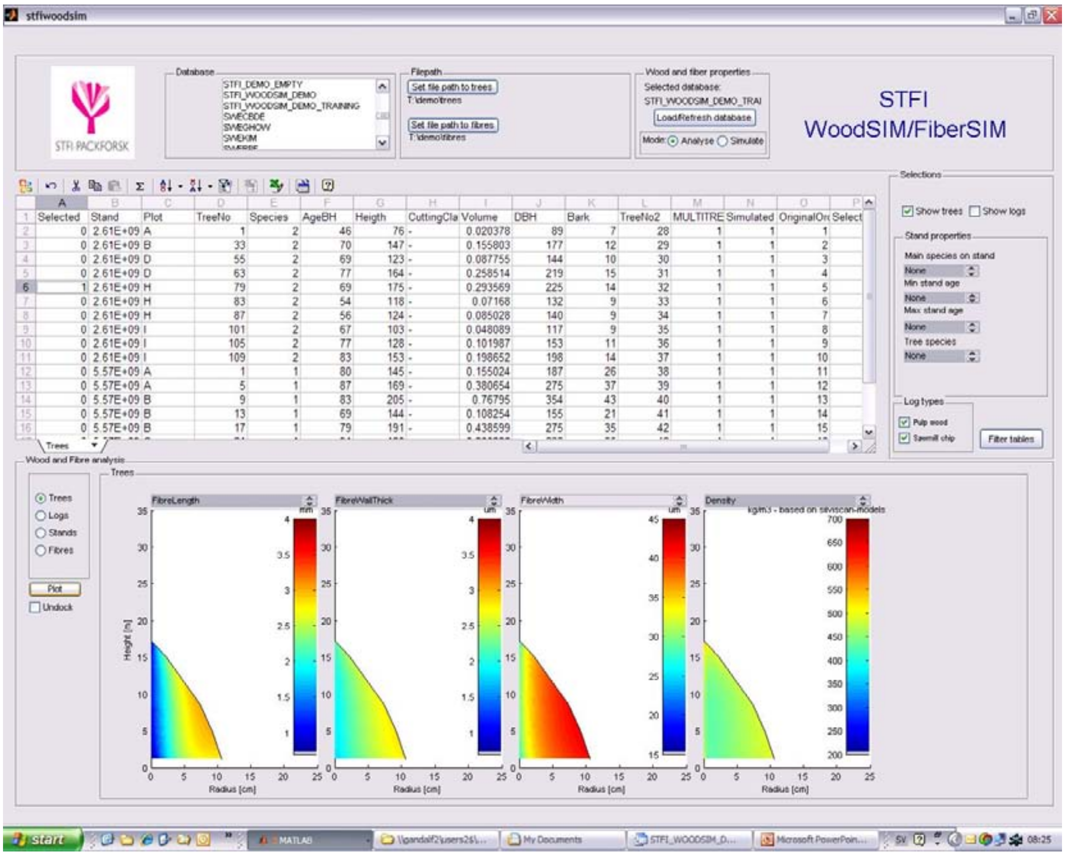

Figure 5. User interface of the combined tools STFI WoodSIM and FiberSIM for the stepwise simulation of size, shape and properties of trees, logs and chips. Each line of data in the upper table defines a tree to be simulated. At the bottom, the variations of four selected properties within the stem of a simulated tree are visualised.

4.1.1 Different types of Resource Databases

The first dataset of this nature was built by STFI-Packforsk in 2002 for the supply area a Finnish pulp mill. In this case, harvester data for a limited number of stands representing the variations in the supply area were used (Lundqvist et al 2003b). The first comprehensive database was a "Regional Resource Database" built in 2005 for the supply area of a Swedish pulp and paper mill, based on a large set of inventory data from company owned forests.

The same year, a severe storm hit southern Sweden. Several mills in other regions asked STFI-Packforsk what would happen with their products if they used storm-felled wood from the south instead of their usual raw materials. Tools to produce the property data needed for an answer were already developed, but it was not possible to answer quickly enough for commercial decisions. To avoid such delays in the future, the "National Resource Database" for all Sweden was built in 2007, providing immediate access to such information. It is based on data from the Swedish National Forest Inventory (Riksskogstaxeringen) and includes information of about 24.000 sample plots, 400.000 trees and 1.500.000 logs, as well as of sawmill chips from the large diameter logs. It has proven to be a powerful asset in both research and contract work for companies.

On compilation of the inventory data used, SLU also added estimated tree heights (Söderberg 1992). For the Västerbotten case study, two databases have been built, re-using inventory data for Västerbotten from this previous project:

1. a small-scale database, based on data from selected stands representing the major forest types in the region.
2. a full-scale database based on all inventory data available, with two levels of detail
   + log length averages
   + internode averages.

Database 1

For each wood species Norway spruce and Scots pine, typical stands for the region have been selected to reflect the variation, in this case from 4 age classes, 2 altitude classes and 2 site index classes (Lundqvist & Grahn 2007c). These 16 types of stands (4 x 2 x 2) per species are simulated and weights are dedicated to each type, reflecting how large a part of the regional wood volume may be seen as represented by each type. When investigating different alternatives, these weights are used together with the volumes and properties in the database to arrive at representative results.

Such a small-scale database is a useful solution in regions where large-scale inventory data are missing and also a practical first step when building a Resource Database for a new region, to identify data and models missing and to specify the most fruitful applications before further steps are taken.

Database 2

The full-scale database includes data on 12000 spruce and 13000 pine trees from about 200 inventory plots. Averages have been simulated both for log length parts of stems and for internodes (stem parts between whorls). Internode averages have been simulated to allow investigation of bucking alternatives. From these data, properties of arbitrary length logs from arbitrary positions along the stems may be calculated for all the 25000 trees. The examples of results below will show both types of data. In current applications, however, log length averages are normally used.

More details on methods and results are given in (Lundqvist et al 2008)

4.2 Examples of results

A very important comment is that the results shown below are based on the actual distributions of tree species, stand and tree ages, growth conditions, etc. in Västerbotten. Therefore, the results specifically reflect the resource in Västerbotten, which is somewhat extreme as compared to other European regions. The possibility to describe not only spruce and pine in general but the properties of a specific regional resource is a strength of the method. But it has to be considered that the results are not generally applicable.

4.2.1 Visualisation of information on single trees property available in the database

First information about each simulated trees available in the database is exemplified with graphs for some wood and fibre properties. The illustrations are based on data from one single tree: a 74 year old Scots pine tree (66 rings at breast height) growing at latitude 64,8 °, altitude 180 m and on site index T20 (estimated height at age 100 years of the large pine trees of the stand). The tree has a diameter at breast-height (1,3 m) of about 21 cm on bark and a total height of about 18 m. The green marks in *figure 6* show the simulated radius of the stem (taper) at all whorls at different heights in the stem. It also shows in what parts within the stem one most probably will find dead knots and fresh knots. In *figure 7*, the parts with heartwood and sapwood are indicated.

In this example, the part of the stem with a diameter < 4 cm under bark is considered not useful for the wood and fibre based industries. It may of course be used for bio-energy but is normally recommended to be left in the forest. The part of the stem with a diameter between 4 and 14 cm is here named as pulpwood and the part with a diameter > 14 cm (the timber limit) is named timber or sawlogs. These diameters and parts are indicated in figure 6.

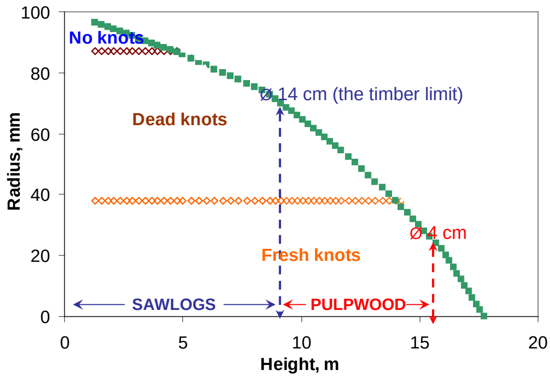

Figure 6. The zones of dead and fresh knots and without knots versus the height above ground at each whorl. The diameters 4 and 14 cm are indicated. (Scots pine)

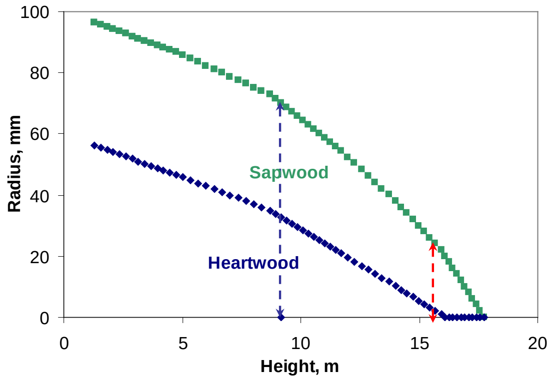

Figure 7. The extensions of heartwood and sapwood versus the height above ground at each whorl for the selected pine tree. The diameters 4 and 14 cm are indicated. (Pine)

This is, of course, an idealised image. Part of the thinner pulpwood will in many cases be left in the forest or used for bio-energy. And parts of the timber will be downgraded and used for pulp production, if they are unsuitable for sawing or if the regional sawmills are not equipped for large dimensions. The same will happen with part of the timber close to the timber limit. The diameter may be large enough for sawlogs but practicalities on bucking may result in it becoming part of a pulpwood log.

Figure 8 shows the estimated wood density (density of air-dried wood) for internodes along the stem, to the left versus the height above ground, the forest perspective, to the right versus the diameter, the industry perspective. For pulpwood, averages for the full stem/log cross-sections are shown. For the timber, averages for the full cross-sections are shown in orange. These averages are valid for timber logs downgraded to pulpwood. The two other graphs for timber represent the inner parts, which normally become sawn products (brown), and the outer part, which normally become sawmill chips (blue).

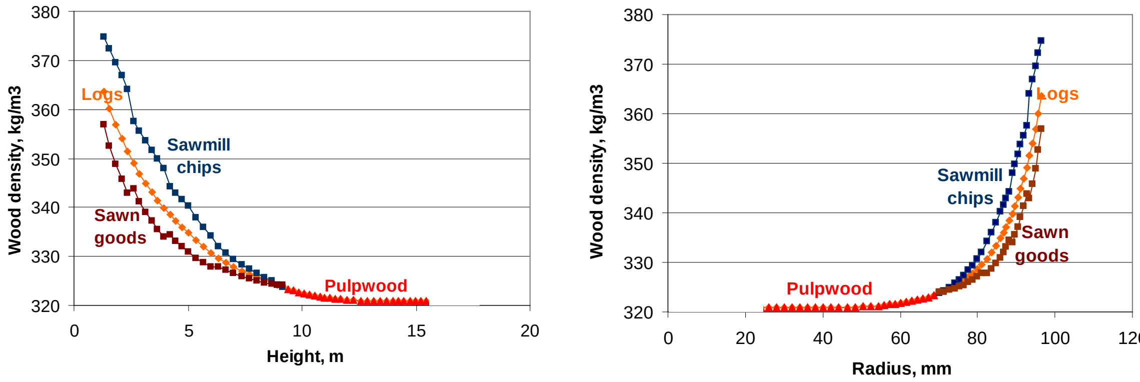

Figure 8. The wood density (air-dried) versus height above ground (left) and radius (right) for all internodes. Graphs are shown for full cross-sections and for what may become sawn goods and sawmill chips. (Scots pine)

Figure 9 shows the variation in fibre length in the same way. It illustrate that the fibre dimensions are quite different when comparing common low-diameter pulpwood logs, down-graded sawn timber allocated to the pulpwood and sawmill chips from pine.

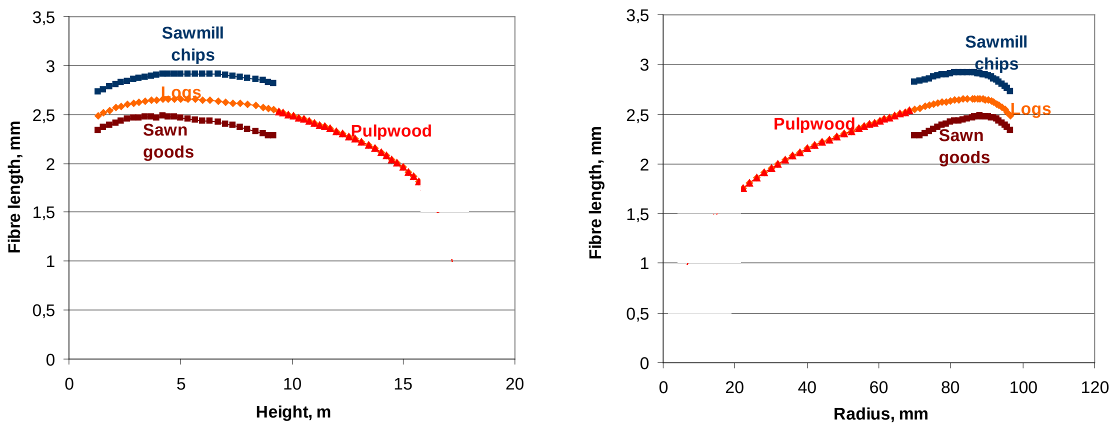

Figure 9. Fibre length versus height above ground (left) and stem radius (right) for all internodes. Graphs are shown for full cross-sections and for what may become sawn goods and sawmill chips. (Scots pine)

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 10*, showing that pulpwood may have about double the number of fibres per gram as compared to sawmill chips.

4.2.2 Properties of industrial raw material flows

The industry will normally not select individual trees and logs for processing. This may happen for very valuable wood for high value products, but it is not common for standard products. Instead, flows of raw materials are created according to a mix of criteria: property demands, practical logistics, costs, etc. These flows may have different average properties, which in many cases is of importance for the products, even though their statistical property distributions often overlap considerably.

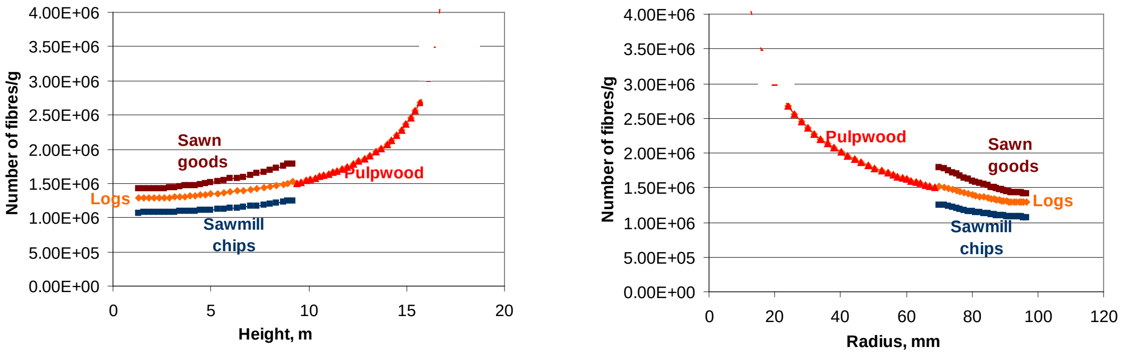

Figure 10. Number of fibres/gram versus height above ground (left) and stem radius (right) for all internodes. Graphs are shown for full cross-sections and for what may become sawn goods and sawmill chips. (Scots pine)

From the Resource Databases, averages and distributions can be calculated using database software. The results may be combined with information of costs, etc. in search for favourable alternatives. As an example, *figure 11* shows the estimated statistical distributions of wood density (left) and fibre length (right) for pulpwood, sawn timber and sawmill chips from pine in Västerbotten. Also here, a timber limit of 14 cm has been used in the calculations. The areas below the graphs represent the relative volumes of the different wood classes, estimated from the simulated trees.

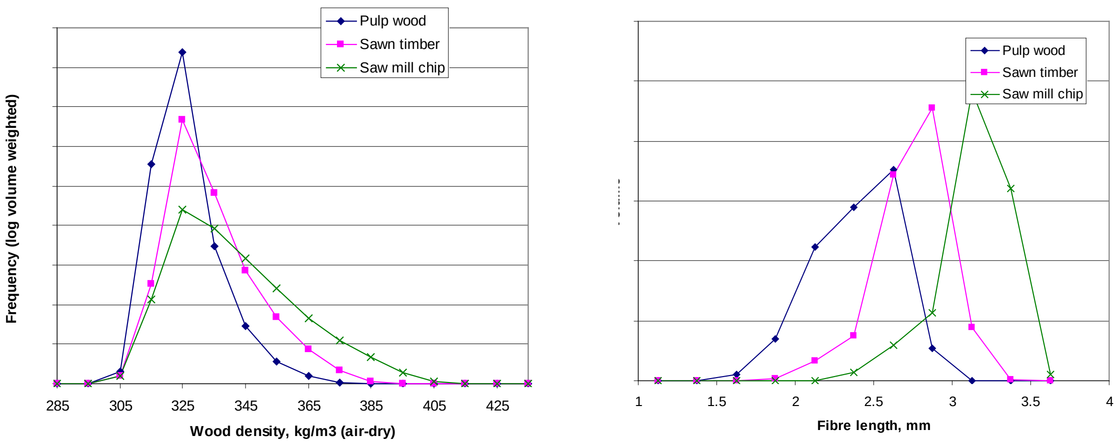

Figure 11. Estimated statistical distributions for wood density (left) and fibre length (right) of pulpwood, sawn goods and sawmill chips available for harvesting in Västerbotten. Timber limit 14 cm. The areas below the graphs represent the relative volumes available of the different wood classes, estimated from the simulated trees. (Scots pine)

Effects of technical and commercial changes may also be investigated. The fibre based and the solid wood based industries are obviously closely linked to each other. The way they divide the raw material between themselves into pulpwood and sawn timber influences not only the volumes obtained by each party, but also the properties of wood and fibres used in both industries. The same is, of course, the case if more or less of the upper part of the pulpwood is used for bio-energy. In *figure 12*, estimated statistical distributions for the wood density of the sawn goods are shown for pulpwood from first thinning and final cutting of pine, assuming two different timber limits: log diameters 14 and 18 cm. The area below each graph represents the volume obtained, if only 30 % of the trees are removed on thinning. The volume of sawlogs from first thinning is as expected very small, especially if larger diameter logs are requested.

