EFORWOOD
Tools for Sustainability Impact Assessment

Key products of the forest-based industries and their demands on wood raw material properties

Sven-Olof Lundqvist and Barry Gardiner

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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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Key products of the forest-based industries and their demands on wood raw material properties

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STFI-Packforsk Report No.: 525

1) Innventia AB
2) Forest Research

March 2007

Results from the project
EFORWOOD
Quality Assessment and Allocation – Report 1

Public

Acknowledgements

This report has been produced within the project EFORWOOD, with the objective to develop tools for assessment of sustainability for the forest-based sector. The project was funded by the European Commission within its 6th Framework Programme (FP6) for research and development and a consortium of co-funders. The work was carried out within the "Quality Assessment and Allocation", managed by Innventia (previously STFI-Packforsk). Sven-Olof Lundqvist, Innventia, was editor of the report and also responsible for the part related to fibres, pulp and paper. Barry Gardiner, Forest Research, was responsible for the parts related to solid wood/wood-based panels and bio-energy. Other contributing researchers are: Andy Hall (Forest Research), Martin Johansson (Innventia), and Franka Brüchert (Baden-Württemberg Forest Research Institute). Support has been given by many experts in industry and at Innventia and Forest Research.

Parts of the background material regarding raw material demands of paper products was produced within the project Innovood, funded by the Swedish-Finnish research programme "Wood Material Science and Engineering" and a consortium of companies.

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Public report

Key products of the forest-based industries and their demands on wood raw material properties

STFI-Packforsk Report No. 525

INNVENTIA

1 Summary

The allocation of wood raw materials with suitable properties to mills, processes and products is crucial for competitive production and also for the sustainability of the forestry wood chains; influencing product quality, production economy, environmental quality and society well-being. To achieve good allocation, information is needed about what properties of wood and fibres are needed or preferred for the production of different forest-based products, as well as the properties and volumes of wood available in the forest resource.

The objective of this report has been to express the demands on wood and fibres in terms of raw material properties for major types of forest-based products. To start with, a set of key products of the forest based industries is defined. The ambition has been to list key products covering at least 80 % of the production within Europe as a whole for the different production chains: the solid wood chain, the fibre chain and the bio-energy chain. Another ambition has been to aggregate the types of products into a reduced set which relates to available statistics on consumption, production, import, export, etc. The large spectrum of forest-based products has been divided into a reasonable size set of key products for each type of chain.

Next, key product demands have been expressed. In some cases certain wood properties are imperative for the production of a specific product. In most cases it is, however, difficult or impossible to define generally applicable threshold values for demanded properties of raw materials for products and processes. There may be alternative ways to produce the product and investments may have been made in processing equipment to manage sub-optimal raw materials, but at extra cost. In these cases the property demands are expressed in indicative rather than absolute terms. For detailed analyses of industrial alternatives these issues have to be precisely specified for each case.

The report has been produced within the EFORWOOD project (http://www.eforwood.org) funded by the EU 6th Framework programme and a number of national funding parties.

2 Introduction

2.1 Sustainability and the EFORWOOD project

This report has been produced within the EFORWOOD[1] project. The aim of the project was to develop tools for assessment of sustainability adapted for the forest-based sector.

Sustainability can seldom be judged from a single narrow perspective. A product may look favourable because less energy is used when it is produced, but in the end it creates waste problems. It may seem attractive to set aside a forest area for conservation, but the consequence may be that local people are deprived of their source of livelihood and is, therefore, not at all sustainable from their point of view. Therefore, sustainability is defined against three categories: environment, economy and society. In a true analysis of sustainability, it is also necessary to involve all changes related to different alternatives along the whole chain of processes. A true sustainability analysis will thus by nature become quite complex, which creates a need for tools and databases. The EFORWOOD project has taken on the challenge to develop this for the forest-based sector.

The general objective of EFORWOOD is to develop a Tool for Sustainability Impact Assessment, ToSIA (Lindner et al. 2007; Rametsteiner et al. 2006), for the analysis of overall sustainability effects on society and industry of forest related activities. It covers the effects of operations all along the chain including:

- establishment and management of forests
- harvesting, allocation and transportation of raw materials
- production of wood and fibre based materials and conversion into products
- distribution, use and recycling/deposition

The analysis includes wood-based and fibre-based products as well as bio-energy. The analysis also includes calculation of effects on a large number of non-industrial factors such as health, recreation, gender issues, etc.

A number of regional analyses have been performed during the development of ToSIA. Towards the end of the project, ToSIA has also been used to illustrate the total sustainability effects of a number of scenarios of different natures and scales. The largest-scale study is pan-European and an important and very demanding part of the project has been to compile compatible cross-European data, which in itself will become a very valuable resource in continued work in the field. The project has also provided a very good basis for the further development of dedicated tools for specific issues, regions, industries, etc.

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[1] The report is based on an EFORWOOD project deliverable PD3.1.2, “Key properties of the forest-based industries and their demands on wood raw material properties” produced in March 2007, which in March 2010 was transformed into a public report.

The project was funded by the European Commission within its 6th Framework Programme (FP6) for research and development and a consortium of co-funders. It was performed in 2006 – 2009 by 38 partners from 21 countries and coordinated by Skogforsk (Sweden). This report has been produced by Innventia (Sweden) and Forest Research (UK) within the workpackage "Quality Assessment and Allocation".

2.2 Allocation of suitable raw materials

The allocation of suitable materials to mills, processes and products is crucial for the sustainability of the forestry wood chains. If unsuitable material is allocated to a process, this will normally lead to use of more material, energy, etc. Product functionality and customer satisfaction may also be compromised. All aspects of sustainability are affected including environmental, economic and societal factors. Important prerequisites for successful allocation are:

a) Knowledge about industrial demands on wood raw material properties for production of different products
b) Information about the volumes and properties of wood raw materials available for harvesting in the forest
c) Procedures and tools to match what the mill want with what is available in the forest.

This report is related to issue a). The aim is to:

- Express the demands on wood and fibres for selected products in major production lines (solid wood to wood products, fibres to pulp and paper products, bio-energy) in terms of raw material properties.

To do this, it is obviously necessary to clearly define the products selected. Therefore, the work has been expanded to include also the task of:

- Defining the key products of the major production chains of forest based industries and the materials processed along each production chains

Within the EFORWOOD workpackage "Quality Assessment and Allocation" all the issues in points a), b) and c) above have been dealt with. A series of four reports have been produced:

1. This report on key products and property demands (Lundqvist and Gardiner 2007)
2. A report on "Forest Resource Databases", a concept for product-oriented mapping of properties and volumes in forest resources (Lundqvist and Grahn 2008)
3. A report on mapping of properties available from the forest illustrated with results from four case studies and a compilation of the models used (Lundqvist et al. 2009)
4. A report illustrating the impact of allocation on different measures of sustainability based on results from two case studies (Lundqvist et al. 2010)

2.3 Key products

The ambition has initially been to identify sets of key products for the major production chains, which are hereafter referred to as:

- solid wood chain
- fibre chain
- bio-energy chain

The ambition has not been to list all possible products produced in all countries, but rather to define the key products or types of products of the different production chains, covering at least 80 % of the production within Europe as a whole. Another ambition has been to aggregate the types of products into a reduced set, which is possible to relate to available statistics on consumption, production, import, export, etc.

The selection of the key products has been performed in cooperation with experts on different wood and fibre based products, the production of primary materials and their conversion into final products. The starting point has been to identify the main types of converted products used by the end-user, such as books, sacks, outdoor furniture, pallets, floor systems, pellets, etc. and to follow the chains back to the raw material. For example, books are a major product. There is a wide diversity of books, but the most common type of books is selected as a representative. A book is in most cases printed with offset or digital printing on printing paper. This paper is in turn often manufactured from bleached kraft pulp (chemical pulp) produced from hardwood and/or softwood; or from thermo-mechanical pulp (TMP) from spruce wood; or from de-inked pulp (DIP) from recycled paper, collected and upgraded for renewed use in paper. Understanding the material requirements of the end product and the processes involved then allows specification of the required raw material properties.

2.4 Key properties and qualitative demands

For each one of the key products defined, sets of key properties have been listed and property demands have been expressed. The key raw material properties which have to be considered are listed and commented on below.

Sometimes it is said that a mill can operate on any available wood raw materials. This may be true for some products with low added value or at the cost of large efforts in the processes of the mill. However, there are cases where unsuitable raw materials are clearly detrimental so that quality specifications can not be fulfilled (i.e. if it is not possible to reach acceptable printability of a paper or stiffness of studs produced) or if the processes can not function (i.e. pulp screens plugged or saws jam in logs with high levels of reaction wood). Then, the properties of wood or fibres have to be tightly controlled. Often it is, however, a question about optimisation of product performance and costs, including costs for the raw material as well as for the processing in the mill. Less suitable materials may result in lower yield and higher operational costs. If the available raw material is not suitable, investments may be necessary to make the available material useable or to allow use of another material.