The example in *figure 13* focuses on the sawn goods. Data on timber logs with diameters within three intervals: 200-300 mm, 300-400 mm and 400-500 mm, have been picked from the Resource Database and averages calculated for the wood density of the inner part of the logs 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 also shows that even this class includes some higher density wood. This wood originates from slow-grown trees. It is, of course, possible to look in more depth into where to find these higher density logs and to include other property demands in the selection process. In Västerbotten, the trees are generally comparably small and there is a limited proportion of large diameter logs. Therefore, the statistical distributions of the large diameter classes are a bit “noisy”.

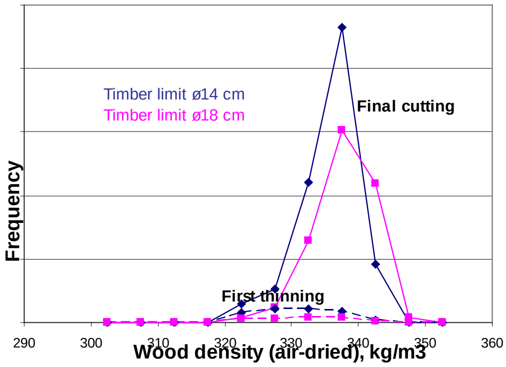

Figure 12. Statistical distributions for the wood density of the sawn products (averages) from first thinning and final cutting, assuming two different timber limits: 14 and 18 cm, in the resource of Västerbotten. The areas below the graphs represent the wood volumes available. (Pine)

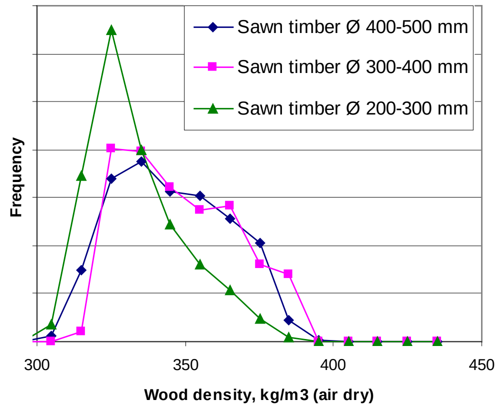

Figure 13. Statistical distributions for wood density of the inner parts of logs, what will become sawn products, from different log diameter classes, in the resource of Västerbotten. (Scots pine)

4.2.3 Allocation of wood and fibres to specific mills and products

To achieve good allocation of wood to mills and products from the materials available, it is necessary to have good knowledge of what industry needs regarding volumes and also properties. If pieces of solid wood for production of furniture without knots are to be produced, it is easily understood that the logs you start with can not be very knotty. It may be less obvious, but still true, that fibres with different properties are beneficial and sometimes needed in different paper products. But in both cases you may have to compromise to get the volumes needed and at a reasonable cost. The Forest Resource Database, with its virtual representation in the computer of the real resource, offers the opportunity to investigate alternatives. You may apply different selection criteria volumes obtained and property averages of distributions. You may also identify typical locations (geographic, type of stand, tree species, part of tree) of wood with specific properties or look for possibilities to replace one wood or fibre source with another with similar properties on shortage or price increase.

We will now look at a number of classes of wood which are already used separately in pulp mills or can be considered as interesting for selective wood supply, based on the Västerbotten data. In practice, all these classes should definitely not be used in parallel. When their properties and volumes are known, they shall rather be grouped together to form a set of raw materials with suitable properties and volumes for a mill or the industries in the region. This is also a basis for the case study on sustainability effects of allocation, addressing a forestry-wood chain starting with fibres from the Västerbotten forest to recycled corrugated boxes in Germany (Lundqvist et al 2009 and EFORWOOD Deliverable 3.1.9).

Wood classes compared

It is possible to use the Resource Database to study very specific selection approaches, such as picking parts of trees with simulated properties according to specifications, see figure 6-10 and chapter 6. This is normally not economically feasible on supply of wood for pulp and paper production. The basis assumption is in this case that all pulpwood of a certain wood species from the harvesting of a stand is handled as part of one class. The wood classes are then distinguished by the following criteria:

1. Tree species: Spruce or pine (one species use to dominated the stands)
2. Operation/age: Thinning or final cut
3. Part of trees: Pulpwood or timber, divided into sawn goods or chips

in total 2 x 2 x 2 = 8 classes. These are in cases complemented with two more classes:

4. Top logs (upper part of the pulpwood; will sometimes be used for bio-energy)
5. Root logs (Timber close to the ground; the part most often affected by rot)

Top logs are interesting because their logs have a very juvenile character and they could also be seen as representing wood for bio-energy, root logs because they include much mature wood and often constitute a major part of the downgraded timber used for pulping.

Wood volumes available for thinning and final cut

In the Resource Database, data are available on volumes and properties of the whole and parts of the stems of the trees callipered, but also volumes per hectare assessed on inventory. These data may be combined to estimate volumes and weighted averages for the resources and parts of it. *Figure 14* shows the total volume of spruce and pine in

Västerbotten ready for thinning or final cutting has been divided into the volumes of the eight wood classes defined by criteria 1-3. In the inventory data, all stands/plots are referred to a cutting class, telling if they are ready for harvesting operations or not. All stemwood with a diameter > 4 cm under bark is included, but only wood from stands/plots classified as ready for thinning or final cut is included,

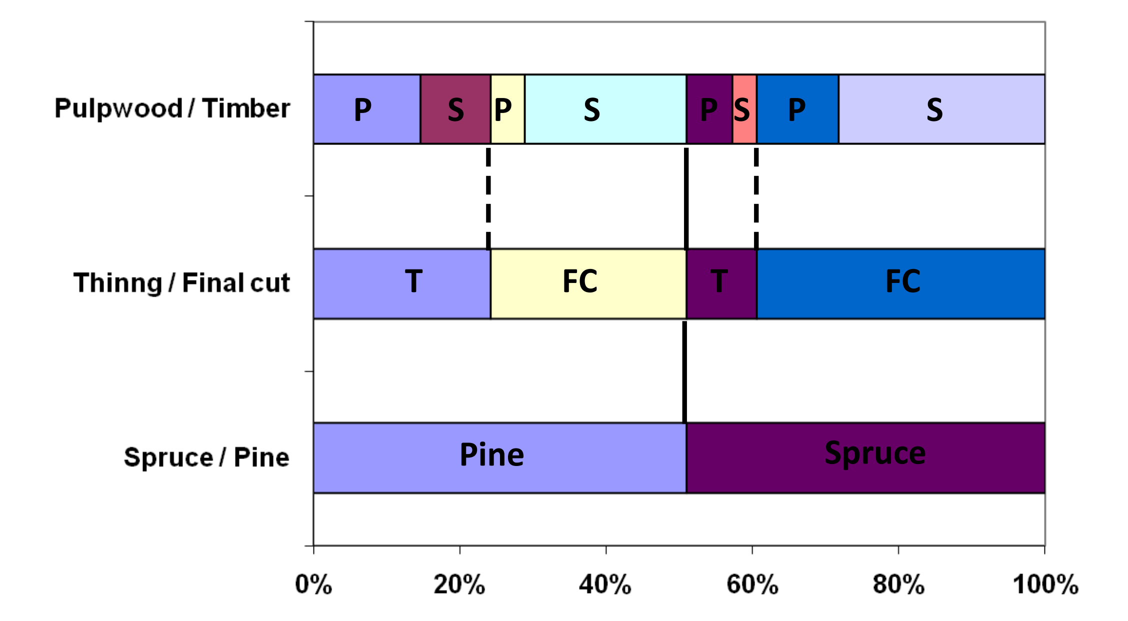

Figure 14. Volume of all wood in Västerbotten in stands ready for thinning or final cut, divided into volumes of pine and spruce, ready for thinning or final cut and pulpwood or timber.

Comments:

The wood named pulpwood includes stemwood which will be used for both pulping and bio-energy and part of the stem named timber will be used for pulp.

All of these volumes in stands ready for thinning or final cut will not be removed on harvesting. For instance, on thinning only 25-40 % of the trees will be cut.

Pine represents 51 % and spruce 49 % of the standing volume ready for thinning or final cut. For pine, the standing volumes available for thinning and final cut are rather similar, while for spruce there are only small volumes available in stands ready for thinning and the more for final cut.

Wood and fibre properties of harvested wood

Such a far-going segregation is not practically feasible, but it is simulated to provide a back-ground for further discussion on what can be the optimal selectiveness.

Figure 15 illustrated the two-dimensional distributions for these wood classes from pine in Västerbotten. We have now moved from standing volumes in the forest to volumes made available to the industry after harvesting. The statistics is based on volume-weighted averages of internodes. All trees of stands classified as ready for thinning or final cut are included, but trees from stands ready for thinning are only included with 30 % of their volumes. The differences and variation are expressed with the averages (+) and the 3rd quartiles of the variation (graphs encircling 75% of the total number of logs).

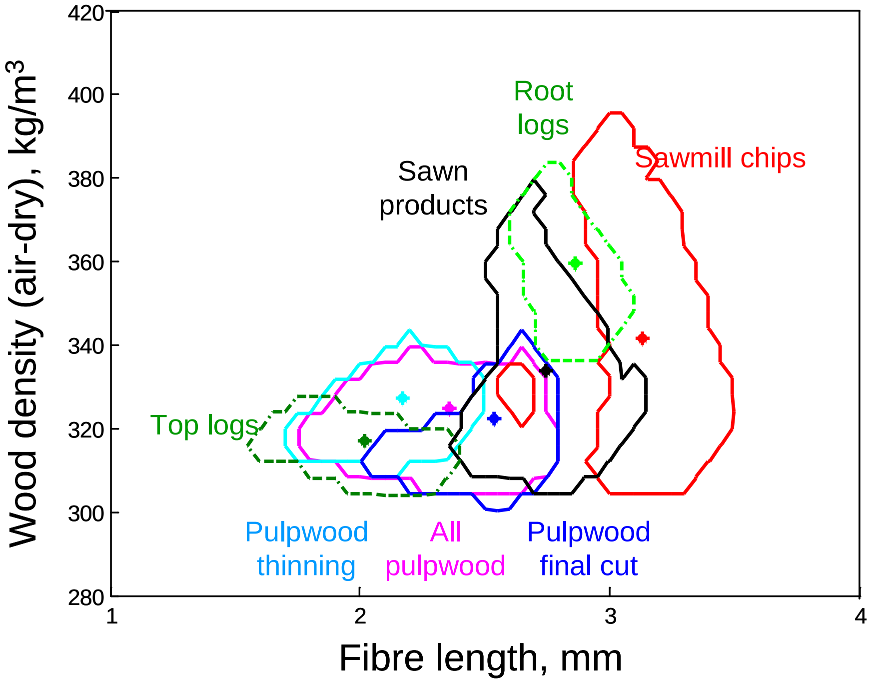

Figure 15. Two dimensional distributions of fibre length and wood density (air-dry) for different classes of wood from pine available to the industry in Västerbotten. (Scots pine)

The differences in fibre length among the distributions reflect that the length of the fibres tend to increase with the number of the growth ring. The average number of growth rings (volume-weighted) is lowest in the top logs and highest in sawmill chips. There is a similar development for wood density (sometimes with exception for the inner rings). The background to this, relevant for pulp and paper, is that the fibre wall thickness and fibre width also tend to increase with ring number/radius, but the wall thickness relatively more, which results in denser wood. On top of this, a tendency of pine to form wood of extra high density at large radii from the pith close to the ground is superimposed. Further, pulpwood from thinning has normally more fast-grown wood than pulpwood from final cut, when the tree is in a more stagnant phase of growth, and will thus have more juvenile wood within a given diameter. Therefore:

- The fibre length increases successively from top logs to sawmill chips
- The density is highest in root logs from final cut
- The density is lower for the sawn products (black) and sawmill chips (red), as these include wood also from logs further up the tree and also some logs from thinning
- Sawmill chips has higher density than the sawn products, due to its origin from more mature wood
- The differences are less pronounced for the pulpwood classes, as the “close to ground features” is less pronounced.

- The reason why pulpwood from thinning has a slightly higher wood density than that from final cut may be that it includes a proportion of root logs from small trees.

Now we will zoom in further on pulp and paper applications and the case study on kraft liner and corrugated boxes mentioned above. The fibre wall thickness is important for many properties of pulp and paper. *Figure 16* presents the estimated statistical distributions for fibre wall thickness of all the wood classes in figure 15 (only pine). The distributions are calculated from volume-weighted averages of internodes. This means that the clearly thinner-walled fibres of earlywood and thicker-walled fibres of latewood are not reflected in the distributions. Distributions on the fibre-to-fibre level may, however, also be calculated with the STFI-Packforsk simulation tools, see examples in (Lundqvist et al 2008).

The distributions are weighted so that the areas under the graphs reflect the volumes of each class available to the industry in the Västerbotten resource, which means from all stands notified as ready for thinning or final cut in the inventory data. For stands to be thinned, the available volumes have been calculated based on a removal of 30 %. The volume of the class of timber downgraded to pulpwood is calculated from data on root logs of trees ready for final cut only. One root log of 30 is assumed to be downgraded.

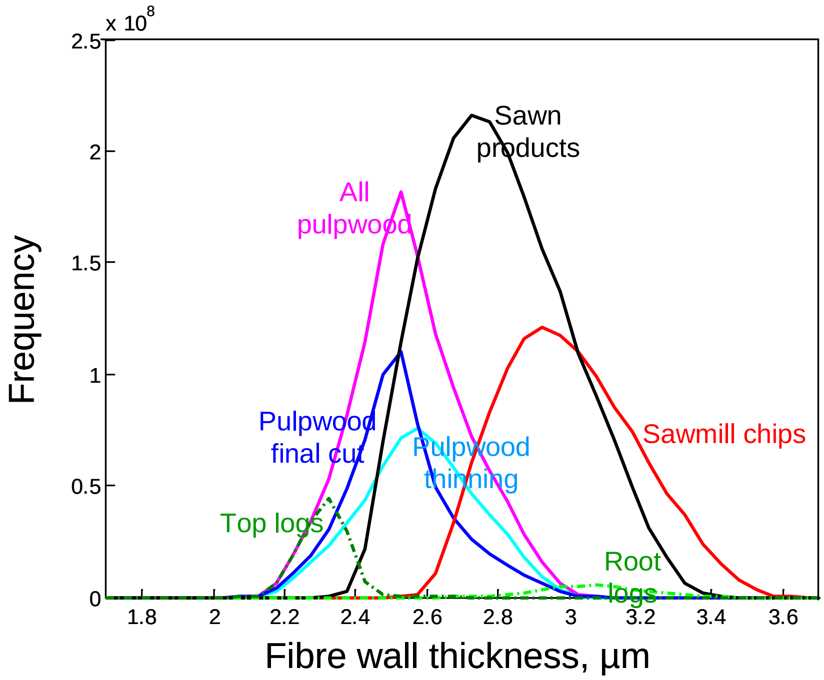

Figure 16. The statistical distributions of fibre wall thickness for different wood classes of pine. The distributions are weighted so that the areas under the graphs reflect the volumes of each class available to the industry in the Västerbotten resource. (Scots pine)

One conclusion from this is that the volume of downgraded root logs is probably normally too small to justify it being handled as a separate wood class in the forest and all the way to the process. Normally, it would probably be put into the pile of pulpwood at the forest road, if these logs do not create problems, such as less stable piles of logs on trucks, extra wood losses in debarking drums or thick-walled fibres ruining the surface properties of printing paper. The volume of top logs is probably also too small to justify separate handling, but there may be cases when it is reasonable.

The graphs also indicate that, if fibre wall thickness would be the only property to consider, the difference in Västerbotten between pulpwood of pine from thinning and final cut is so small that all pulpwood from pine should be handled as one class, possibly with exception for top logs for special pulps.

There are, however, also other properties to consider. In *figure 17*, the major wood classes prioritized above are shown for both spruce and pine. Based on similar graphs figures for property distributions and available volumes and of potential wood classes from harvesting in the Västerbotten resource, strategies for allocation of more uniform and suitable fibres to mills and products may be formulated. Tools to support operation according to the allocation decided on may also be developed.

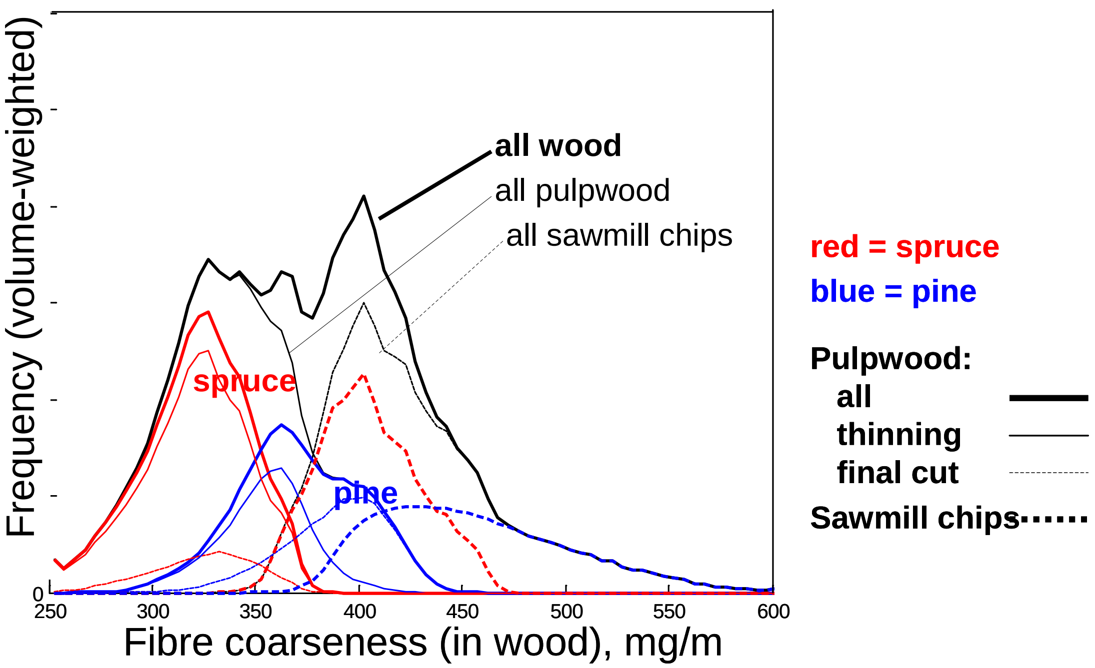

Figure 17. The statistical distributions of fibre coarseness for different wood classes of Norway spruce and Scots pine. The distributions are weighted so that the areas under the graphs reflect the volumes of each class available to industry in the Västerbotten resource.

4.2.4 Uniformity

High uniformity of the wood and fibres fed into the process (small property variations over time) is in itself a very important factor for efficient production and high quality. Variations may cause disturbances in the production process, leading to additional costs and insufficient quality. In most cases, the mills will judge improved uniformity as more important than improved properties. Better management of the raw materials also creates a basis for improved uniformity.

Property variations in time are illustrated in *figure 18,* showing simulated variations for fibre length in pulpwood delivered to a mill on trucks from the forests of Västerbotten.

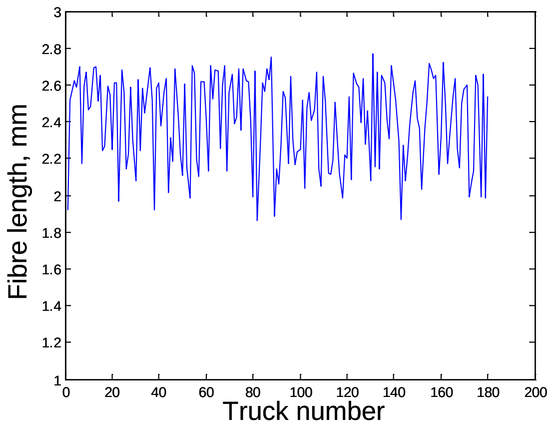

Figure 18. Simulated variation of fibre length in pulpwood delivered to a mill in Västerbotten.

The example may be brought to further perfection, but it is useful as an illustration. It is based on the assumption that all pulpwood logs of each harvesting operation are randomly put into a pulpwood pile at the forest road and that trucks loaded from it will carry piles with the same averages as the pulpwood from the stand. The trucks delivering pulpwood to mill is assumed to originate randomly from all harvesting operations, resulting in the time series shown. 200 trucks correspond to about 1 days of production for a medium-size mill.

The figure indicates a span in fibre length among truckloads of 2,0 – 2,7 mm, which is a lot in pulp and papermaking, but around a stable average of 2,4 mm. At the pulp mill, these fibres will be mixed with fibres from other materials and blended, resulting in decreased variations in time of the chips entering the process. The example shown in the figure is, however, an ideal case where pulpwood from different sources is delivered randomly. This is not always the case. Variations in the proportions of wood of different origins may lead to difficulties in process and product. Sustainable supply for uniformity is also an important factor in allocation.

4.3 Conclusions and comment

Forest Resource Databases are very useful for investigations of raw materials available in geographic areas of different sizes: the supply area of a mill, a region or larger. Information may be obtained on volumes and properties of the total resource, in stands ready for harvesting or in harvested materials of different types. This may be used to design strategies of allocation for more uniform and suitable materials to mills and products, based on what is available in the supply area at hand. It may also be used in operational applications.

The reader has to be consider that the examples shown are based on the actual forest resource of Västerbotten with its distributions in tree species, tree ages, growth conditions, etc., which are quite extreme due to the location in the far north, slow growth, etc. This possibility to describe the properties and their variations in a specific resource rather than looking at spruce and pine in general is a strength of the method. But it also means that the results may not be generally applicable for resources of other regions.

5 Characterisation of wood supply by bucking simulation of forest inventory

5.1 Objective

The objective of the bucking simulation analyses was to forecast and characterise the expected supply of logs (frequencies of log dimensions, wood, knot and fibre properties) from forestry to industries within the nearest future of the “Eforwood Västerbotten case” (Valinger et al 2008).

5.2 Materials and methods

The analyses have been based on basic industrial demands in terms of ordinary price relations between different assortments, existing forest resources represented by 600 stands ready for final cut of 6941 stems of Scots pine and Norway spruce extracted from the Swedish National Forest Inventory, 2001-2005 (Valinger et al 2008). This inventory was used for simulation of log production by CTL-harvester (Cut-To-Length) technology. The analyses have been performed by Skogforsk’s bucking simulation tools “TimAn2” and “Pri-analysis” (Arlinger et al 2004) and additional SAS-routines for input/output of inventory data and additional models not yet included in Pri-analysis. An earlier preliminary analysis based on the same approach applied on the “Eforwood Nordic test chain” has been presented in Wilhelmsson et al 2006.-Examples are also given in (Valinger et al 2008), showing dimensions and properties of sawlogs. Fibre properties may also be included, using the models presented by Ekenstedt et al, 2003. Some of the models are given in chapter 3.4 above, while more comprehensive presentations are given in the original publications referred in chapter 3.4 “Models used” and compiled for implementation (including SAS-code and some slight adjustments of coefficients) in Lanvin et al 2008 (appendix 9). Examples of a pricelist and a stem profile are given as screen shots in *figures 19 and 20. Table 2* shows the different assortments included in the bucking simulation.

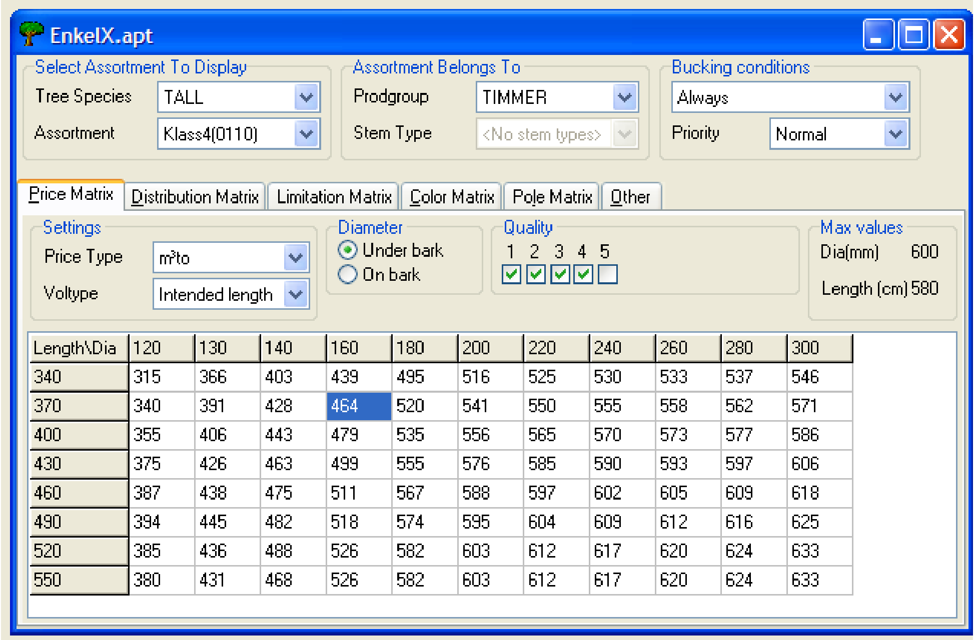

Figure 19. Screen shot of a Price Matrix for Pine(Tall) sawlogs from TimAn2/Aptan bucking simulations. Each (competing) assortment is defined by a price matrix or fixed prices per volume unit. The bucking simulation can be strictly controlled to perform the highest value according to the pricelist or to fulfil demands given as required apportionments of specific log lengths and log diameter combinations within specified limitations of accepted losses in price (value to forest owner).

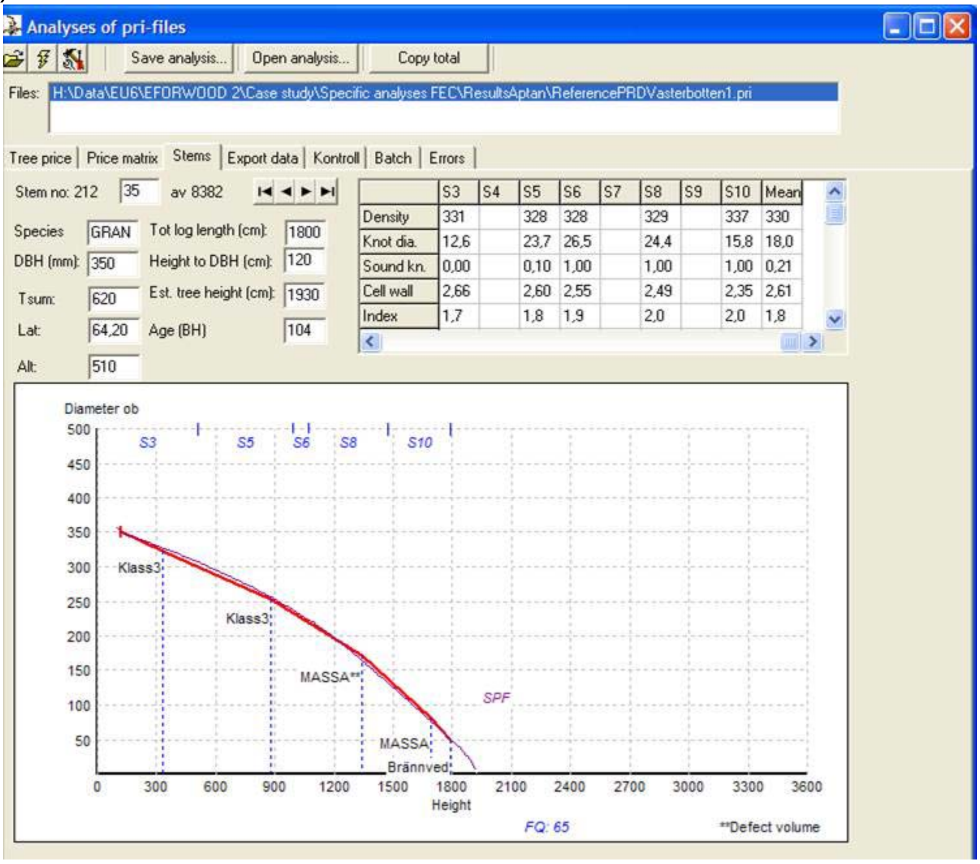

Figure 20. Example of graphic profile and predicted properties of logs from one stem profile. Screen shot from Pri-analyses.

Table 2. Short description of the different assortments included in the bucking simulation.

Assortment no	Assortment description
1	Scots pine butt sawlogs with mainly loose knots and 4-5% knot free surfaces (Anon, 2007).
2	Scots pine middle and top sawlogs.
22	Scots pine sawlogs selected for long distances between branch whorls. Most commonly middle logs. No butt logs.
23	Scots pine sawlogs selected for high heartwood content
3	Pulpwood of Scots pine
5	Norway spruce butt sawlogs .
6	Norway spruce middle and top sawlogs
26	Norway spruce logs selected for high MOR (Higher average C-classes)
27	Norway spruce logs selected for high heartwood content
7	Pulpwood of Norway spruce (including slightly decayed buttlogs accepted as kraft pulpwood)

5.3 Examples of results and discussion

The results from a bucking simulation can be presented as log tallies comprising information on total volumes per log assortment and dimension (*figures 21-24*) as well as characterised (predicted) properties of each log (log averages) (*figures 25-30*). It will also comprise log position in each stem as well as location and recorded conditions of the stand it originates from. The resulting volume shares in the examples given indicate the expected distributions of the 16491 virtual logs produced.

The accuracy of individual log properties will vary depending on the accuracy of input data and the predictability of each model used. This means that properties of individual logs may have considerable inaccuracy in detailed properties (reflected by measures like prediction errors, RMSE etc that can be extracted from the referred publications). However, as long as the individual predictions are unbiased (which may be reasonable to assume if the input data are unbiased) averages of log piles may be fairly accurately predicted even though individual logs are not. It is also important to observe that standard deviations of different properties presented in the diagrams below reflect the standard deviations of predicted values only. To get an estimate of the total expected variation expressed as a standard deviation of a predicted average one can square the standard deviation in question (from diagram below) and add the squared prediction error of the model used (from referred publications) and then the square root of this sum.

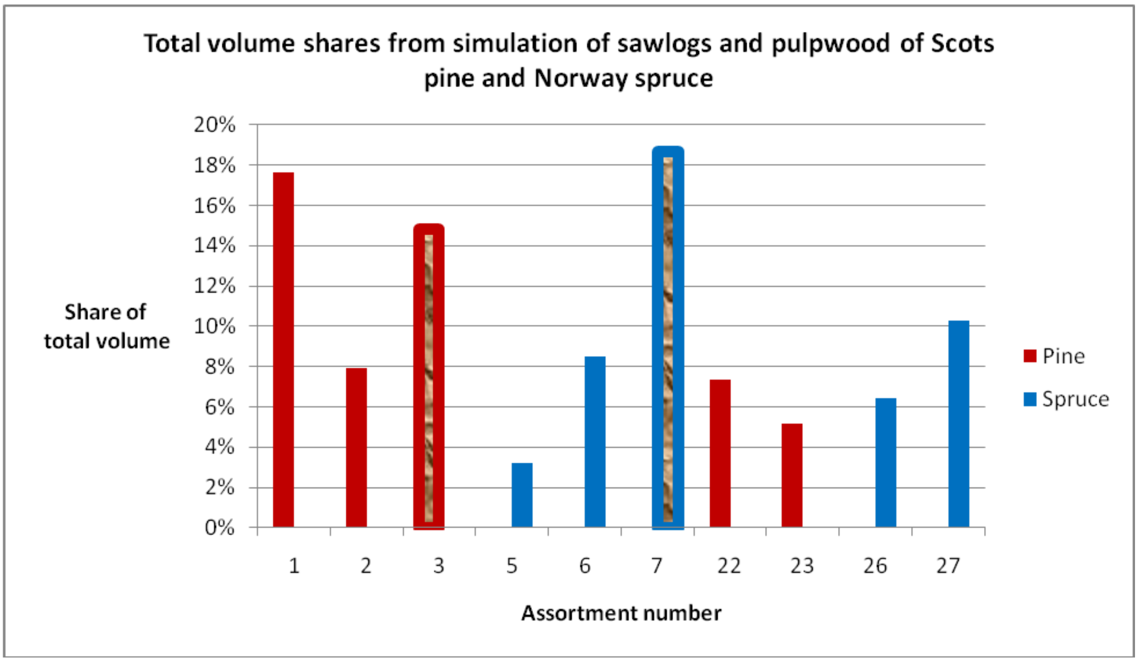

Figure 21. Total volume shares per assortment (according to table 2) of 16491 logs from 6941 stems from 600 stands (final cut). Assortments 1, 2, 22 and 23 are pine sawlogs, 5, 6, 26 and 27 are spruce sawlogs, while 3 and 7 are pulpwood (to some extent alternatively used as energy wood) from pine and spruce respectively.