In some cases, it is possible to express property demands with specific values, for instance when the mechanical properties of wood materials for constructions have been standardised. Where it has been possible to define such threshold values these have been included.

In many cases, however, it is not possible to express the product demands in general terms because the same type of product may be producible on production lines designed with more of less advanced processing stages, able to handle materials with different but specific properties. However, this does not imply that the raw material properties in these cases are of less importance, but that alternatives have been developed and investments made to allow the use of materials that would otherwise be regarded as unacceptable or not economically feasible. Researchers may have developed and producers invested in new processing equipment to deal with the problem. The associated costs for the investment and sustainability impacts of the modified operation (use of energy, chemicals, person-hours, etc.) have, of course, to be considered. Such development may also make it possible to offer the customer a better product or a good-enough product at a lower cost or price, provided that proper investment is made. Use of particularly suitable materials may, on the other hand, increase product yield, quality, added value, customer satisfaction and reduce material use, transportation, etc. Innovations in new or improved products and processes as well as market supply and demand will continuously change the conditions and bring new possibilities or difficulties. Some of these optimisations can be performed gradually to adapt to the current situation, others will involve large investment and are performed stepwise after major decisions and where it may also be the only alternative to shutting down the operation.

Property variations in the processed materials may, therefore, to some extent be dealt with through optimisation and investments in the long or medium term, and through process adjustments based on assessment and measurements and process control in the short term. Even so, it is important to bear in mind that product quality and production efficiency are normally improved by use of materials with uniform properties.

From this insight, it has been concluded that the property demands in many cases can only be expressed in a qualitative way rather than quantitative and general terms. An obvious observation is that the more steps of conversion or processing that are involved in the manufacturing of a product, the more alternatives will be possible and the more difficult is it to define property demands for the initial wood raw material. It may be rather straight-forward for a board but less so for a wood-based construction element or a paper product in which the wood fibres have been totally restructured.

The more the materials have been converted, the more expertise is needed to make a realistic judgement on the property demands and how allocation and processing can be optimised when dealing with a specific forest resource, production facility and product. This is also to some extent reflected in the character of the sections below dealing with fibre chains, solid wood chains and bio-energy chains respectively. In the section related to production of pulp and paper, which is more complex and also assumed to be less familiar to most readers than the other production chains, a brief presentation of relationships between properties of fibres and paper has been added.

3 Fibre chains

3.1 Key products

The key products selected from the fibre chains and the materials from which they are produced are illustrated in *table 1*, and are divided into:

- Graphic products (1a – 1d)
- Packaging products (2a – 2e)
- Hygiene products (3a – 3b)

The list includes a total of 11 key types of converted products produced from 13 key paper types. In many cases the paper products are built up by mixing fibres with different properties together with other materials, in order to optimise quality/functionality and cost/price. Higher cost materials or further processing (with associated costs) may be used to produce higher quality grades, and vice versa. Some of the paper types are multi-ply materials, where the different layers serve different purposes, for instance to enhance an important property or to reduce costs. The layers are often produced from different types of pulps, which are processed to optimise the material as a composite.

Some basic product properties are common for many of the key products of the fibre chains: printability, stiffness, runnability on the paper machine, in printing presses and other converting, etc. The properties obtained in the paper depend both on the fibre raw materials used and the processing of the materials in the production line (equipment and conditions). As the fibres have similar influences on several properties important for many products, these relationships are commented on separately.

3.2 Key products and case studies

The lists of key products have also proven useful in the definition of chains for sustainability analyses. The establishment of the layout of fibre chains for an Iberian case study is given as an example. In the study, a consumer perspective on the forestry wood chains was applied. All major operations performed in different countries to provide fibre-based products were to be included, from remote forests to the Iberian consumer. The first step was to look into the statistics for paper consumption in Spain and Portugal. Four product types from the list in *table 1* constituting about 70 % of the Iberian consumption of paper were identified. It was then concluded that most of these products were based on wood harvested on the Iberian Peninsula or recycled fibres collected in the same region, but that one type of paper and bleached long-fibre pulp were imported in substantial volumes. The countries providing the major parts of these volumes were identified (Sweden and Finland) and the chains to be analysed were constructed accordingly.

Table 1: Key products of fibre chains and fibre based materials used along each production chain

Chain	Converted product	Paper	Pulp	Fibre raw material
	Graphic products			**Suitable fibres from …**
1a	**Newspapers (cold-set web offset)**	**Newsprint**	DIP (de-inked pulp)	Recycling
			TMP	Spruce
1b	**Catalogues, journals and magazines (gravure printing)**	**Magazine paper**	TMP, CTMP, SGW (stone groundw.)	Spruce, aspen
			Kraft pulp, bleached	Softwood
1c	**Books, brochures and folders (offset and digital printing)**	**Printing paper**	Kraft pulp, bleached	Hardwood, softwood
			TMP, CTMP	Spruce, aspen
			DIP (de-inked pulp)	Recycling
1d	**Fine/Office paper (no conversion)**	**Woodfree paper**	Kraft pulp, bleached	Hardwood, softwood,
			Office waste	Recycling
	Packaging products			**Suitable fibres from …**
2a	**Corrugated boxes**	**Kraftliner**	Kraft pulp, unbleached/bleached	Softwood, hardwood
		Testliner	OCC (Old Corrugated Containers)	Recycling
		Fluting	DIP(de-inked pulp)	Recycling
			NSSC	Hardwood
2b	**Carton boards containers (flexographic/offset/digital printing)**	**Paper board (mainly)**	Kraft pulp, bleached/unbleached	Softwood, hardwood
			Mid-layer: TMP, CTMP, DIP	Spruce, recycling
2c	**Liquid carton board containers (flexographic/offset/digital printing)**	**Liquid carton board (mainly)**	Kraft pulp, bleached/unbleached	Softwood, hardwood
			Mid-layer: CTMP	Spruce
2d	**Sacks**	**Sack paper layers (mainly)**	Kraft pulp, bleached/unbleached	Softwood
2e	**Bags**	**Kraft paper**	Kraft pulp, bleached/unbleached	Hardwood, softwood
	Hygiene products			**Suitable fibres from …**
3a	**Hygiene – Household**	**Tissue paper**	Office waste	Recycling
			Kraft pulp, bleached	Hardwood, softwood
3b	**Sanitary goods**	**Absorbants**	Kraft pulp, bleached	Softwood
			CTMP	Softwood

3.3 Key demands on wood and fibres

The properties of the fibres, pulp and paper used in the different parts of the production chains are very important for the product properties and the production efficiency. For paper products it is not possible to specify general threshold values for the properties of the materials used along the production chains, as discussed above.

When the basic functionalities of a pulp or paper product are fulfilled, the uniformity is often said to be the most prominent "property". Uniformity shall in this context be understood as constant property distributions over time, i.e. low variation over time. When a printer has adapted his press to a certain paper, he wants to print on paper with the same properties all the time. And this constancy should preferably start with the wood raw material fed into the process. Homogeneity of the fibre material may be beneficial for efficient processing, but for the properties of the product, some heterogeneity in fibre properties may even be beneficial: Some long fibres in the pulp will provide good strength for the wet paper sheet on the paper machine and will improve the runnability of the machine (few breaks of the web), but if they are too many the fibres will start to flock and the formation (uniformity in grammage, g/m^2) of the paper will suffer. The statistical distributions of the fibre properties shall, therefore, not necessarily be very narrow but suitable for the product and reasonably constant in time. If suitable distributions cannot be obtained from a single type of pulp, different pulps or materials are mixed to match the specifications. A typical example of this is the addition in many products of some "reinforcement pulp" (long-fibre kraft pulp) to increase strength.

3.3.1 Basic properties common for several paper products

Paper is basically a network of fibres. The properties of a paper are determined by the properties of the fibres, the structure of the network and the character of the bonds between the fibres. It is also influenced by materials added to the network to improve specific properties or to reduce costs, such as starch and fillers. Very often, paper is produced from mixtures of pulps and other materials and often in multiple layers, where each layer has specific properties which contribute to the properties of the engineered composite and reduce costs. A good example of this is multi-ply carton board, which has to be stiff. The solution is to use two surface layers with high tensile stiffness and to separate these surfaces with material of lower density and cost. The fibres used in the different layers are selected and processed to fulfil the requirements for runnability and other properties at the lowest possible cost.