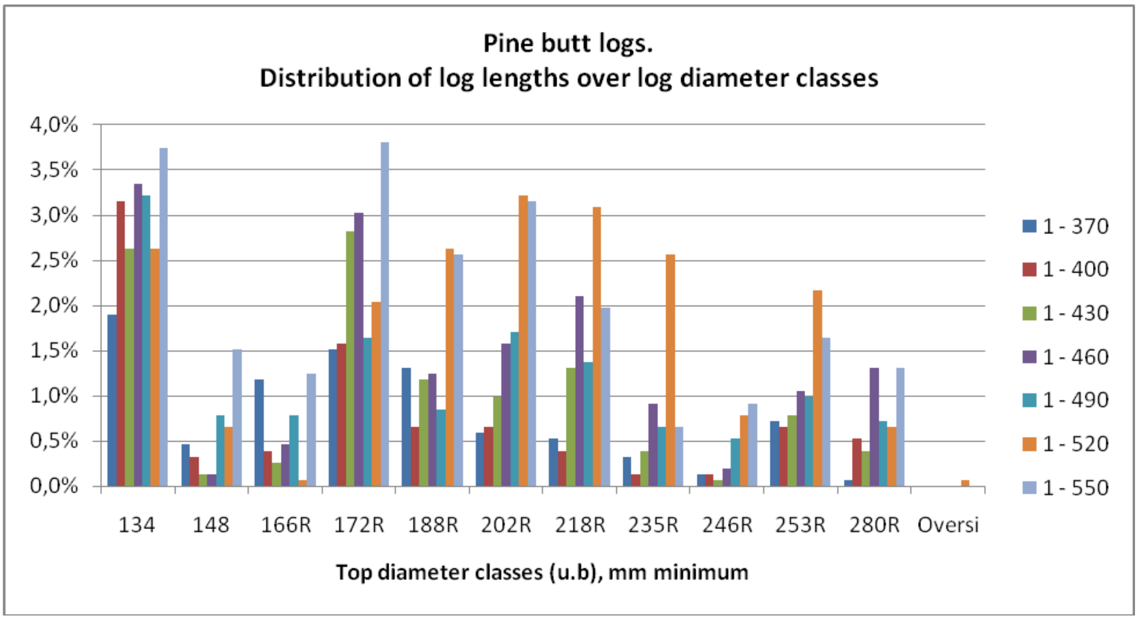

Figure 22. Pine butt sawlogs . Volume shares of different log diameters (categories in mm top diameter of class bottom) under bark e.g. 134=134 -147 mm; R=Class with butt logs only. Legend (370 – 550) represents log lengths in cm.

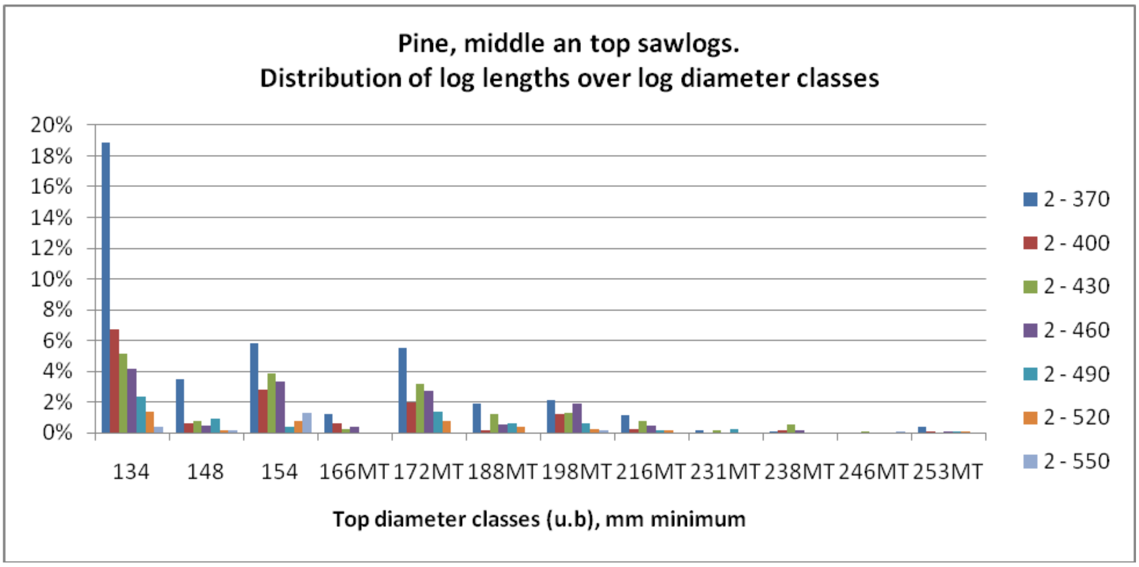

Figure 23. Pine sawlogs, butt-logs excluded. Volume shares of different log diameters (categories in mm top diameter of class bottom) under bark e.g. 134=134 -147 mm; MT=Middle and Top logs only. Legend (370 – 550) represents log lengths in cm.

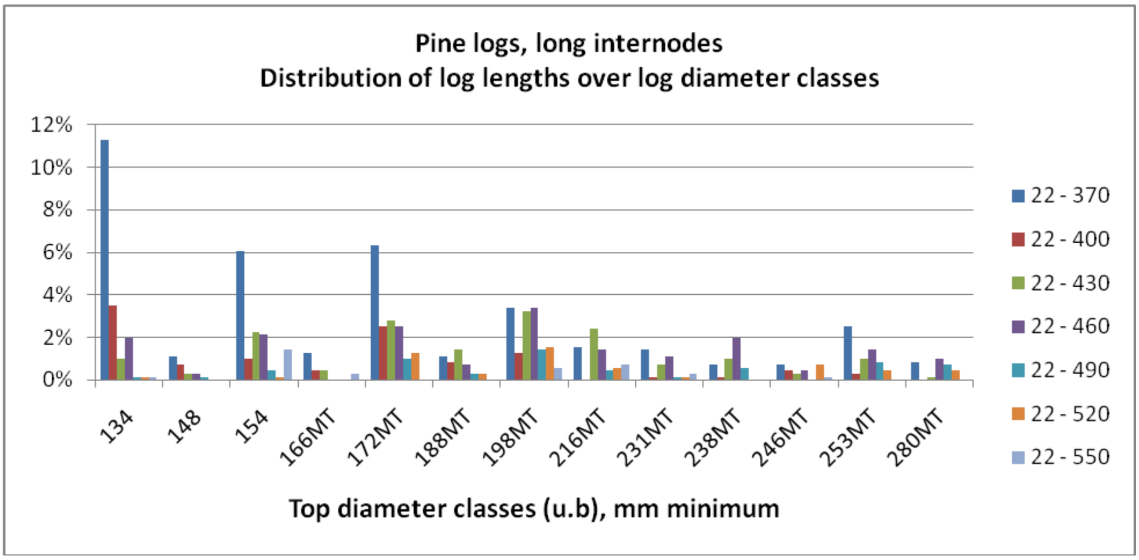

Figure 24. Pine sawlogs selected for long distances between branch whorls (internodes) (Assortment 22). Volume shares of different log diameters (categories in mm top diameter of class bottom) under bark e.g. 134=134 -147 mm; MT=Middle and Top logs only. Legend (370 – 550) represents log lengths in cm.

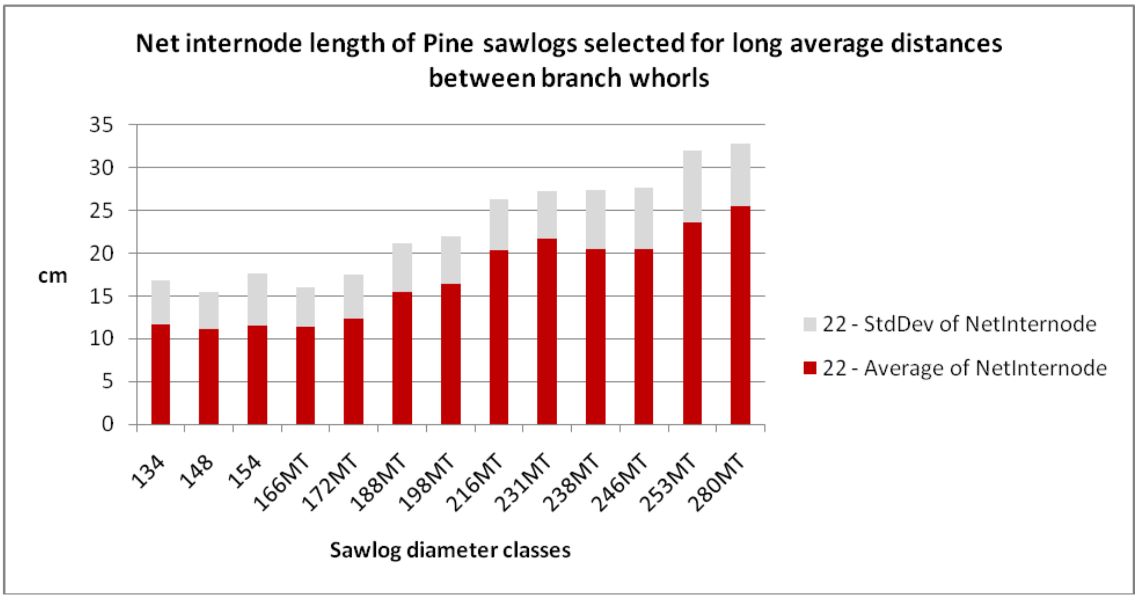

Figure 25. Pine sawlogs selected for long distances between branch whorls (internodes) (cm) (Assortment 22) (Model under publication). Predicted net internode lengths (cm) defined as the knot free part between two branch whorls. Categories are different log diameters (categories in mm top diameter of class bottom) under bark e.g. 134=134 -147 mm; MT=Middle and Top logs only. Lower bars represent averages and upper bars + 1 standard deviation in predicted values. (See discussion above)

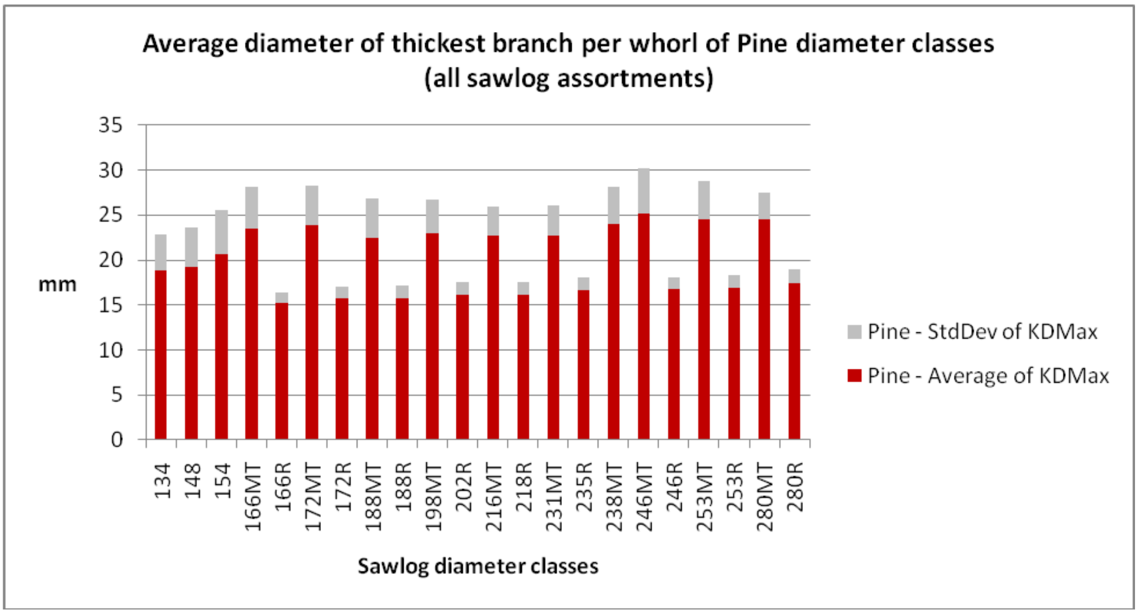

Figure 26. Pine sawlogs, all assortments. Predicted values of average diameters of thickest branch per whorl (KDmax) (mm) (model: Moberg 2000). Categories are different log diameters (categories in mm top diameter of class bottom) under bark e.g. 134=134 -147 mm; R=Butt logs only, MT=Middle and Top logs only. Lower bars represent averages and upper bars + 1 standard deviation in predicted values. (See discussion above)

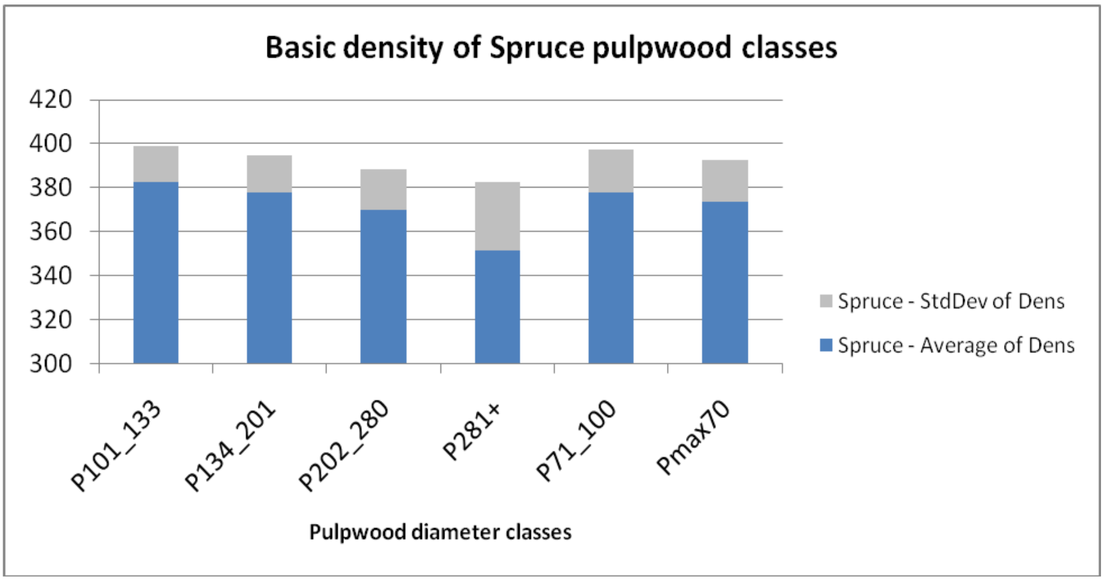

Figure 27. Predicted basic density (model: Wilhelmsson et al, 2002) of Norway spruce pulpwood. Categories represent different diameter classes (top diameters u.b.) where class P101_133 means pulpwood between 101 and 133 mm, P134_201 means pulpwood between 134 and 201 mm. Lower bars represent averages and upper bars + 1 standard deviation in predicted values.

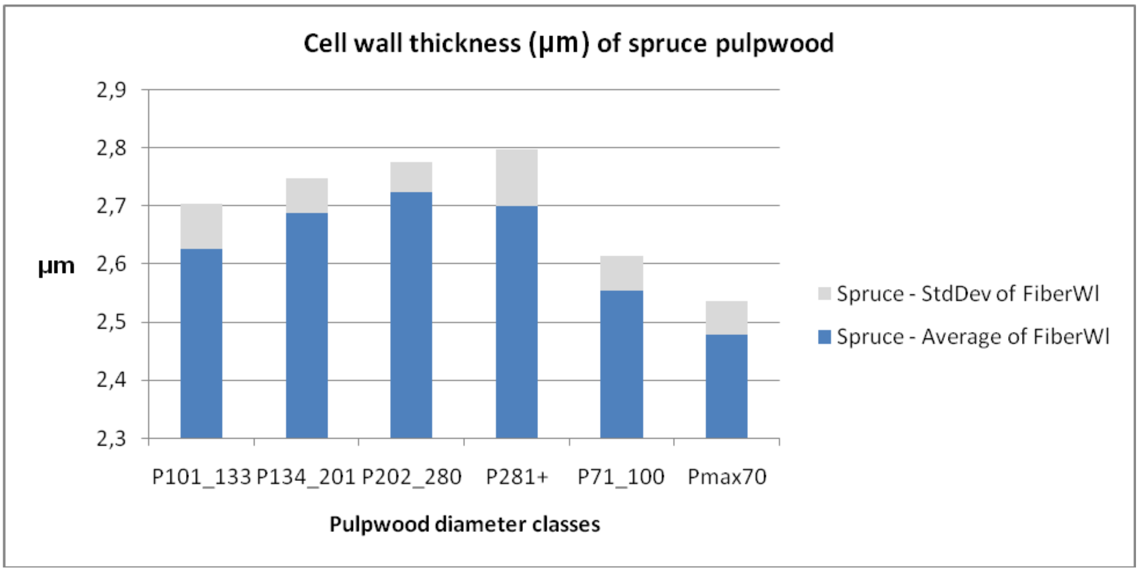

Figure 28. Predicted cell wall thickness (model: Ekenstedt et al 2003) of Norway spruce pulpwood. Categories represent different diameter classes (top diameters u.b.) where class P101_133 means pulpwood between 101 and 133 mm, P134_201 means pulpwood between 134 and 201 mm. Lower bars represent averages and upper bars + 1 standard deviation in predicted values.