For all types of paper certain strength properties have to be fulfilled to provide acceptable runnability on the paper machine, in printing presses and other converting equipments and for the expected functionality by the end user. Different levels of strength and mechanical and fracture properties (stiffness, tensile, tear, delamination, puncture, etc.) are important depending on the final product. Dimensional stability is also important for many products. Surfaces need to stay flat and packaging materials need to remain rigid, even with reasonable humidity variations, while other products need to have some elasticity to absorb sudden loads.

The structure of the fibre network is also important and particularly its evenness/homogeneity. Only limited variations in sheet grammage (formation), thickness and density are acceptable.

Otherwise the paper cannot be optimally used. Local deviations may also initiate breaks. High bulk (low sheet density) is sometimes valued in order to save material (for instance in the mid-layer of paper board in the example above) and for porosity. Porosity and surface properties of the paper are also important for printing, absorption, coating, lamination and tactile properties.

Nowadays, most types of paper products carry printed information, which brings demands not only on surface properties as mentioned above, but also on optical properties like light scattering, uniform appearance, etc.

As an example, a cross-section of a magazine paper is shown in *figure 1*, more specifically an LWC paper (light weight coated) with spruce fibres of thermo-mechanical pulp (TMP) in the middle and coating layers for improved printing properties on each side. The fibre structure includes two un-collapsed thick-walled fibres which disturb the upper surface and the printing properties.

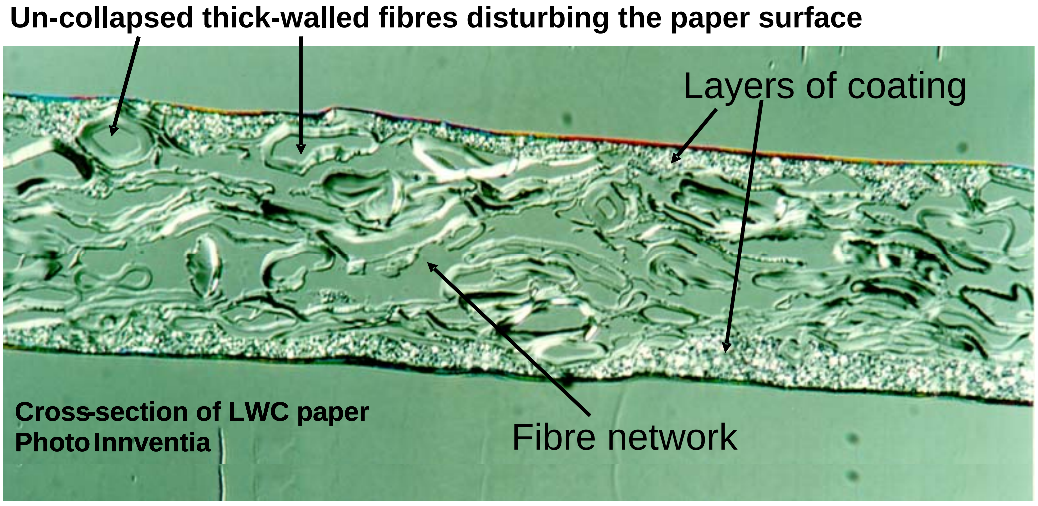

Figure 1. A cross-section of a magazine paper, an LWC paper (light weight coated) with spruce fibres of TMP in the middle and coating layers for improved printing properties on each side. Two un-collapsed thick-walled fibres disturb the upper surface and the printing properties.

3.3.2 Important properties of fibres in relation to paper properties

The dimensions of the fibres (length, width and wall thickness) are important in themselves, especially the fibre length and fibre wall thickness. A number of relationships between fibre length, width and wall thickness are also very important in papermaking and for the properties of the finished products. Some important fibre properties are listed below. Their level of importance depends on the product and processes used:

- Fibre length
- Fibre wall thickness
- Fibre coarseness (g/km fibre), defined by fibre width and wall thickness (and process yield)
- Number of fibres/g, defined by fibre length, width and wall thickness (and process yield)

- Fibre stiffness (bending), defined by fibre width, wall thickness and microfibril angle (and processing)
- Number and character of vessel elements (relevant for some hardwood species)

An important property closely related to fibre stiffness is fibre collapsibility and this is discussed in more detail below.

Other properties which may be of importance are:

- Wood density
- Chemical composition
- Microfibril angle

3.3.3 Effects on paper properties

The following highly simplified comments can be made about the influences of these fibre properties (the comments are valid in most but not all cases and depend on final product, process used, etc.):

- o Long fibres are normally positive for fracture properties and wet strength on the paper machine but negative for formation.
- o Thin-walled fibres are normally positive for surface properties (printability, smoothness) and optical properties.
- o Flexible fibres are normally positive for strength properties but negative for bulk.

It is not easy to generalise about the importance of each one of the fibre dimensions length, width and wall thickness. They are often to some extent correlated with each other. Shorter fibres are often more thin-walled and slimmer (less wide). This is at least true for wood and fibres from the same tree species grown in regions with similar climate, etc. An important factor behind this correlation is the content of juvenile wood from annual rings close to the pith, more about that below.

Such correlations are illustrated in *figure 2 and 3*[2], based on data for Scots pine in Sweden. The wood samples represent pulpwood logs from the top of the tree and from the mid part of the stem, sawmill chips and root logs from slow-grown small trees. Figure 1 shows large differences in fibre length and fibre wall thickness among the wood of different origins. The data relate to small volumes of well defined materials to illustrate extremes from top logs and slow-grown wood. The figure illustrates the spectrum of wood raw materials which could be offered to a mill from the pine forest in a region, if it is economically feasible. The wood delivered to a pulp mill is, however, normally a variable mixture of these classes and materials from other wood species. This variable mixture will bring variations in property averages and distributions. At the mill materials are often blended to improve the uniformity of the chips fed into the process.

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[2] Figures 2-4 were produced within the Innovood project of the Swedish-Finnish research program “Wood Material Science and Engineering” (Lundqvist (editor) 2007). More information is available at www.innventia.com/innovood.

Figure 2 also shows that there is some correlation between fibre length and wall thickness, but also large systematic deviations from this correlation. Such correlations sometimes make it difficult to understand the real origin of problems with paper quality and to act accordingly. When it has become possible to efficiently analyse a property, for instance fibre length or fibre coarseness, it is used to predict pulp and paper properties, and this may be quite successful for certain species and products. However, this may disguise the fact that other fibre properties like collapsibility or stiffness, which are not as easy to determine, may have a stronger fundamental relationship to the properties of the product.

Figure 2: Fibre length (STFI FiberMaster, length-weighted) and fibre wall thickness (SilviScan). Wood representing different parts of Scots pine trees (Lundqvist (editor) 2007).

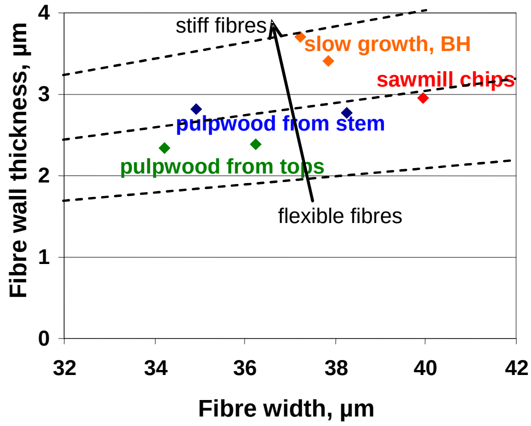

Figure 3: Fibre width (STFI FiberMaster) and fibre wall thickness (SilviScan). Wood representing different parts of Scots pine trees. The broken lines indicate different levels of fibre collapsibility (Lundqvist (editor) 2007).

As indicated above the effects on paper properties are often related to combinations of dimensions rather than to one single dimension. The ability of the individual fibres to collapse has a strong influence on several paper properties. Collapsible fibres will turn into flexible bands in the paper structure, whereas those which do not collapse will become stiff rods in the structure. Collapsibility is largely related to the relationship between fibre wall thickness and fibre width. This is illustrated in figure 3 with data from the same samples as figure 2. The broken lines indicate different wall thickness to width ratios. In this case, the fibre width shows a rather small variation and, therefore, the collapsibility is mostly influenced by the wall thickness. But this is not true in general. Fibres with thin walls may also be hard to collapse if they also are slim, for instance fibres from hardwood species like eucalypts. If we look at the distribution of properties rather than the averages, all the samples illustrated in the figures have fibres with both high and low collapsibility but in varying proportions.

The angle of the microfibrils in the fibres (in relation to the fibre axis) is also important for the collapsibility of the fibres and has an influence on a range of mechanical properties. Fibres with a large angle tend to be less collapsible at the same width and wall thickness. This issue tends to be more important for material from fast-grown plantations in the Americas, possibly also in Western Europe, than for slow-grown Nordic trees.