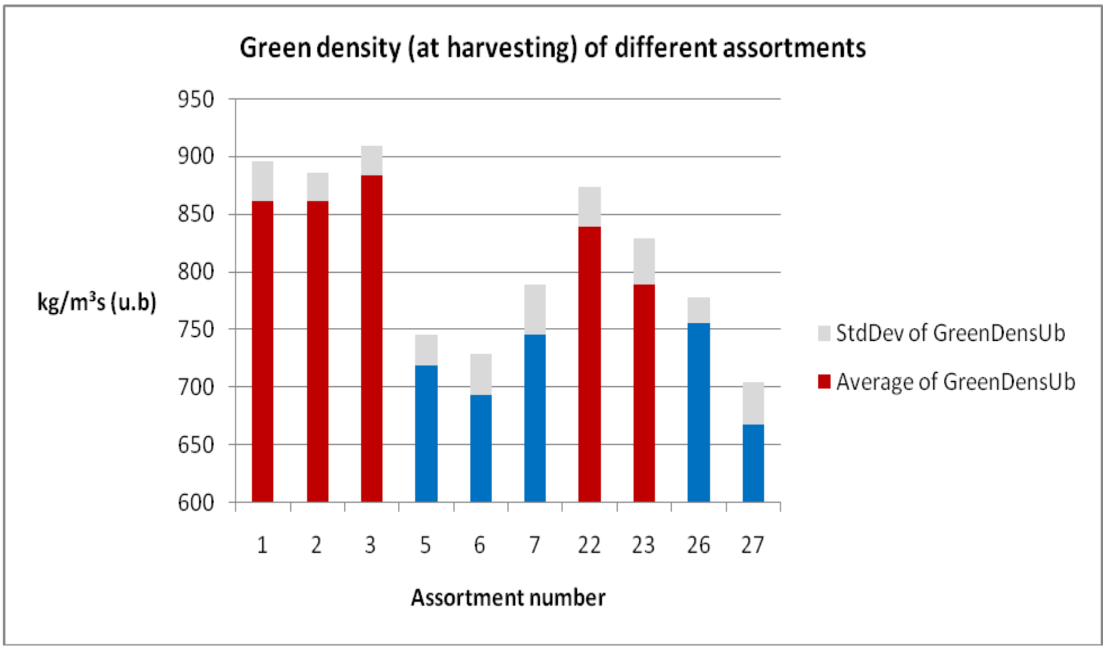

Figure 29. Predicted green density (kg/m³s u.b.) (Model: Wilhelmsson & Moberg 2004) of all assortments (table 2). Lower bars represent averages and upper bars + 1 standard deviation in predicted values. Green density is of interest e.g. for haulage operations (possible loads/truck) and freshness estimates at industry gates.

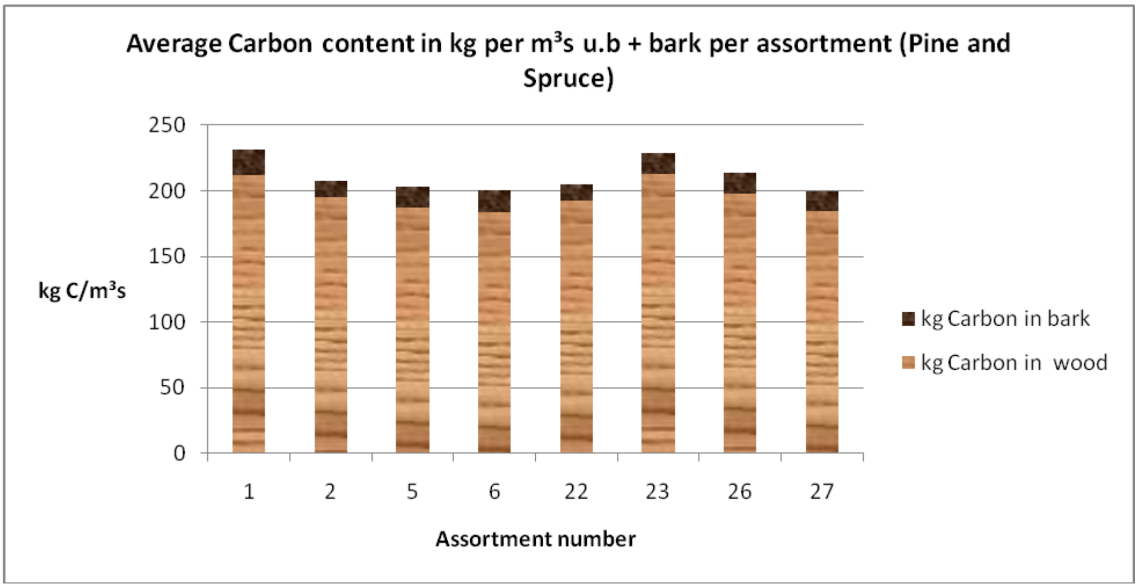

Figure 30. Predicted carbon content (Tentative models extracted from Lamlom & Savidge 2003) of wood and bark in sawlogs and pulpwood (assortments table 2).

5.4 Utilisation of results from bucking simulations

As the coordinates of each sampled stand and the standing volumes average tree sizes and species are included in the forest inventory data, the expected cost consumption of liter diesel per m³ for harvesting, sorting and forwarding operations (*figure 31*) can also be estimated (functions harvesting: Brunberg 2007, sorting Brunberg & Arlinger 2001).

Differences in tree sizes, volumes per hectare, different site conditions and the sorting regimes affect the productivity.

When specific assortments are destined to specific industries it is also possible to estimate and add the cost for haulage operations (*figure 32*). This makes it possible to estimate the total costs for alternative forest and haulage operations to industry and predict the possible differences in assortments, log dimensions and predicted wood, knot and fibre properties (Wilhelmsson et al 2007). To achieve efficient selection, sorting and bucking of logs that are optimally (cost/benefits economically/environmentally) adapted to actual industrial processes and products, there is a need for developed industrial valuation and specification of the real impact from logs of different properties. By developing and utilising this knowledge into transparent valuation of costs and benefits along alternative production chains, the different value of different wood and log dimensions may also be efficiently reflected at the wood market. If this can be better achieved by frequent bucking simulation the forestry sector will be able to supply the most beneficial industrial utilisation of the forest resources.

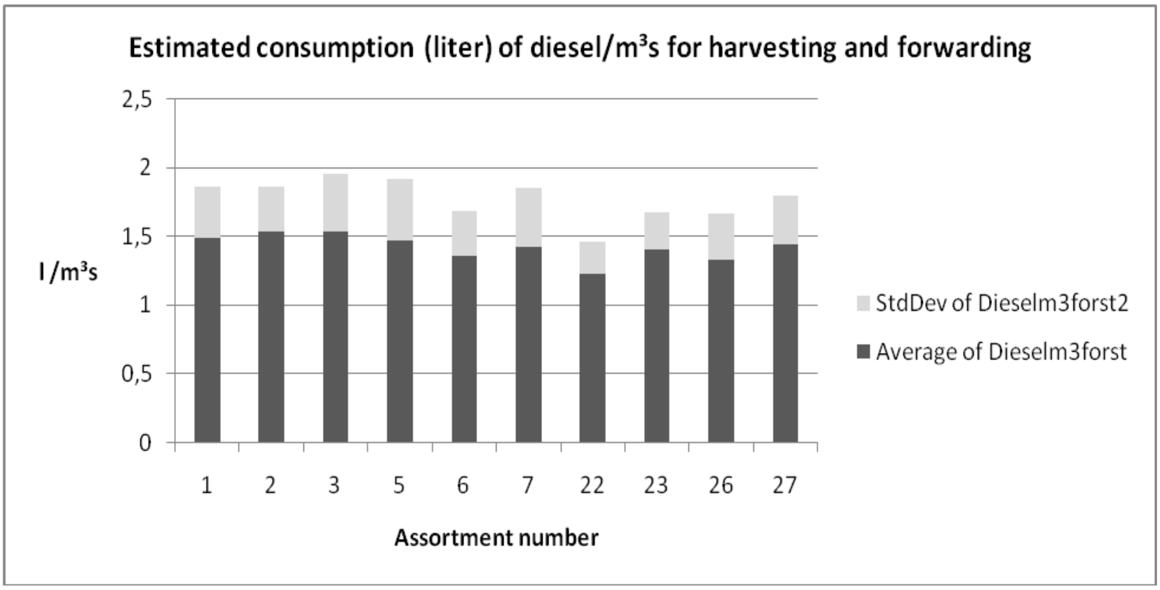

Figure 31. Estimated consumption of liter diesel per m³s (u.b) + bark per assortment (table 2), based on models by Brunberg 2007 and Brunberg & Arlinger 2001.

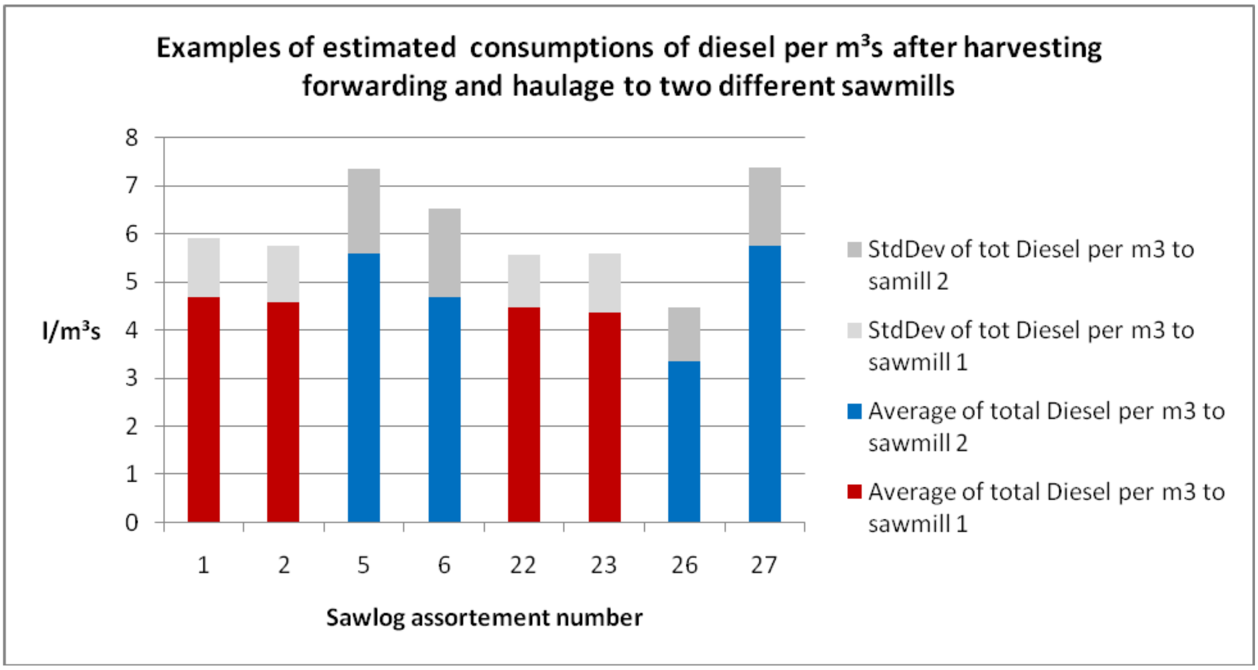

Figure 32. Example of estimates of total consumption of liter diesel per m³s (u.b) + bark per assortment (table 2), based on estimated costs of forest operations and a simplified calculation of haulage distances based on the location of 600 forest stands and two arbitrary industries (Wilhelmsson et al 2007).

6 Case Baden-Württemberg

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 study 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 and is described in Eforwood PD 3.0.3.

6.1 Context, objectives and methods

The Forest Research Institute Baden-Württemberg (FVA) has developed special models and tools, which match the inventory data and roundwood grading classes of Baden-Württemberg, to estimate the grades of saw logs from spruce trees in the forest resource. Virtual grading was applied according to EN 1927-1 (2008) and former grading standard HKS which will be succeeded by RVR in 2009. Inventory data and models are used to simulate the size and shape of the spruce trees and to derive quantity of roundwood grades of sawlogs both for conventional bucking to pole length and to standard length. The grading criteria are:

- the average annual ring width at the top of each log
- the diameter of its largest branch.

From these properties, the grade is estimated.

This is an example of modeling and simulation emphasizing a specific task. The result and its application should be very useful for optimal allocation of sawlogs to the regional mills and their products.

6.1.1 Cascade calculation structure

The resource database for Baden-Wuerttemberg is built as a cascade of 58 equations and consecutive queries. It is built upon the database of the national inventories I (1987) and II (1999-2002). The framework of the model cascade scheme is shown in the *figure 34*. The scheme of calculations is an efficient adaptation to the specific application of the general scheme referred to above.

Input data from the inventories are shown in violet rectangle signatures (“BWI2”).

The boxes with a double frame are derived from these inputs and other data of the inventory. Both data sets are used to calculate variables in the different models (blue boxes) to be used as input in consecutive calculations.

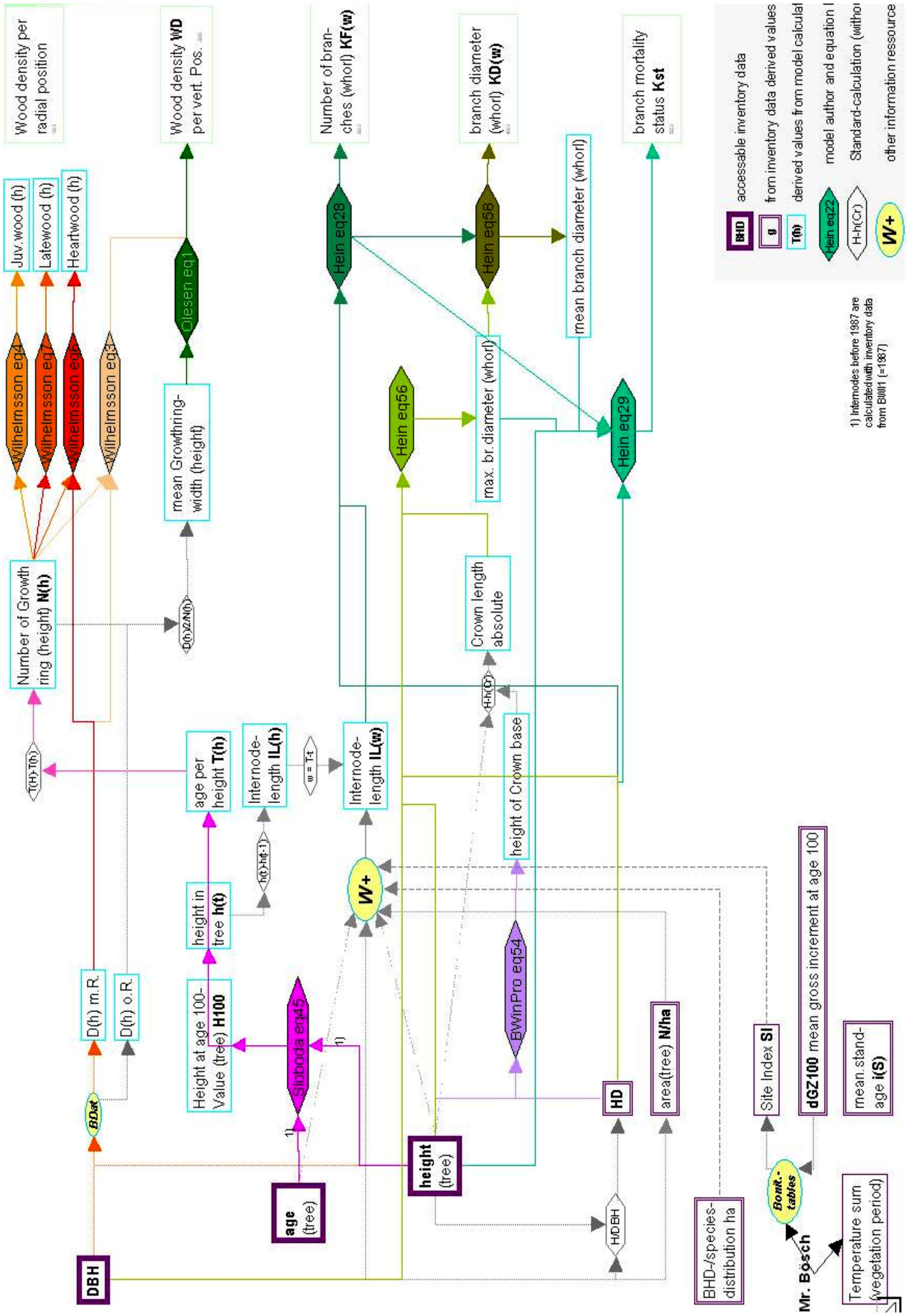

Figure 34. Scheme of consecutive calculations for estimation of property variations within and between trees.