The size or mass of the fibres (length, width and wall thickness) will determine the number of fibres per gram and also properties of paper. In sheets specified to have the same grammage, the use of fibres with lower coarseness and shorter fibres will mean a longer total length of fibres in the sheet, a larger number of fibres and more bonds, which will influence the sheet structure for good or bad depending on the product. This illustrates that it is important to be concerned with individual fibre dimensions but also the combination of fibre dimensions. Lower coarseness and shorter fibres may be obtained from hardwoods like birch, poplar and eucalypts in preference to softwoods like spruce and pine. Alternatively they can be obtained within a particular softwood species, but with smaller overall difference, by use of pulpwood and especially pulpwood made from forest thinnings rather than use of sawmill chips, which are obtained from the outside of sawlogs. More about this below.

During processing in the mill, the properties of the fibres are modified to match the properties needed in the product, as far as possible. It is not always possible to achieve this and the cost will depend on the properties of the fibres from the raw material. An example is given in *figure 4*, showing sheet densities and air permeance (porosity) of sheets produced in the laboratory in the same way. Refining of pulp, an energy-consuming mechanical treatment, is an effective tool for modifying the fibres. For each type of wood material in figures 2 and 3, sheets have been produced from unrefined pulp and from two levels of refining (PFI). The figure shows that there are large differences between the sheets made from different raw materials. It also shows that the fibres can be modified to some extent for a specific product by refining, but of course at a cost and with a related sustainability impact. The sheets made from the fibres of top logs have a high density and low porosity even if the pulp is not refined. The sheets from the most slow-grown wood have a high porosity and low density even if produced from refined pulp (Lundqvist (editor) 2007). Most paper properties are related to sheet density one way or another and variation in fibre dimensions will thus have an impact and have to be considered. High sheet density is needed in some paper products but most often lower sheet density is strived for, as long as the product specifications regarding surface smootheness and other properties are fulfilled, because the material use is reduced.

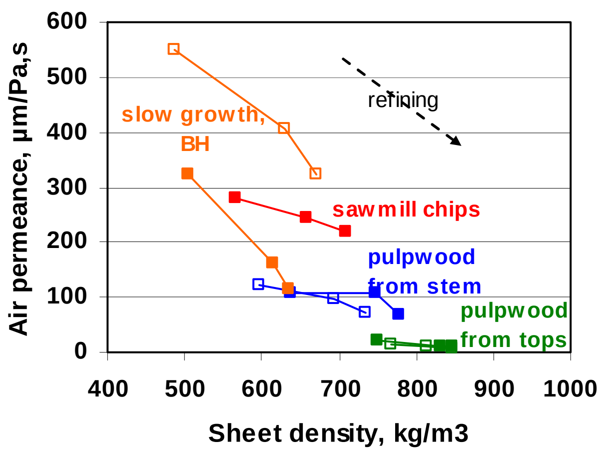

Figure 4: Density and air permeance (porosity) of sheets from pulps of various origins and refining. The pulps are produced from wood representing different parts of Scots pine trees. The sheets from fibres of top logs have a high density and low porosity even if the pulps are not refined. The sheets from the most slow-grown wood have a high porosity and low density even if produced from refined pulp. (Lundqvist (editor) 2007)

Wood density is also mainly determined by the fibre width and wall thickness. In hardwood species the wood density is in addition influenced by the number and size of vessel elements in the wood. A high wood density is beneficial in reducing the wood volume per ton of pulp and paper being transported and for production capacity (if the process equipment is designed for this), but it may be good or bad for quality and production efficiency depending on the particular product and process. Different fibre cross-sections can result in the same wood density so wood density cannot be used as a general measure of fibre properties. However, for a specific mill with given products and processes, the alternatives in wood supply regarding wood species and origin are normally quite well established. In this case the wood density may be a useful property to monitor in order to stabilise the fibre properties, and possibly also to differentiate wood with different properties for specific production lines and products.

The chemical composition of the wood (contents of lignin, cellulose, hemi-celluloses, extractives, etc.) also influences the yield of the pulping processes and the properties of the pulp. In mechanical pulping processes, a high content of extractives is a problem. Therefore spruce wood is preferred in comparison to pine wood. In chemical pulping, the lignin is dissolved and removed from the pulp (to different degrees depending on the product). The lignin is then used for generation of steam and electricity or part of it sometimes for production of other products. For papermaking, it is normally beneficial to preserve the hemicelluloses in the fibres, as the need for refining of the pulp is reduced.

3.3.4 Predictable differences between and within wood species, stands and trees

There are large variations in the wood and fibre properties between and within wood species, stands and trees. Some of these differences are known and predictable and may sometimes be exploited through allocation of particularly suitable fibre materials to specific mills and products, if economically feasible. The rest of the variation is stochastic in nature and negative for the uniformity of the properties (as defined above). Its impact may, however, be reduced though blending of the material.

Some highly simplified comments on differences between fibres in various types of wood are given below:

Hardwoods species (broad-leaves) have normally shorter and slimmer fibres with thinner walls than softwoods. They also have vessel elements (special cells to conduct water) and these can cause problems in paper grades for printing. In both hardwoods and softwoods there is a successive change from juvenile wood in the centre of the stem to mature wood formed further out from the pith. The annual rings are normally broader in the juvenile wood than in the mature wood, see *figure 5*. Juvenile wood has typically shorter, slimmer and more thin-walled fibres, as well as fibres with a higher microfibril angle, than mature wood fibres in the same stem cross-section. As a consequence, the properties of logs will differ as a function of the number and structure of their growth rings. Pulpwood from small diameter parts of the stem with a larger content of juvenile wood will typically have shorter fibres, lower wood density and higher microfibril angle than sawmill chips from the outer part of the higher diameter sawlogs at the base of the tree.

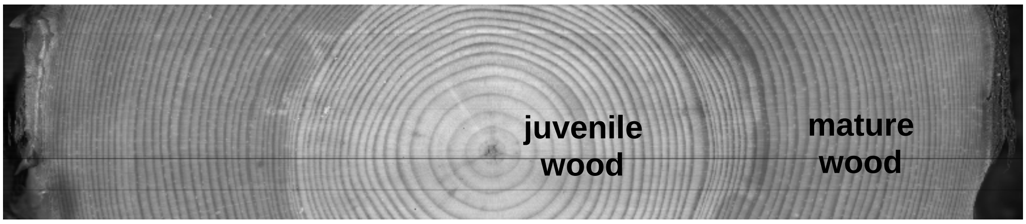

Figure 5: Cross-section of stem of Norway spruce, with the locations of juvenile wood and mature wood indicated.

Another structural variation within softwood trees is the difference between earlywood and latewood, see *figure 6*. Latewood is formed towards the end of the growing season and has typically more thick-walled and slimmer fibres than the earlywood formed earlier in the growing season. These differences explain why we can see annual rings in stem cross-sections. It also means that latewood has a higher wood density and its fibres are less collapsible and stiffer than earlywood fibres, sometimes with consequences as illustrated in figure 1. All parts of the tree show this mixture of fibres with different properties, but the proportions of earlywood and latewood, as well as their specific properties, vary among locations in the stem, as illustrated in figure 6, and within stands and trees in a systematic way.

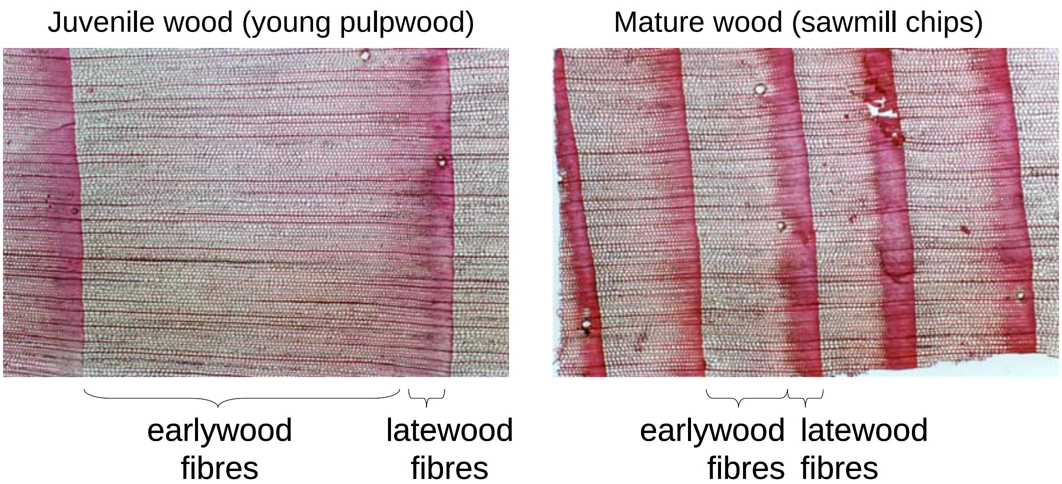

Figure 6: Annual rings of Norway spruce (softwood) with earlywood and latewood fibres in juvenile wood, typical for pulpwood, and mature wood, typical for sawmill chips.