"Calculated variables" are derived or calculated through

- "standard equations" without a equation-ID,
- "regular" equations which are described on detail in the database under a special ID
- other information resources with an external origin (e.g. software modules).

The equations for the calculation are given in figures in hexagonal format.

"Standard" equations describe usual conversions and are not listed in the framework of used model equations.

Equations describing a predictive model are shown as hexagonal symbols in specific colour, the text specifies the name of the author and the ID of the equation as it is listed in the database. The models predicting wood density and the contents of juvenile wood, latewood and heartwood are the same as the ones used in Västerbotten, (4) to (7), based on data from the Swedish project "Forest-pulp-paper". However these model steps were not used for the quantification of grades as presented below. Output to input relations between models are represented by arrows coming from input-data to the equation.

Yellow signatures represent information which is linked to calculations that are specified elsewhere, because the model package is integrated completely into the structure. For example "BDat" is a software, whose DLL-libraries are integrated.

Targeted variables are placed in green boxes.

6.1.2 Data basis and computation

Input values from 2nd National Forest Inventory Survey 2002 are for *Picea abies* (L.) Karst:

- dbh-values 2002, if applicable 1987 (1st NFI);
- height of tree,
- tree age

The taper is computed assuming a mean stem form given by the stem taper functions implemented in "BDatPro" (Kublin, 2002).

Branchiness is modelled for whorl branches only and is calculated with the model introduced by Hein (2007). The model is parameterised based on data from experimental plots in Baden-Württemberg.

Height, internodes and number of growth rings

Height increment is modelled by a well proven equation from Sloboda (1971). At the same time it gives information about the number of growth rings at a given height as long as we can take height information from 1987 and 2002 as precisely.

Height at age 100 (=SI100)

$$SI100 = 65^{a_1} \cdot \left(\frac{H}{65^{a1}}\right)^{\exp(b1/(c1-1)\cdot 100^{(c1-1)})} - \frac{b1}{(c1-1)\cdot T^{(c1-1)}}$$

Height by age and SI100

$$H = 65^{a1} \cdot \left(\frac{SI100}{65^{a1}}\right)^{\exp(b1/(c1-1)\cdot T^{(c1-1)})} - \frac{b1}{(c1-1)\cdot 100^{(c1-1)}}$$

Age at a specified height and SI100

$$Alter = \left[\frac{b}{\frac{b\cdot(c-1)}{(c-1)\cdot 100^{(c-1)}} - (c-1)\cdot\left(\ln\left(\frac{\ln\left(\frac{SI100}{65^{a}}\right)}{\ln\left(\frac{H}{65^{a}}\right)}\right)\right)}\right]^{\frac{1}{(c-1)}}$$

where:

H	height of tree
SI100	tree specific dominant height at 100years
T	age
a1	0,950341
b1	0,631875
c1	0,871933

Taper

Taper is assumed to be mid-form as it is described in BDatPro-Manual (Kublin 2002):

$$E\ q_{Hx} = S_h(h_x) + S_H(h_x)*H + S_D(h_x)*D_{0.05} + S_d(h_x)*q_{0.30} \quad (1)$$
$$= E\,[\,D_{Hx} / D_{0.05}\,|\,H_x; D_{0.05}, q_{0.30}, H\,]$$

Branchiness

Crown base height of Norway spruce is computed based on equations implemented in the simulator BWinPro7 (Nagel et al 2006):

$$KA = H \cdot \left[1 - e^{(-\alpha+\beta\cdot H/D)^2}\right]$$

where:

KA	Crown base height
H	height of tree
H/D	height/DBH-ratio

The branchiness model (Hein, 2007) consists of the following parts:

1. Maximum branch diameter in a whorl:

$$\ln(BRD\max lptw) = c_0 + c_1 \cdot DBH_{lpt} + c_2 \cdot HD_{lpt} + c_3 \cdot DIST1_{lptw} + c_4 \cdot DIST3_{lptw} + \gamma_{lpt} + \gamma_{lptw} + \gamma_{lptwb}$$

2. Individual branch diameter in a whorl:

$$\ln\left[\frac{BRD_{ptwb}}{BRD\max_{ptw}} / \left(1 - \frac{BRD_{ptwb}}{BRD\max_{ptwb}}\right)\right] = d_0 + d_1 HD_{lpt} + d_2 R_{lptwb}$$

3. Number of branches in a whorl:

$$\ln(NBRT_{lptw}) = a_0 + a_1 HD_{lpt} + a_2 IH_{lptw} + \alpha_{lpt} + \alpha_{lptw}$$

4. Branch mortality status:

$$\ln\left[\frac{\Pr(BRS_{lptwb})}{1-\Pr(BRS_{lptwb})}\right] = b_0 + b_1 HD_{lpt} + b_2 DIST3_{lptw} + b_3 \frac{BRD_{ptwb}}{BRD\max_{ptw}}$$
$$+ \beta_{lpt} + \beta_{lptw} + \beta_{lptwb}$$

where (Hein, 2006):

BRD	branch diameter,excluding the thickest branch of a whorl
BRDmax	Maximum branch diameter in a whorl [mm]
BRS	Branch status [living=1; dead=0]
DIST	Distance between the whorl and stem apex
DIST1	DIST/(H-HCB)
DIST3	ln(DIST1)
HCB	Height of the crown base (lowest living branch), measured from stem base
HD	Height[m]/diameter at breast height [cm]*100
IH	annual height increment
NBRT	Total number of branches in a whorl (living and dead combined)
R	Rank of the branch, ordered from largest to smallest diameter

b0	11,6636
b1	-0,0486
b2	6,3084
b3	0,092
d0	3,5509
d1	-0,0084
d2	-0,3424
a0	2,0103
a1	-0,0072
a2	0,3424
c0	4,031
c1	0,0196
c2	-0,0013
c3	-0,7723
c4	0,6271

6.2 Simulation run specifications and results

Specifications

For the simulations of the roundwood quality distribution for spruce in Baden-Wuerttemberg, the following harvesting specifications were defined:

- timber log length 5m standard length
- cutting height, stock height 0.2m
- Minimum top diameter 14cm

Targeted quality property: taper according to ENV1927-1

Threshold-values for the classification are taken from ENV 1927-1.

	mid-stem size	A	B	C	D
Taper	<20cm	<=1,25	<=1,25	<=2	>2
	<35cm	<=1,5	<=1,5	<=2,5	>2,5
	>=35cm	<=2	<=2	<=4	>4

size class	**LO**	**L1a**	**L1b**	**L2a**	**L2b**	**L3a**	**L3b**	**L4**	**L5**	**L6**
threshold-value [cm]	<10	<15	<20	<25	<30	<35	<40	<50	<60	>60

Results – taper

Figure 35 shows the distribution of roundwood (5m-size logs) according to stem taper classification for Norway spruce in Baden-Württemberg as simulated based on diameter, height and age inputs from the National Forest Inventory 2002. The taper classification follows the thresholds given in EN 1927-1. It must be noted that thresholds for grade “B” are identical with the threshold for grade “A”, thus there is no “B”-class present.

Queries for classification on the base of max branch diameter per log and average ring width at top diameter are already included on the cascade structure, but are not presented here.

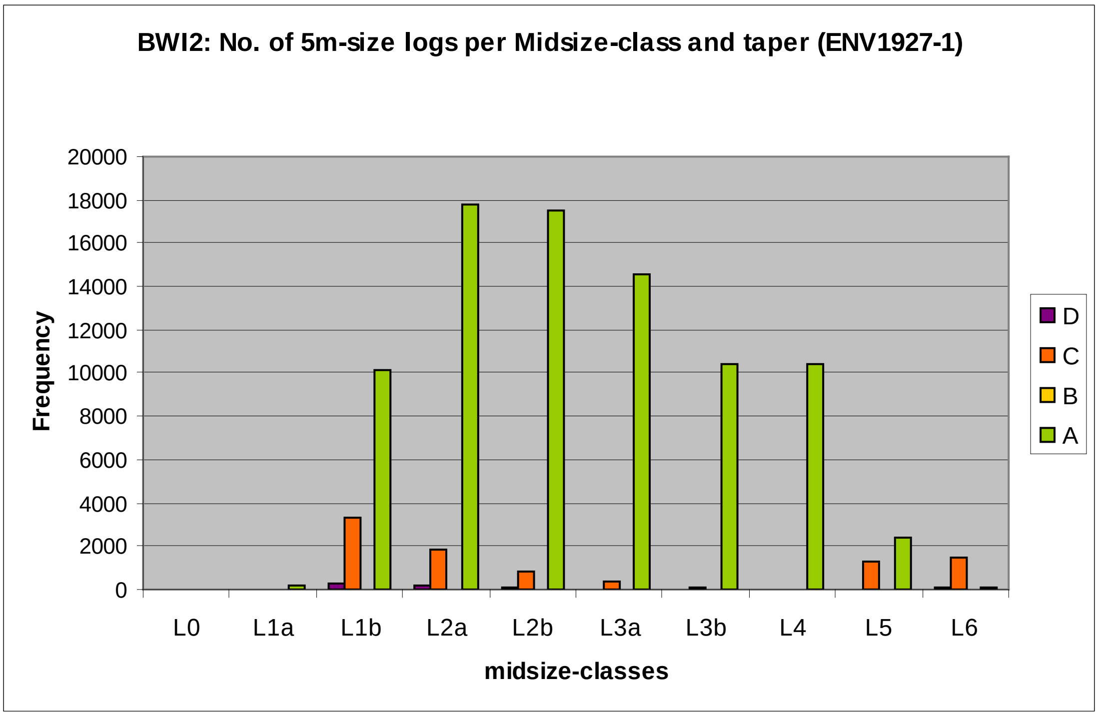

Figure 35. Frequency of taper-classes A-D (acc. to ENV1927-1) in the National Forest Inventory 2002 for Baden-Württemberg, *Picea abies* only; Number of 5m-size logs=93364; Number of trees=24636.

Observations and experiences

This is an 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 results presented here only consider one criterion "taper" for grading to illustrate . This simplistic example shows already the potential for well-directed allocation decisions. Stem taper and log dimension are important features as both characteristics determine yield of the sawn product fundamentally in the sawmill production. The dimension of the log directly reflects on the potential maximum cross-sectional dimension of the sawn product, and thus on the potential final utilisation when considering the sector of construction timber for example.

Figure 35 illustrates the availability of very straight logs and the development of stem taper with increasing stem dimension. It also shows the differentiation in stem taper for the different diameter classes which can be used for allocation decisions.

The example shown is based on the full set of all data available for trees in the database of the Baden-Württemberg forest inventory. However, a smaller number of trees can be selected from the full data represent for a smaller, more specific area or a specific region around individual sawmills. This allows a regionalised view of the forest resource in geographic areas of Baden-Württemberg.

Conclusions and further development

This simulation shows an initial step to build a Forest Resource Database for Baden-Württemberg. The models and relations implemented in the simulation cascade however are not all validated for the Baden-Württemberg resource and might require further refinement and re-parameterisation due to the heterogeneous characteristics of the growth conditions and silvicultural management in Baden-Württemberg. We started to build the database for the resource of Norway spruce representing about 60% of the standing stock. However important tree species such as beech, fir, oak, pine are not considered yet, but should be implemented in future when a similar set of relations on wood properties will be available.

7 Case South Scotland

A regional case study covering the South of Scotland has been developed within EFORWOOD by Forest Research. The case study covers only processes in M2 and M3 (i.e. from forest establishment to the mill yard). The model currently deals with Sitka spruce managed under a number of different management scenarios. The growth of the trees under these management options is forecast from standard growth and yield models (Edwards and Christie 1981). 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. 2009). 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 (Anonymous 1993). 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). Such information will form part of the production forecast for UK forests due in 2011.

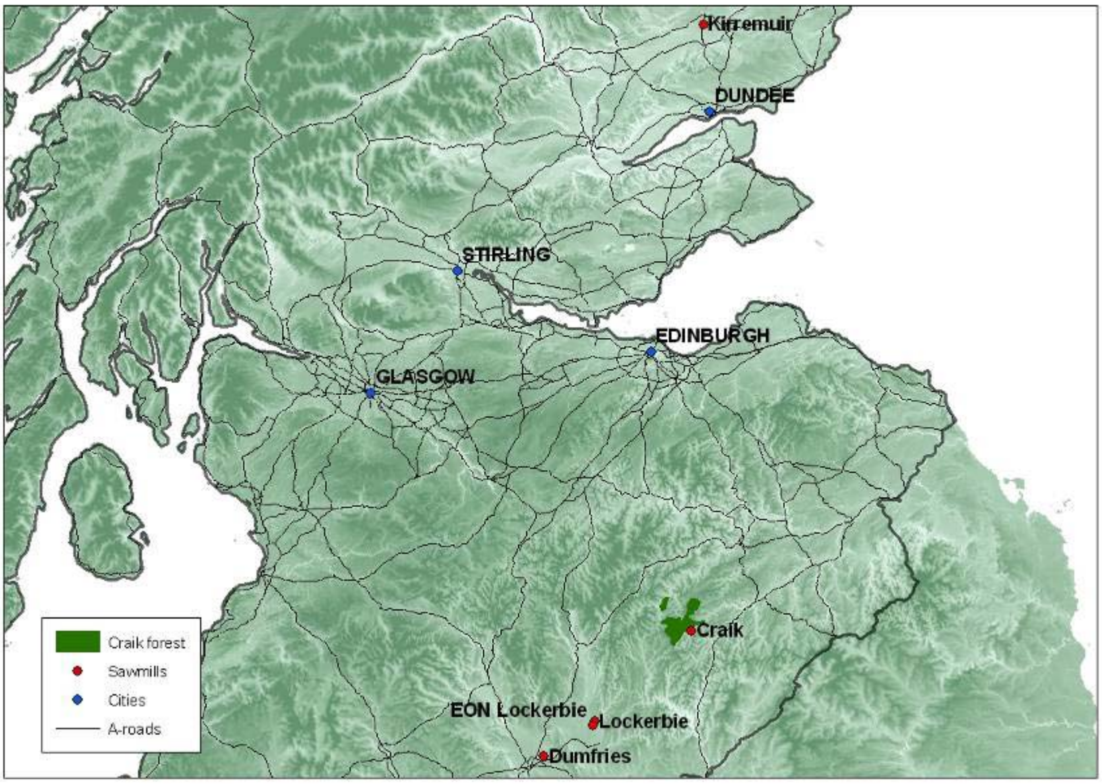

Figure 36: Location of Craik Forest.

7.1 Objectives and methods

As part of the South Scotland regional case study Craik Forest, *figure 36*, has been studied in particular detail. This is in order to develop the possibility of using predictions of tree and wood properties as a method for product assortment and allocation. Craik Forest is an upland forest of predominately Sitka spruce planted from the end of World War II onwards but with large areas planted from 1971-1975, *figure 37*. Based on a recent survey of the forest (Evans, 1998) 83 % of the forest area is Sitka spruce with the remaining area composed of Norway spruce (7 %), Lodgepole pine (5 %), larch (4 %) and Scots pine (1 %), *figure 38*. There are a few very isolated and small areas of broadleaves. The Sitka spruce is growing at a General Yield Class average of 16 (Edwards and Christie 1981). The majority of stands are in Wind Hazard Classification 5 (Miller et al. 1987) which means that thinning is restricted and risk of wind damage is an dominating management issue.

Forests in South Scotland on elevated and exposed sites can have problems with stem form (Stirling et al. 2000.) and wood stiffness (Moore 2009). Statistical models have been developed, which can predict mean or median stem straightness (Gardiner et al. 2009) and mean stand wood stiffness (Moore 2009). The objective of the resource mapping exercise was to initially map the distribution of predicted tree size, stand straightness and stiffness and then to develop allocation strategies at forest, stand and tree level based on these characteristics.

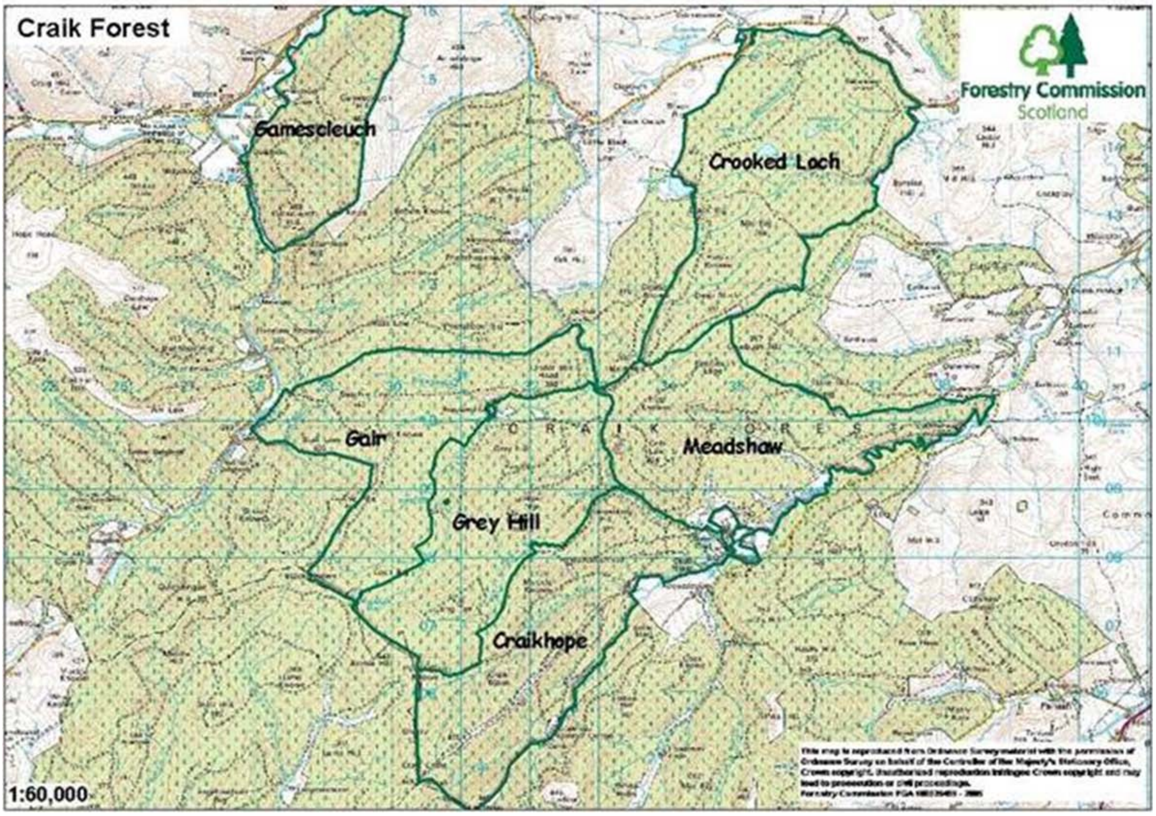

Figure 37. Map showing Craik Forest with Forestry Commission areas outlined in green.

7.2 Data Used

Craik Forest is managed by Forest Enterprise (Scotland), which is the forest management part of Forestry Commission Scotland. Data for all management units (sub-compartments) in the forest are held in a database (SCDB = sub-compartment database). Some key information contained in the SCDB is shown in *table 3*. This includes planned felling year for each sub-compartment based on agreed forest management plans. The SCDB was used as input to yield models to forecast the forest growth into the future and to give predicted thinning and final felling volumes. For this exercise all stands due to be felled in Craik Forest between 2005 and 2030 inclusively were selected.

Table 3: Example parameter data in the Forestry Commission Sub-compartment Database (SCDB).

Variable	Units	Comments
Forest number	Number	
Compartment	Number	Clear variations in compartment such as planting year and species are identified alphabetically as sub-compartments
Sub-compartment	Letter	
Soil	FC Code	Not always available
Elevation	m	
Cultivation	FC Code	
Thinning status	FC Code	
Species	FC Code	May be pure or mixed e.g. SS=Sitka spruce MB = Mixed broadleaves
Planting year	Year	
Yield Class (YC)	m^3/ha/year	
Planted spacing	m	
Area	Ha	
Productive area	%	
Rotation number	Number	1st, 2nd, 3rd, etc.
Planned felling year	Year	

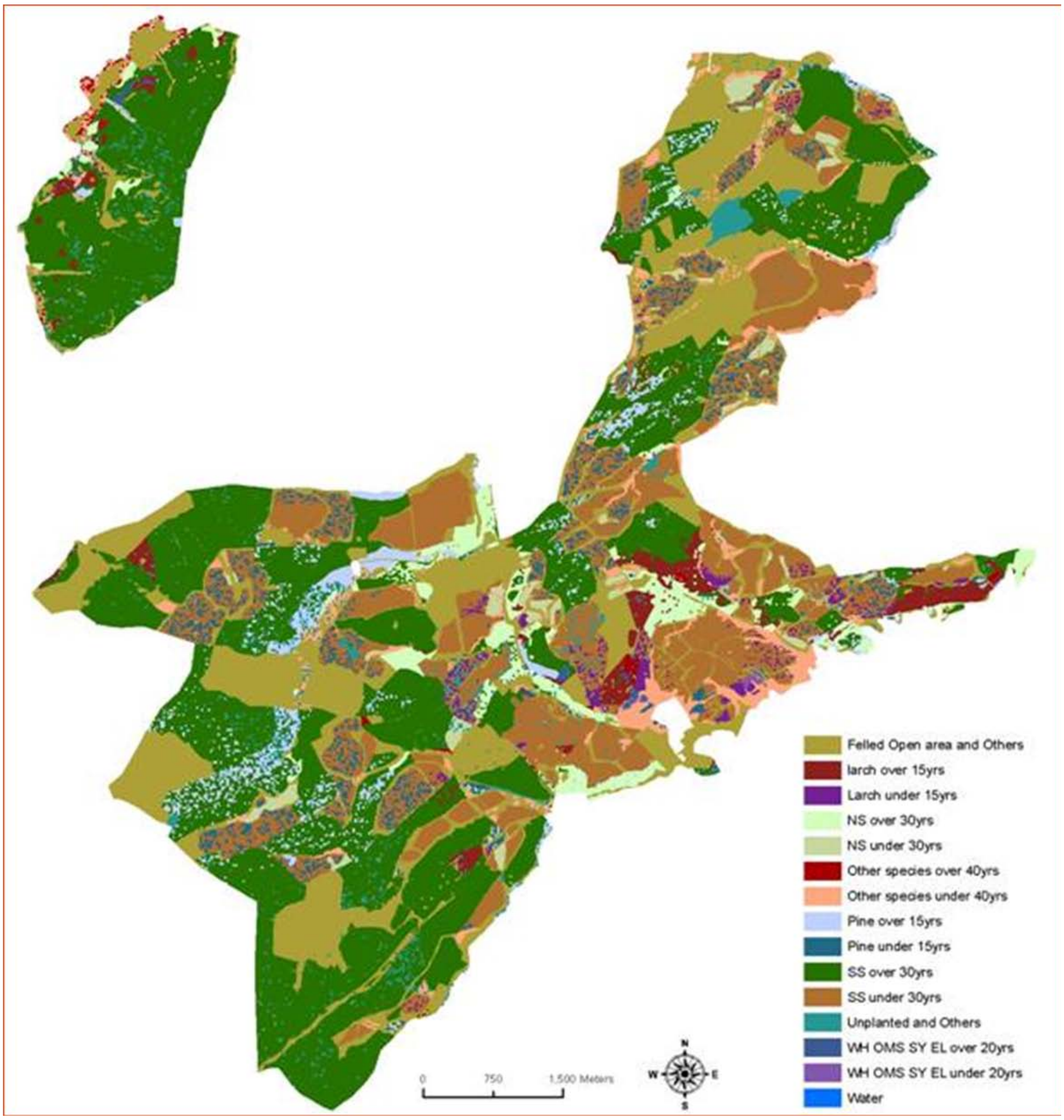

Figure 38. Species distribution map for Craik Forest.

7.3 Models Used

7.3.1 Growth Models

Tree growth is predicted using the yield models developed by (Edwards and Christie 1981). These have been developed from an array of permanent sample plots located across the UK. Models only exist for specific combinations of yield class (YC), initial spacing (IS) and thinning pattern. For combinations that do not have an associated yield model it is necessary to use the closest available model.

The models provide information at 5 year intervals on stand top height (mean height of 100 largest diameter trees per hectare), mean diameter at breast height (*dbh*) (cm), basal area (m^2/ha), number of trees per ha and tree spacing (m). The 5 year intervals are due to the measurement periods for the permanent sample plots and intervening year information need to be interpolated.

7.3.2 Volume Assortment Models

At thinning or harvesting the output of the yield models were used to produce a range of products with different top diameters over bark (*dtop*). These were sawlogs (*dtop* ≥ 18cm), pallet log (18 > *dtop* ≥ 14cm), pulp log (14 > *dtop* ≥ 7 cm) and biomass (*dtop* < 7cm). The log volumes were calculated from volume assortment models based on data in Edwards and Christie 1981:

Thinned stands

$$Rd = Exp\left(-0.8456 \times \frac{dtop^{4.2233}}{dbh^{4.0229}}\right)$$

Unthinned stands

$$Rd = Exp\left(-0.8796 \times \frac{dtop^{3.5031}}{dbh^{3.3597}}\right)$$

Wide spaced stands (>3m)

$$Rd = Exp\left(-0.9354 \times \frac{dtop^{4.6695}}{dbh^{4.467}}\right)$$

where *Rd* is the ratio to multiply the tree volume by to obtain the volume to a diameter given by *dtop*. Sawlog volume is simply the volume to 18cm (*Rd* = 18), pallet log volume is obtained by subtracting the volume to 18cm from the volume to 14cm, pulp log volume by subtracting volume to 14cm from the volume to 7cm and biomass by subtracting the volume to 7cm from the total volume.

7.3.3 Taper Models

In order to obtain estimates of available log length it is necessary to use taper models such as developed by Fonweban et al. 2009 and Achim et al. 2006:

$$d_{hi} = dbh\left[\frac{(H-hi)}{(H-1.3)}\right]^{0.762023+0.560651\left(\frac{hi}{H}-1\right)+1.523838\left(\exp\left(-4.71007\frac{hi}{H}\right)\right)}$$

or

$$d(z,H,dbh) = 0.8878dbh\left(1-\frac{z}{H}\right)^{k(z,\theta)}\left(1+0.3367e^{-\theta_4\frac{z}{H}}\right)$$

where

$$k(z,\theta) = \theta_1(H, dbh) + \theta_2\left(1 - \frac{z}{H}\right)$$

$$\theta_1(H, dbh) = 1.0006 - 0.3520\left(\frac{H}{dbh}\right)$$

$$\theta_2(age) = -0.4029 - 0.00331(age)$$

$$\theta_4(age) = 4.3135 + 0.2498(age)$$

7.3.4 Stem Straightness Models

Predictions of Sitka spruce stem straightness at a stand level are based on extensive surveys across Great Britain using the methodology of (Macdonald et al. 2001). The models predict mean and median stem straightness for stands and the probability of a stand having a particular quality grade. See Macdonald et al. 2009 and Gardiner et al. 2009 for further details.

$$MeanSS = 0.855 + 0.1147 \times dbh \text{ - } 0.0398 \times DAMS$$

where *DAMS* is a measure of wind exposure (Quine and White 1994) and *dbh* is in cms.

$$MedianSS = -1.0773 + 0.2837 \times thin + 0.0506 \times age + 0.2427 \times \frac{IS}{1000}$$

$$-0.2832 \times \frac{elevation}{100} + 0.0301 \times YC + 0.0704 \times dbh$$

where *thin* is 1 for thinning and 0 for no thin, *IS* is the number of trees/ha at initial planting, and *elevation* is in m.

7.3.5 Green Log Conversion Models

From stand mean and median stem straightness it is possible to make a prediction of the percentage of “green” and “red” logs as defined by their straightness and knot size (Anonymous 1993). “Green” logs attract a higher price and green log percentage is an important determinant of stand quality.

$$\frac{\text{Green Log Volume}}{\text{Total Log Volume}}\% = 8.632 \times MeanSS \text{-} 1.443$$

$$\frac{\text{Green Log Volume}}{\text{Total Log Volume}}\% = 5.17 \times MedianSS + 20$$

7.3.6 Wood Stiffness Model

The stiffness model used is based on the benchmarking study of Moore 2009. The model is based on measurements of the acoustic velocity in the outer wood of standing trees from 64 sites across Scotland and Northern England. The model for *MOE* (modulus of elasticity) is:

$$MOE = 19.656 + 0.05173 \times Age - 0.6097 \times YC - 0.05071 \times elevation - 0.005335 \times Lat$$
$$-0.002454 \times IS + 0.00001729 \times elevation \times Lat + 0.00231 \times YC \times elevation$$
$$+0.0001536 \times YC \times IS + 0.00001089 \times elevation \times IS - 0.0000006935 \times YC \times elevation \times IS$$

where variables are as described previously and *Lat* is the distance north in km from the UK National Grid origin.

In addition a model was developed to predict the expected variation in wood stiffness based on acoustic measurements on populations of trees in uniform stands:

$$P_r = \exp(-MOE_x)$$

where

$$MOE_x = \left(\frac{(GradeMOE \times 0.95) - W_A}{W_B} \right)^{W_C}$$

$$W_{AB} = 1.08719 \times MOE - 0.01656$$

$$W_B = 1.20557 \times MOE - 4.688$$

$$W_A = W_{AB} - W_B$$

$$std = 0.48949 \times MOE$$

$$W_C = 1.13629 \times \frac{MOE}{std} - 1.14085$$

MOE is the site mean stiffness as defined in the previous equation, *GradeMOE* is the mean stiffness required for a particular strength class (CEN 2003) and P_r is the proportion of trees within a site exceeding this strength class. The factor of 0.95 is because the stiffness needs to be only 95 % of the grade mean value.

7.3.7 Wood Density Models

Although not currently used in the Craik simulations it is also important to know the mean density of wood from standards in order to meet the grading rules as discussed above. In future simulations the stand mean density will be calculated using the model developed by (Gardiner et al. 2009):

$$SG(RN, RW) = 0.4322\left(1 + 0.5829 e^{-RN/5.3193}\right)\left(1 + 0.002RN - 0.0472RW\right)$$

where *SG* is the specific gravity, *RN* is ring number from pith, and *RW* is ring width (mm).

7.4 Examples of results

A total of 48 sub-compartments in Craik Forest were identified as producing felled material between 2005 and 2030. Details of the stand characteristics and the model derived predictions are given in *table 4*.

Table 4. Parameter values for sites planned for felling in Craik forest between 20005 and 2030.

Parameter	Minimum	Mean	Maximum
Felling Year	2005		2028
Age	23	42	63
Yield Class	12	18	22
Initial Spacing (m)	1.7		2
Elevation (m)	225.5	295.7	411
DAMS	13	15	19
Felled Volume (m^3)	16	1514	13583
Dbh (cm)	21.3	31.2	46.5
Mean Tree Height (m)	11.7	20.5	30.2
Mean stand straightness	2.8	3.8	5.7
Green Log Percentage	22.4	31.6	47.6
MOE (GPa)	6.4	7.6	8.7

The results indicate that the stands are generally at relatively high elevations for Great Britain (225.5 to 411 m) with moderate to severe exposure (*DAMS* = 13 to 19). The mean yield class of 18 is higher than average suggesting that these are productive stands. The volumes extracted are very variable with extremely small volumes (16 m^3) from some of the smaller stands (0.33 ha) to large volumes (13583 m^3) from large stands (27.6 ha) at the tops of hills.

The predicted straightness of the stands ranges from 2.8 to 5.7 with an average of 3.8 (*figure 40*). This is considerably better than the average for South Scotland reported by (Stirling, Gardiner et al. 2000.) of 2.94, which suggests a high percentage of “green” sawlogs will be able to be cut (31.6 % average). Of particular interest is the change of straightness and “green” log percentage with age as illustrated in *figure 41*. This shows that in general the straightness and “green” log percentage increases with age because mean *dbh* is increasing but that for stands over approximately 45 years age there is a decline in straightness. Further investigation shows that these older stands are all at higher elevations with increased exposure (*DAMS*) and the models predict this has a negative impact on tree form.