Figure 6 illustrates the typical wood structure of softwood species. For hardwood species the difference between earlywood and latewood fibres is smaller. Therefore, hardwoods typically have more homogenous fibre properties than softwoods. Another difference is of course the occurrence of vessels in hardwoods.

The proportions of earlywood and latewood on the one hand and juvenile wood and mature wood on the other hand have a strong influence on the wood and fibre properties in the different parts of an individual tree (for softwoods in particular). This fact is also a reason why it is often possible to predict wood and fibre properties reasonably well from readily available data and to implement practical systems for good wood and fibre allocation.

Pulpwood logs with small diameter will not only typically have shorter fibres than sawmill chips due to higher content of juvenile wood; they will also typically have thinner-walled fibres due to higher content of earlywood. This offers an opportunity to obtain materials with clearly different properties from the same resource, beneficial in different products separately or in proper mixes. But it also creates a need for proper control of the mix of chips from pulpwood and saw mill chips feed to the process. Fibres of different characters may also be obtained through selection of materials from different tree species, types of stands, parts of trees, etc. Examples are given in (Lundqvist et al. 2009). Procedures to provide more suitable and uniform raw materials for specific products are in operations at many mills around the world.

3.3.5 Qualitative relationships between properties of wood raw materials and key paper products

As stated above, it is not possible to state generally applicable threshold values for wood raw material properties in relation to paper products and processes. To clarify important relationships, some general influences of basic fibre properties such as fibre dimensions and of the combined variables listed above have been compiled in qualitative terms in *table 2a* and *2b*. The tables differentiate between various types of pulps typically used in the different key products to enhance special qualities of paper grades or in different layers of multi-ply products. Hopefully, this qualitative information can be of help when alternatives in the allocation of wood and fibre raw materials are discussed. Note that even if no preferred value is indicated, the property distribution should be reasonably constant in time.

3.4 CPA codes

When defining the limited set of key products listed in table 1, we also envisaged that it should be possible to find data on the aggregated types of products in the available European statistics on consumption, production, import, export, etc. For the fibre chains, we have in the first place related our work to the statistics available from CEPI (Confederation of European Paper Industries) but statistics for some European countries has also been investigated.

Other sources of statistical data are structured according to the Classification of Products by Activity (CPA) codes used within the European Union. *Table 3* describes the connection between the aggregated types of products of table 1 and 2 and these codes. The CPA codes are sometimes difficult to apply. Difficulties occur for instance when grades of different product types are summed up in the same CPA category. For example, the CPA code 22.13.11 probably includes grades of both product type 1a and 1b and products of the categories 22.11.10-51 could belong to either 1c or 1b according to the CEPI statistics. Code 22.21.15 covers both product type 2b and 2c. In the table, the most probably CPA codes are given for each key product of the fibre chains.

Table 2a: Important relationships between properties of fibres and key properties of paper products, part a.

Paper and pulp	**Type of pulp**	**Fibre dimensions**		**Combined fibre properties**				**Wood**
		fibre length	**Fibre wall thickness**	**Fibre coarseness**	**Number of fibres per gram**	**Fibre stiffness (bending)**	**No of large vessel elements**	**Wood density**
1a Newsprint								
1a.1 Pulp for printability	DIP, TMP	-	-	-	+	-	-	-
1a.2 Pulp for strength	TMP, SBK	+	1)	1)	+			+
1b Magazine paper								
1b.1 Pulp for printability	TMP, SGW	-	-	-	+	-	-	-
1b.2 Pulp for strength	TMP, SBK	+	1)	1)				+
1c Catalogues, brochures, folders								
1c.1 Pulp for printability	HBK,TMP,DIP	-	-	-	+	+	-	
1c.2 Pulp for strength	SBK	+	-	-				
1d Fine / Office paper	HBK, SBK, Office waste	-	-	-	+		-	

Continued

+ = relatively high (and stable) value preferred; - = relatively low (and stable) value preferred

S=softwood; H=hardwood; B=bleached; U=unbleached; K=kraft pulp; TMP=thermomechanical pulp; CTMP=chemi-thermomechanical pulp; SGW=stone groundwood pulp; NSSC=Neutral Sulfite Semi Chemical pulp; DIP=de-inked pulp

[1)] For a specific wood source, the fibre wall thickness is often positively correlated with the fibre length, see figure 1. Fibre wall thickness and tear strength will correlate, but the surface and printability properties will suffer from too thick-walled fibres. If fibres with the same length but thinner walls can be obtained at a comparable cost, for instance from another wood species, these fibres would normally be preferred, as they result in sheets with more fibre layers at the same grammage.

Table 2b: Important relationships between properties of fibres and key properties of paper products, part b.

Paper and pulp	**Type of pulp**	**Fibre dimensions**		**Combined fibre properties**				**Wood**
		fibre length	**Fibre wall thickness**	**Fibre coarseness**	**Number of fibres per gram**	**Fibre stiffness (bending)**	**No of large vessel elements**	**Wood density**
2a Corrugated boxes								
2a.1 Kraftliner (surface, new fibr.)	USK, SBK, UHK, HBK		+ [1)]	+ [1)]	+			+
2a.2 Testliner (surface,recycl.fibr)	Recycled containers							
2a.3 Fluting (corrugated)	DIP, NSSC					+		
2b Carton board containers								
2b.1 Pulp for surface and print	SBK, HBK	-	-	-	+	-	-	
2b.2 Pulp for mid-layers	TMP, CTMP	-	+	+		+		+
2c Liquid carton board containers								
2c.1 Pulp for surface and print	SBK, HBK	-	-		+	-	-	
2c.2 Pulp for mid-layers	CTMP, SBK		+	+		+		+
2d Sacks	SUK, SBK	+			-			-
2e Bags	SUK, SBK, HUK, HBK	+				+		
3a Hygiene Household / Tissue	HBK, SBK, Office waste	+	- [2)]	-	+	-		-
3b Sanitary goods / Absorbants	SBK, CTMP	+	+ [2)]	+		+		+

\+ = relatively high (and stable) value preferred;   - = relatively low (and stable) value preferred

S=softwood; H=hardwood; B=bleached; U=unbleached; K=kraft pulp; TMP=thermomechanical pulp; CTMP=chemi-thermomechanical pulp; SGW=stone groundwood pulp; NSSC=Neutral Sulfite Semi Chemical pulp; DIP=de-inked pulp

[1)] For a specific wood source, the fibre wall thickness is often positively correlated with the fibre length, see figure 1, and also coarseness. If fibres with the same length but thinner walls can be obtained at a comparable cost, these fibres would normally be preferred, as they result in sheets with more fibre layers at the same grammage.

[2)] - if tactile properties like softness are emphasised, + if absorption has priority

Table 3: CPA Codes for the key products of fibre chains listed in Table 1.

Chain	Converted products	CPA Code	CPA definition
Graphics products			
1a	**Newspapers (cold-set web offset)**	22.12.11	Newspapers, journals and periodicals, appearing at least four times a week; printed
		22.13.11	Newspapers, journals and periodicals, appearing less than four times a week; printed
1b	**Catalogues, journals and magazines (gravure printing)**	22.22.12	Trade advertising material, commercial catalogues and the like
1c	**Books, brochures and folders (offset and digital printing)**	22.11.10	Printed books, brochures, leaflets and similar printed matter, in single sheets
		22.11.21	Books, brochures, leaflets and the like; printed
		22.11.31	Dictionaries and encyclopaedia, and serial instalments thereof; printed
		22.11.41	Atlases and other books of maps or charts; printed
		22.11.51	Maps and hydrographic or similar charts, globes, other than in book form; printed
		22.22.11	New stamps; stamp-impressed paper; cheque forms; banknotes and the like
		22.22.13	Other printed matter n.e.c.
		22.22.20	Registers, account books, binders, forms and other articles of stationery, of paper or paperboard
1d	**Fine/Office paper (no conversion)**	21.23.13	Other paper and paperboard, of a kind used for writing or printing or other graphic purposes, printed, embossed or perforated
Packaging products			
2a	**Corrugated boxes**	21.21.13	Cartons, boxes and cases, of corrugated paper or paperboard
2b	**Carton boards containers (flexographic/offset/ digital printing)**	21.21.14	Folding cartons, boxes and cases, of non-corrugated paper or paperboard
		21.21.15	Box files, letter trays, storage boxes and similar articles of a kind used in offices, shops or the like, of paper
2c	**Liquid carton board containers (flexographic/offset/ digital printing)**	21.21.14	Folding cartons, boxes and cases, of non-corrugated paper or paperboard x
		21.21.15	Box files, letter trays, storage boxes and similar articles of a kind used in offices, shops or the like, of paper
2d	**Sacs**	21.21.12	Sacks and bags of paper
2d	**Bags**	21.21.12	Sacks and bags of paper
Hygiene products			
3a	**Hygiene - Household**	21.22.11	Toilet paper, handkerchiefs, cleansing or facial tissues and towels, tablecloths and serviettes, of paper
3b	**Sanitary goods**	21.22.12	Sanitary or hospital articles, articles of apparel and clothing accessories, of paper pulp, paper, cellulose wadding or webs of cellulose fibres

4 Solid wood and wood-based panels chains

4.1 Key products

In this section the term solid wood is used to describe both solid wood and wood-based panel products. The products/materials dealt with are classified as Converted Products for end use, Intermediate Products, including secondary and primary products from sawmills, etc. and logs.

The key products selected from these chains and the materials from which they are produced are displayed in *table 4a*, and are divided into:

- Solid-wood furniture (4a – 4c)
- Solid-wood joinery (5a – 5b)
- Solid-wood packaging (5a – 5b)
- Solid-wood construction (7a – 7d)
- Panel products (8a – 8d)

The list includes a total of 25 key types of converted products produced from a range of softwood and hardwood species including species grown outside Europe. It is impossible to cover the enormous range of solid-wood/wood-based panel secondary and primary products used in Europe in their entirety so they have been aggregated into broad categories. The list in *table 4a* is designed to enable the building of production chains from forest to product and the modelling in ToSIA for the analysis of sustainability. It corresponds to *table 1* for fibre-based products.

Table 4b describes the connection between these products and the Classification of Products by Activity (CPA) codes used within the European Union. Due to the broad categories used it is impossible to ascribe absolute values to the wood properties and so these must be ascribed at an individual case level. Instead we have given general indications of the relationship between wood properties and solid-wood products in *table 4c*. Furthermore, the properties of the logs used in primary processing can only be divided into broad categories because the capabilities of each sawmill will vary as will the demand of the final customer. Therefore, we have proposed a set of 5 broad log categories (with sub categories) that cover the basic range of requirements for different end-products and these are given in *table 4d.*

4.2 Key demands on solid wood

The key demands on solid wood vary according to the final product but can be broken down into a number of categories:

- Density (kg/m^3). The basic density of wood varies enormously depending on species, growth rate and position the wood has been cut from in the tree. Values vary from around 100 kg/m^3 for balsa wood to 1300 kg/m^3 for lignum vitae. However, most softwoods in use in Europe will vary between 300 – 500 kg/m^3 and most hardwoods from 500 – 900 kg/m^3. The density of wood is correlated to its strength and toughness.

- Knot size and status: The size of knots, the area they occupy as a ratio of the area of the solid timber (KAR) and their status (dead or alive) have important consequences for the usability of timber. Knots are a key characteristic that defines the visual grading of timber into different categories. Knots also have important consequences for wood strength because the presence of knots leads to grain distortion and strength reduction (clear wood with no knots can be twice as strong as a typical piece of sawn timber). Dead knots which may fall out of sawn timber will disqualify its use in joinery, cladding, veneer, parquet etc.
- Grain angle: The fibres in timber are approximately aligned along the tree axis. However, deviation from this axis reduces the stiffness of the timber and increases its tendency to twist during drying. Grain angle varies from pith to bark usually increasing rapidly in the first few years of growth and then decreasing slowly and, if the tree is old enough, reversing direction. Grain angle is a function of species, growth rate and exposure to the wind. Trees planted at wider spacings or in windy locations will generally have higher grain angles.
- Microfibril Angle (MFA): The middle layer of the secondary cell wall of wood cells is dominated by cellulose microfibrils wound in a helix. The angle of these microfibrils in relation to the long axis of the cell has profound consequences for the stiffness of the wood, with angles close to zero giving the stiffest wood. Microfibril angle varies from pith to bark with generally higher values close to the pith and lower values in the more mature wood towards the bark. Microfibril angle is also affected by the presence of reaction wood, with compression wood in gymnosperms having higher values and tension wood in angiosperms having very low values (see below).
- Reaction wood: In gymnosperms compression wood is produced to direct stems and branches into the desired orientation to access light. Compression wood is highly lignified with rounded, thick walled cells and high microfibril angles. Typically it is denser and more brittle than normal wood. The presence of compression wood in a piece of timber can lead to bow and spring due to the lignified cells having higher longitudinal shrinkage during drying. Tension wood is the equivalent form of reaction wood in angiosperms. It is characterised by lower lignin content and higher cellulose levels than normal wood and a gelatinous G-layer forms in the centre of the cells. Microfibril angles are generally lower than in normal wood. Due to its high longitudinal shrinkage it is also liable to lead to distortion in drying timber.
- Hardness: The hardness of the wood (i.e. its ability to take punishment) can be a very critical requirement in uses with high wear and tear such as flooring. Hardness will be primarily a function of species and growth rate and is related to wood density.
- Appearance: The visual appearance is important for a number of applications, particularly those with high value. The characteristics of importance for appearance vary with the application but will be a function of knot size and status, grain angle, location within the stem (sapwood/heartwood) and the presence of any stain. In some

circumstances a property such as wavy grain will be highly desirable in one application but not in another.

- Durability/Permeability to Preservatives: For outdoor applications in particular, the natural durability (resistance to pathogens and environmental degradation) is crucial. The presence of high levels of extractives, especially phenols, enhances the durability of wood, and heartwood is generally more durable than sapwood. Furthermore, heartwood formed in mature wood is more durable than heartwood formed in juvenile wood. If a timber is not durable it can still be of value for outdoor applications if the wood is amenable to preservative impregnation. Some species such as spruce can be very difficult to impregnate with preservatives and may have limited outdoor use.
- Moisture content: The moisture content of wood is generally <18 % following processing. The moisture content of the wood will change in service and typically might be around 12 % in sheltered outdoor locations and 8 % in indoor use. Any changes in moisture content can lead to potentially undesirable timber movement. Also if the moisture content becomes too high then rot can be a problem. For panel products it is desirable to have low moisture contents of the raw material being used in order to keep the energy requirements in manufacturing to a minimum.

For any product a combination of desirable properties is usually required and a general description of desirable properties is set out in *table 4c.*

4.3 Key demands on logs

In a similar way to the properties of the wood we can define a set of log properties of importance in the manufacturing of solid-wood products. These are:

- Stem size: The size of the stem is one of the most important considerations for primary processing. Sawmills will have very tightly defined upper and lower limits for the size of logs they are able to handle. Specialised mills are built to deal with small and oversize logs.
- Straightness and roundness: The straightness of the log is a key filter for different products. Construction timber and timber used in laminated products such as veneer wood or glulam will generally require straighter and rounder logs than other products. However, it is not possible to completely generalise because some sawmills are able to curve saw and some veneer mills are able to deal with out of round logs.
- Grain angle: As in the discussion above the grain angle of wood has to be small enough to be acceptable for a number of converted products. Logs with external grain angles greater than certain values could be rejected for these end-uses and converted into other less demanding products.
- Knot size and status: Knot size and status is a key requirement for a number of products as discussed above. If the external knots on logs are too large or numerous or dead the log may be rejected for a particular end-use (e.g. joinery). Unfortunately, sometimes it is not possible to determine the knot extent and status until the log has been first sawn.

- Appearance: Log appearance is important for directing the log for primary processing. Logs with obvious external damage or rot will be separated and sent to a lower value end product such as the manufacture of panel products. If the symptoms are too severe the logs may not be suitable for any solid-wood product end-use.
- Hardness: The hardness of wood is most directly associated with the species. Therefore, for certain end products such as parquet only certain species will be acceptable.

As is the case for wood properties, different products will require a number of log properties to be met. In *table 4d* we have grouped these properties into five log categories for simplification. Particular products will require logs meeting the requirements of a particular log category. This is meant as an indicative system only and is not part of any official European log grading system.

Table 4a: Key products of solid wood and wood-based panel chains and materials used along each production chain.