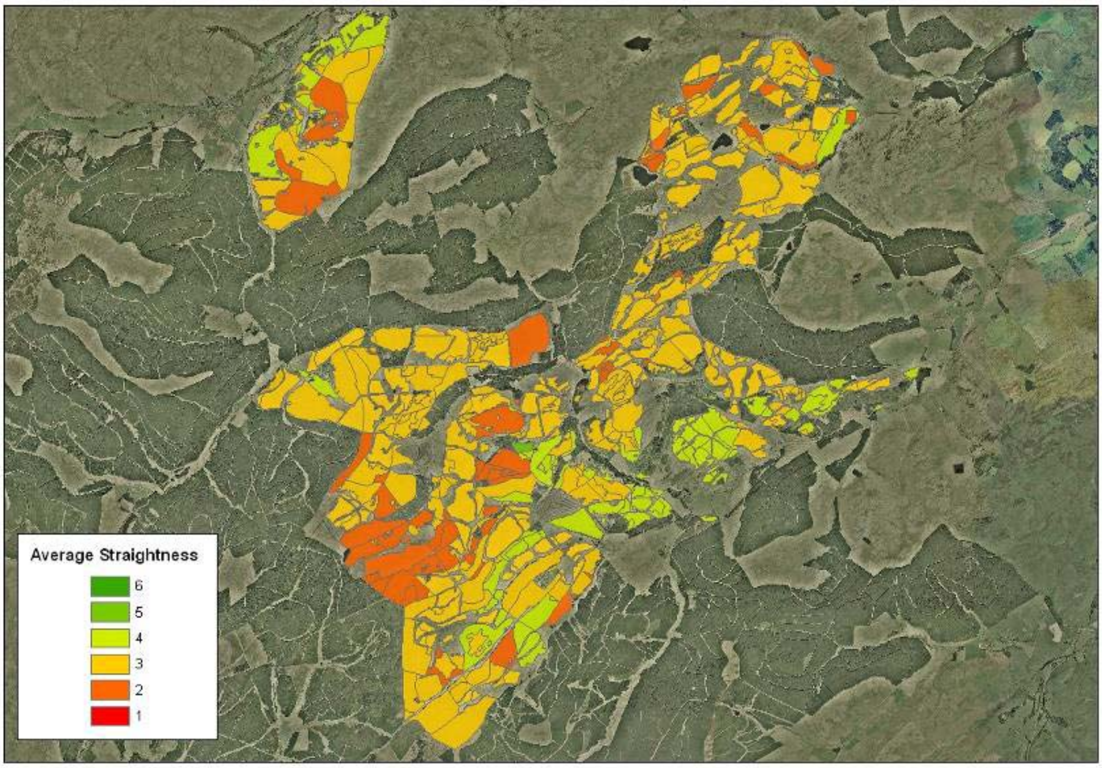

Figure 40. Predicted mean straightness of Sitka spruce stands in Craik Forest

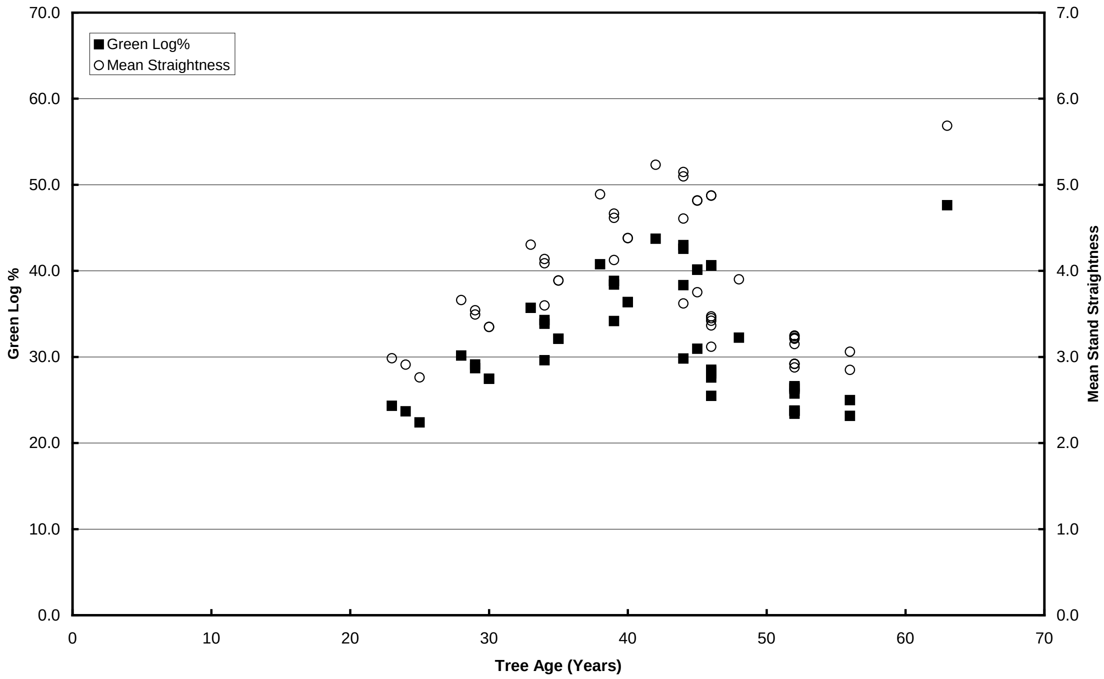

Figure 41. Change in predicted mean stand straightness and “green” sawlog percentage as a function of age at felling.

In contrast the mechanical properties (*MOE* & P_r) show a steady increase with age, *figure 42*, because the mature wood on the outside of the tree increases in density. The proportion of trees exceeding the lower limit *MOE* value for C16 strength class increases with time and is always above the necessary 95% level but not until the trees are over 50 years of age does the mean strength meet the requirement of 8 GPa. Therefore, the stands planned for felling at longer rotation lengths (>45 years) generally have acceptable mechanical properties but will have poorer form and will have a lower percentage yield of “green” sawlogs (millable) due to the wind exposure of the selected sites.

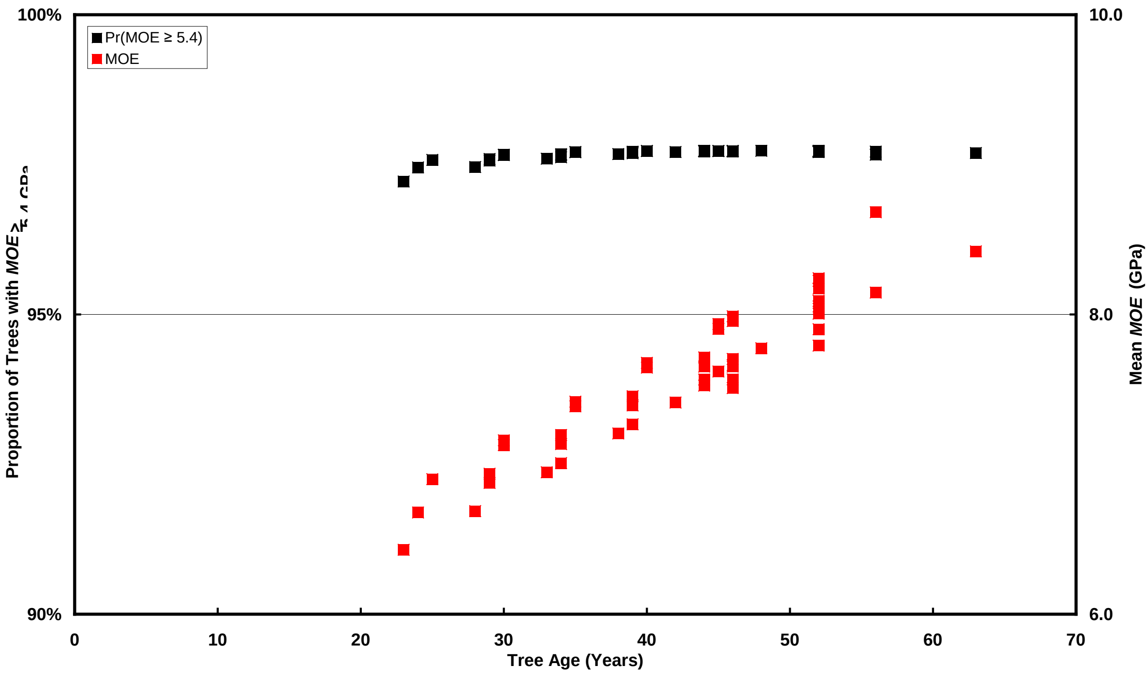

Figure 42. Change in predicted mean wood stiffness (MOE) and proportion of trees exceeded the lower limit of C16 strength grade class as a function of age at felling.

7.5 Conclusions and further development

The modelling of the tree and wood properties of the stands due for harvesting in Craik Forest from 2005 to 2030 has indicated operationally significant differences. In particular the analysis has highlighted the fact that trees in the more exposed locations are being left longest before harvesting. In addition to being at high risk of wind damage (see *figure 43* below), their forecast straightness is less than sites at lower elevations. In contrast because of the extended rotations of greater than 45 years at these higher elevation sites the wood mechanical properties are forecast to be amongst the best within the forest because of the addition of increasing volumes of mature wood. Therefore, the stands within the forest with the best wood mechanical properties are likely to produce short (<4m) sawlogs, whereas the stands with better form at lower elevations are being harvested early before they have developed substantial volumes of mature wood.

The analysis points to the possibilities of investigating alternative management scenarios with an overall improvement in the timber properties of harvested material and more appropriate management that accounts for site characteristics. These ideas are explored in further detail in the report on material allocation (Lundqvist et al., 2009).

Further developments of these ideas will be made with the addition of predictions of wood density to complement forecasts of wood stiffness. In addition, field work is currently underway to further refine and validate the straightness and stiffness models used in this analysis. Finally, the variation within stands from tree to tree (typically 50% of all variability) needs to be addressed more systematically so that decisions at an individual tree level can be made. An initial attempt has been made to do this with the predictions of the proportion of trees likely to exceed specific stiffness thresholds, but similar models are also available for predicting the distribution of stem straightness within stands (Gardiner, Mochan et al. 2009).

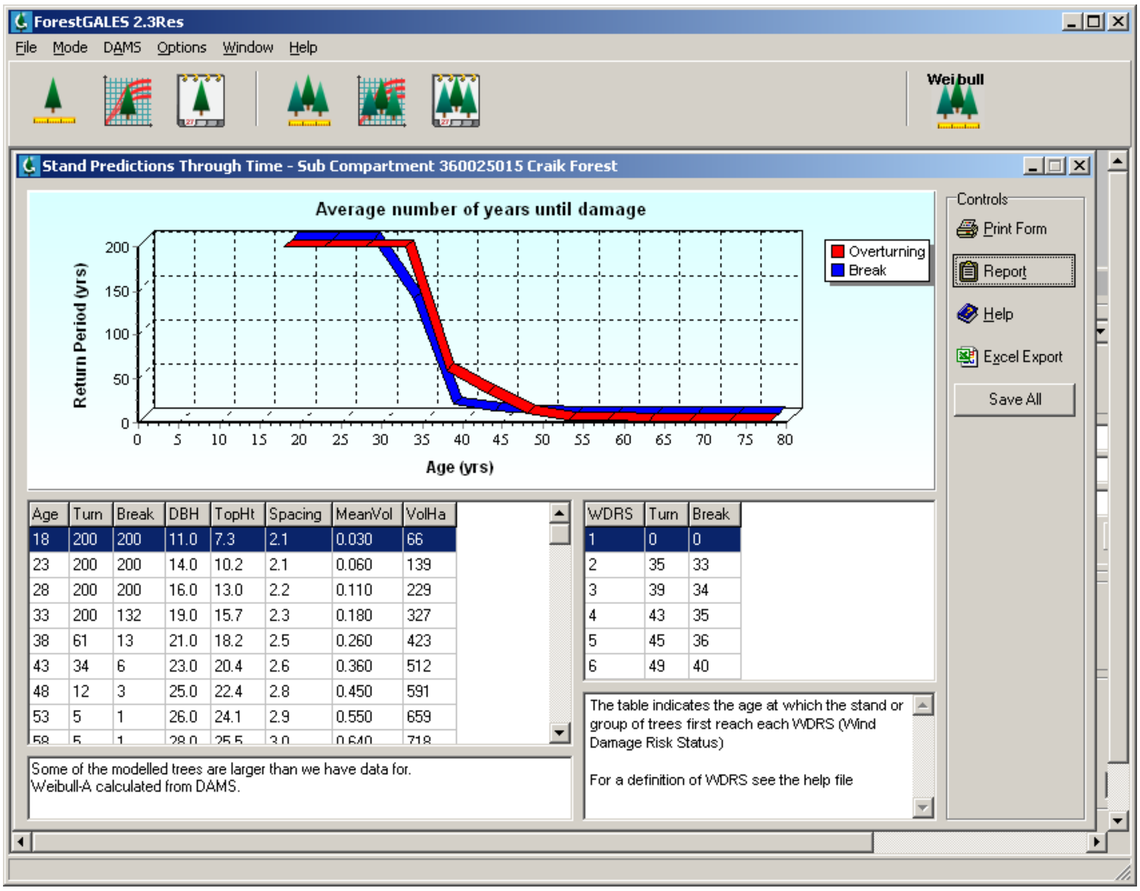

Fig 43: Risk of windblow and windsnap for sub-compartment 360025015. This site has a high level of wind exposure (DAMS = 19) and when planned for felling at age 52 years will be in the highest risk category (WDRS = 6).

8 Conclusions

The allocation of suitable materials to mills, processes and products is crucial for the sustainability of the forestry wood chains, affecting both economics, environment and society. If unsuitable material is allocated to a process, this will normally lead to use of more material, energy, etc. than necessary and the quality, product functionality and customer satisfaction may be compromised.

One crucial prerequisite for successful allocation is access to information about the volumes and properties of the wood raw materials available in the forest resource, in relation to industry needs. These issues have been dealt with in the EFORWOOD workpackage “Quality assessment and allocation”. Mapping of properties in forest resources have been achieved through simulation with models for properties of wood, fibres and knots, resulting in data to support optimal allocation of wood to various products and also efficient processing. Such mapping of properties in forest resources has previously been done for some regions, wood species and properties, but it has now been tried for a wider variety of applications.

The four examples given in this report, illustrating a number of approaches designed for different applications based on regional EFORWOOD case studies. They show that such mapping is possible and useful in a wide range of regions and tree species and products, both from the forestry perspective, to direct available materials for better value and profits, and from the industrial perspective, to save materials, energy, chemicals, etc. through the use of more suitable raw materials. Such optimal use of forest resources will bring improved sustainability in different forestry-wood chains.

The mapping is based on simulation, using sets of integrated models and forest inventory or harvester data. Models are today available for the major European timber tree species, regions and properties, but additional work has to be done to cover more of the total European resource. Routines for sampling, measurements and modelling are, however, already established, which facilitates further development. Furthermore, it is possible to reduce the efforts needed when dealing with specific applications. It is also possible to proceed stepwise, starting with a limited-scale database, which is expanded when a better feeling about the specific needs have been obtained.

Applications of mapping are already being developed for industrial use, but for a more general and wide-spread use of these promising methods, it would clearly be fruitful to analyse in further detail the applicability of the concept in a wider selection of European regions with further tree 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 used in the simulation for mapping of regional forest resources for specific applications.

9 Recommendations

Knowledge on the forest resource, not only volumes and growth of different tree species in various regions but also properties of wood and fibres in different stands, is crucial for its sound use. It is a basis for sustainable operations and industrial use to the benefit of forest owners and industry, as well as of the public. Today, however, this knowledge is limited. Normally volumes and growth are emphasised and in many regions also such information is sparse. The results of the current report show that it should possible to improve the situation. Some recommendations are given below. It is acknowledged that such work is demanding and has to be achieved successively over many years:

a). A standardized methodology and data format for inventorying forest resources, description of standing stand and tree characteristics, to be adopted across Europe. The data should also include information about factors with strong influence on important properties of wood and fibres. Properties possible to assess in the forest should be included. Other properties may be estimated by models (see below). Such a methodology and data would allow direct comparisons between regions and allow a comprehensive assessment of the quality of the European timber tree resource to be made if integrated within National Inventories. Some of these matters are already being addressed in COST E43 (2006).

b) A standardized set of non-destructive methods for determining the wood and fibre quality and properties of standing trees and logs be adopted across Europe. For example, this might include acoustic tests, NIR for density and pulp yield, tree cores for measurement of wood density, fibre dimensions, microfibril angle, and *MOE*, and grain angle measurements on cores or on outer fibres. By standardizing existing methods it would be possible to assess at some level the quality of the future European wood supply

c) A set of tree and wood quality measurements performed with the standardized set of methods b) are added to all National inventories. At present inventories are heavily focussed on volume and tree health but measurements to enable the future quality of the European timber resource to be determined should now be incorporated.

d) Sets of integrated models for major European tree species to estimation of important wood and fibre properties, using the enhanced inventory data a) as input and with the possibility to use the data from c) for validation. The models would be designed for mapping of resources, application in harvestsers, as illustrated in this report, and other applications.

e) Start-up of a successive mapping of tree and wood properties of industrial importance for the key tree species across Europe, using models and data as described above. The results are initially likely to be patchy and difficult to compare directly but with time would lead to a comprehensive assessment of the quality of the European forest resource, including both volumes and properties.

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11 Innventia Database information

Title

Mapping of forest resources and models used

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Abstract

Allocation of suitable materials to mills, processes and products is crucial for the sustainability of the forestry wood chains. For successful allocation, information is needed about volumes and properties of the wood raw materials available in the forest resource in relation to industry demands. Mapping of properties in forest resources have been achieved through simulation with models for properties of wood, fibres and knots. Four examples illustrating different applications are given in this report, showing that such mapping is possible and useful both from the forestry perspective, to direct available materials for better value and profits, and from the industrial perspective, to save materials, energy, chemicals, etc. through the use of more suitable raw materials.

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

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