Chain	Converted product Secondary product	Primary product	Species Choice	Desired Wood Properties	Log Properties (see Table 4c below)
	Solid-wood furniture:		Suitable species	Appearance, strength, knots (number, size, status), stiffness, slope of grain, compression wood, dimension stability, wane, cracks, splits, hardness, permeability, resin pockets, durability, ring width	species, dimension, taper, knots (number, size, status), straightness, colour, percentage of heartwood, density, slope of grain, compression wood, shakes, rot, stains, cracks, resin pockets, ring width, internode length
4a	**Home and office furniture**	**Solid Wood**	Pine, Beech, Oak	Clear wood, Tight knots if present. Knots <2.5cm. No stain. Good visual appearance	Log Type II
		Laminated Sheet	Birch, beech + spruce/pine	Clear wood. Knots <1cm. No stain, straight grain.	Log Type I
4b	**Kitchen / Bathroom furniture**	**Solid Wood**	Pine, Beech, Oak	Clear wood, Tight knots if present. Knots <2.5cm. No stain.	Log Type II
		Laminated Sheet	Birch, beech + spruce/pine	Clear wood. Knots <1cm. No stain, straight grain.	Log Type I
4c	**Outdoor furniture**	**Decking**	Cedar, larch	Natural durability (heartwood) at least durable or permeability to preservatives. Long clear wood sections, no resin pockets.	Log Type II+
		Furniture Components	Tropical hardwoods, treated softwoods	Natural durability (heartwood) at least durable or permeability to preservatives. Long clear wood sections, no resin pockets.	Log Type II+
	Solid-wood joinery:				
5a	Floor covering	**Parquet**	Hardwoods, pine	Long clear wood sections. Knots <1cm. High hardness. No stain.	Log Type III
		Laminated sheet	**Hardwood + spruce**	Long clear wood sections. Knots <2.5cm. high hardness. No stain.	Log Type III-

Chain	Converted product Secondary product	Primary product	Species Choice	Desired Wood Properties	Log Properties (see Table 4c below)
5b	**Doors & windows**	**Solid wood components**	Pine, oak, beech	Natural durability (heartwood) at least moderate durability or permeability to preservatives. Long clear wood sections. Knots <2.5cm. No resin pockets.	Log Type IV
		Finger jointed components	Pine	Long clear wood sections. Knots <1cm. No stain.	Log Type IV-
	Solid-wood packaging				
6a	**Pallets**	**Solid wood boards**	Spruce	High stiffness. High strength. High impact resistance	Log Type V
6b	**Boxes**	**Solid wood boards**	Softwoods	High stiffness. High strength. High impact resistance	Log Type V
		Veneer sheets	Hardwoods (oak, cherry, walnut, maple, etc, etc..)	Clear wood, straight log, No stain, straight grain. Knots <1cm	Log Type III+
		Plywood solid sheets	Birch, spruce, tropical hardwoods	Clear wood, straight log, No stain, straight grain. Knots <1cm	Log Type III+
	Solid-wood construction:				
7a	**External & internal wall (incl. timber frame)**	**Cladding**	Douglas fir, cedar, larch, treated spruce & pine	Natural durability (heartwood) at least moderate durability or permeability to preservatives. Long clear wood sections, no resin pockets.	Log Type IV
		Construction timber	Spruce, pine	High strength, High stiffness (□C16), low longitudinal shrinkage, small knots (<2.5 cm).	Log Type I

Chain	Converted product Secondary product	Primary product	Species Choice	Desired Wood Properties	Log Properties (see Table 4c below)
7b	**Floor systems**	**Solid wood joist**	Spruce, pine	High strength, High stiffness (□C24), low longitudinal shrinkage, small knots (<2.5 cm).	Log Type I
		Engineered wood joist **Parallel Strand Lumber**	Spruce, pine	Wood fibres (often recycled)	Log Type V-
		Engineered wood joist **Laminated Strand Lumber**	Birch, aspen, poplar	Long clear wood sections. Knots <1cm	Log Type V+
		Solid floor boards	Spruce, pine	High strength, high stiffness	Log Type I
		Laminated Veneer Lumber	Softwoods (pine, hemlock, Douglas fir)	High stiffness, long clear wood sections	Log Type I-
		Glulam	Douglas fir, pine	High stiffness (□C30), long clear wood sections. Knots <1cm	Log Type I-
7c	**Roof**	**Solid wood joist**	Spruce, pine	High strength, High stiffness (□C24), low longitudinal shrinkage, small knots (<2.5 cm).	Log Type I
		Engineered wood joist **Parallel Strand Lumber**	Spruce, pine	Wood fibres (often recycled)	Log Type V-
		Engineered wood joist **Laminated Strand Lumber**	Birch, aspen, poplar	Long clear wood sections. Knots <1cm	Log Type V+
		Laminated Veneer Lumber	Softwoods (pine, hemlock, Douglas fir)	High stiffness, long clear wood sections. Knots <1cm	Log Type I-
		Glulam	Douglas fir, pine	High stiffness (□C30), long clear wood sections. Knots <1cm	Log Type I-

		Roof shingles	Cedar	Natural durability (heartwood) at least moderate durability or permeability to preservatives. Long clear wood sections, no resin pockets.	Log Type IV
7d	**Complete house**	**Floor system**	See above		
		Roof systems	See above		
		External & internal wall	See above		
	Wood-based panels:				
8a	**Veneer sheets**	**Veneer sheets**	Hardwoods (oak, cherry, walnut, maple, etc, etc..)	Clear wood, straight log, No stain, straight grain. Knots <1cm	Log Type III+
8b	**Plywood**	**Plywood solid sheets**	Birch, spruce, tropical hardwoods	Clear wood, straight log, No stain, straight grain. Knots <1cm	Log Type III+
8c	**Particle board**	**OSB**	Softwood chips	High density. Low levels of Compression Wood. No rot.	Log Type V- and some recycled material
		Chipboard	Softwood chips, sawdust, shavings	No rot. Low MC <18%	Mainly recycled + Log Type V-
8d	**Fibreboard**	**MDF**	Spruce & pine fibres	No rot. Low MC <18%	Mainly recycled + Log Type V-
		Softboard	Spruce & pine fibres	No rot. Low MC <18%	Mainly recycled + Log Type V-
		Hardboard	Spruce & pine fibres	No rot. Low MC <18%	Mainly recycled + Log Type V-

Table 4b:CPA Codes for Converted Products

Chain	Converted products	CPA Code	CPA definition
Furniture:			
4a	**Home and office furniture**	36.14.12	Wooden furniture of a kind used in the bedroom, in the dining room and in the living room
		36.12.12	Wooden furniture of a kind used in offices
		36.12.13	Wooden furniture for shops
4b	**Kitchen / Bathroom furniture**	36.13.10	Kitchen furniture
		36.14.13	Wooden furniture n.e.c.
4c	**Outdoor furniture**		
Joinery:			
5a	Floor covering	20.30.12	Parquet panels, shuttering for concrete constructional work, shingles and shakes, of wood
5b	**Doors & windows**	20.30.11	Windows, French windows and their frames, doors and their frames and thresholds, of wood
Packaging			
6a	**Pallets**	20.40.11	Pallets, box pallets and other load boards of wood
6b	**Boxes**	20.40.12	Other wooden containers and parts thereof
Construction:			
7a	**External & internal wall (incl. timber frame)**	20.30.12	Parquet panels, shuttering for concrete constructional work, shingles and shakes, of wood
		20.30.13	Builders' joinery and carpentry, of wood, n.e.c
7b	**Floor systems**	20.30.12	Parquet panels, shuttering for concrete constructional work, shingles and shakes, of wood
		20.30.13	Builders' joinery and carpentry, of wood, n.e.c
7c	**Roof**	20.30.12	Parquet panels, shuttering for concrete constructional work, shingles and shakes, of wood
		20.30.13	Builders' joinery and carpentry, of wood, n.e.c
7d	**Complete house**	20.30.20	Prefabricated wooden buildings
Wood-based panels:			
8a	**Veneer sheets**	20.20.21	Veneer sheets and sheets for plywood and other wood sawn lengthwise, sliced or peeled, of a thickness ≤ 6 mm
8b	**Plywood**	20.20.11	Plywood consisting solely of sheets of wood
		20.20.12	Other plywood, veneered panels and similar laminated wood
8c	**Particle board**	20.20.13	Particle boards and similar boards of wood or other ligneous materials
8d	**Fibreboard**	20.20.14	Fibreboard of wood or other ligneous materials

Table 4c: Important relationships between properties of wood and solid-wood products

	Reaction Wood		Knot size	Knot area ratio	Dead knots	Resin*	Density	Stiffness	Strength	Appearance	Dimensional Stability	Durability	Internal Bond	Surface Soundness
Product														
Batten	-		-	-	?	-	+	+	+	+	+	+		
Fencing	-		-	-	-	=	=	+	+	=	+	+		
Pallet	-		=	=	=	=	=	=	+	=	=	=		
OSB	N		N	N	N	N	+	+	+		+	=	+	
Particleboard	N		N	N	N	N	+	+	+		+	=	+	+
Veneer	?		-	-	-	-	?	?	?	?	?	?		
Joinery (Furniture)	-	+	=	=	-	-	=	=	=	+	+	=		
Joinery (Windows/Doors)	-		=	=	-	-	=	=	=	+	+	+		
LVL	-		=	-	=	?	+	+	+	=	+	=		
Glulam	-		=	-	=	?	+			=	+	=		
Cladding	-		=	=	-	-	=	=	=	+	+	+		
Rail Ties (Sleepers)	=		=	=	=	=	+	=	+	=	=	+		
Piling	=		-	-	-	=		+	+	=	=	+		
MDF	N	N	N	N	N	N	+	+	+	+	+	=	+	+

Legend

Correlation	**Code**
Strong positive	+
Weak positive	
Neutral	=
Weak negative	-
Strong negative	-
Not Applicable	N
?	Still needs defining

*** "Resin" relates to natural tree resin**

Table 4d: Log Types by Properties for Solid-Wood Chain

Log Type:	Properties: No absolute values. These are indicative only. **Need to be decided for each case**
I	Stem Size > 16 cm top diameter Straightness < 1cm in 1m deviation Grain Angle < 5 degs Knot Size < 5cm Appearance
I-	As for I but 50 cm top diameter >stem size> 16cm top diameter
II	Stem Size > 20 cm top diameter 3cm in 1m deviation < Straightness < 1cm in 1m deviation Knot Size < 5cm Live Knots Appearance
II+	All II plus Permeable to treatment or Durability □ moderate durability
III	Knot Size < 1cm Appearance Hardness
III+	III plus 50 cm >Stem Size> 20 cm
III-	III but 1cm < Knot Size < 2.5cm
IV	Live Knots Permeable or Durability □ moderately durable Grain Angle < 5 degs Reaction Wood < Appearance
IV-	All IV but No criteria for knots
V	Stem size< 16cm > Straightness > Reaction Wood<
V+	All V and knots<
V-	All V but no straightness requirements

5 Bio-energy chains

5.1 Key products

The final Converted Products in the bio-energy chain can be broken down into:

- Heat (9a)
- Electricity (9b)
- Pellets and Briquettes for small scale users (9c)
- Wood chips for small scale users (9d)
- Firewood for small scale users (9e)

Products likely to appear on the market in the future but which are not considered further here include the following:

- Liquid Biofuel (substituting traffic fuel or heating oil) (9f)
- Synthetic Gas (substituting & supplementing natural gas) (9g)

The distinction between different types of products (Converted products, Intermediate products and raw materials) is less obvious in the bio-energy chain than in the fibre and wood chains. For example, a local district heating plant, a power plant or a CHP-plant may also use wood chips or pellets/briquettes for producing the final product, such as heat and electricity. Therefore, a list of Intermediate Products has been identified. Process liquors such as black liquor in a pulp mill and other liquid industrial by-products used for energy production within the mill are seen as internal carriers of energy and not as products for the market, but electricity and/or heat produced from these may appear as a market product. For the same reasons, process steam mainly used in industrial processes is assumed to not be a final product.

The Converted Products in the chain (*table 5a*) can be derived from 6 Intermediate Products:

- Wood Briquettes
- Wood Pellets
- Wood Chip/Hog Fuel
- Log Wood
- Charcoal
- Composite Residue Logs (CRL)

As noted above some of these Intermediate Products (Wood Briquettes, Wood Pellets and Wood Chips) are also final Converted Products. The Intermediate Products themselves are derived from 4 primary sources of raw materials *(table 5a)*:

- Solid wood processing by-products (chemically untreated wood fractions from pulp and paper industry and mechanical processing, i.e. sawdust, bark and chips)

- Forest residue (tops, branches, stubs or whole tree chips from thinnings, small-sized trees or rejected logs)
- Refuse derived wood (construction and demolition wood, packing or paper waste, wood as a municipal waste fraction, chemically treated wood residue)
- Biomass from energy forestry
- Blends and mixtures of the above

For further information on the conversion of these primary sources of raw material to final products it is recommended to visit:

http://www.forestresearch.gov.uk/woodfuel or http://www.biomassenergycentre.org.uk

5.2 Key demands on manufactured products in bio-energy chain

The requirements of the intermediate products in the bio-energy chain are regulated by CEN/TC 335, which is the technical committee developing the draft standard to describe all forms of solid biofuels within the European Union (EU), including wood chips, wood pellets and briquettes, logs, sawdust and straw bales. The requirements of each product are set out in *table 5b* in terms of the origin of the material, moisture content, density, dimensions, ash content, additives, net calorific value, mechanical durability, percentage of fines, and percentage sulphur content where applicable.

See http://www.biomassenergycentre.org.uk/portal/page?_pageid=77,19836&_dad=portal&_schema=PORTAL for further information.

Table 5a: Key products of biofuel chains and materials used

Biofuel chain **Final product**	**Intermediate Product** **(see Table 5b for properties)**	**Wood raw material**
9a Heat **9b Electricity** **9c Pellets** **9d Wood chip** **9e Fire wood** **Future option** **9f Liquid Biofuel** **9g Synthetic Gas**	**Forest and Plantation Wood:**	
	Logs, chips, pellets, Hog fuel *(i.e. rough chips/larger chips)*, briquettes, charcoal and composite residue logs (CRL)	Whole Tree *(hardwood, softwood, SRC, scrub, blends and mixtures)*
	Logs, chips, pellets, charcoal and composite residue logs (CRL)	Stem wood *(hardwood, softwood and blends and mixtures)*
	Composite residue logs (CRL) and Hog fuel	Logging residues *(Wet inc leaves/needles, dry and blends and mixture)*
	Chips and Hog fuel	Stumps *(hardwood, softwood, SRC, scrub, blends and mixtures)*
	Chips and Hog fuel	Bark
	Logs, chips some CRL and Hog fuel	Arboricultural arisings
	Wood processing industry, by-products and residues:	
	Chips, Hog fuel, pellets and briquettes	Chemically untreated wood residues *(wood without bark, wood with bark, Bark from industry ops and blends and mixtures)*
	Chips, Hog fuel and briquettes	Chemically treated wood residues *(wood without bark, wood with bark, Bark from industry ops and blends and mixtures)*
	Hog fuel, pellets…	Fibrous waste from the pulp and paper industry *(chemical treated and untreated)*
	Used Wood:	
	Chips, Hog fuel, pellets and briquettes	Chemically untreated wood *(wood without bark, bark and blends and mixtures)*
	Hog fuel, pellets…	Chemically treated wood *(wood without bark, bark and blends and mixtures)*
	Blends and mixtures:	
	Chips, Hog fuel, pellets and briquettes	

Table 5b: Key properties of biofuel intermediate products (STANDARDS REF: CEN335).

Material	Origin	Moisture Content	Density	Dimensions	Ash Content	Additives	Net calorific value	Mechanical durability	% of fines	Sulphur Content %
Wood Briquettes:	Origin required	<10 w-%	1.00 – 1.09 kg/dm^3	diameter mm, length mm	<0.7 w-% of dry matter	<2 w-% dry basis. Only products from primary forestry biomass, not chemically modified are approved as additives for pressing	≥ 4.7 kWh/kg = 16.9 MJ/kg	97.5 w-% of a pellet batch of 100g uncrushed after testing		
Wood Pellets:	Chemically untreated wood without bark	< 10 w-%		6mm ± 0.5 mm and length < 5 x diameter. 8mm ± 0.5 mm and length < 4 x diameter. Max 20 w-% of pellets may have a length of 7.5 x diameter	<0.7 w-% dry matter	<2 w-% dry matter and may consist of bio-based chemically material			% after sieving through > 3.15 mm. Shall not exceed 1 or 2 w- %	<0.05 w-% 0f dry matter (sulphur is normative only for chemically treated biomass and if sulphur containing additives are used)
Wood Chip /Hog Fuel:	Origin of stem wood required	Range expressed as w-%		Expressed as main, fine and coarse fractions – w%. Range 16 mm, 45mm, 63mm, 100mm and 300mm			> 900 kWh/bulk m^3			
Log Wood:	Origin of stem wood required	< 20 w-%		diameter and length mm. Range <200, 200, 250, 330, 500 and 1000 mm with tolerances						
Charcoal: No CEN standard			800 grams favoured for high quality UK charcoal	Large fairly evenly sized pieces. This can only be produced from timber that has been cut to consistent sizes and generally is no smaller than 4 inches diameter.					Charcoal out of the kiln has to be run over a sieve before it can be bagged. This removes the smallest pieces (known as fines) which are then bagged off and utilised in mulches.	
CRL: No CEN standard	Stem wood, branch, needle and leaves	Moisture content important but no standard		Diameter and length (m)	Ash content important but no standard		Net calorific value important but no standard			

6 Quality-based allocation of wood raw materials to key products and analysis of sustainability effects

The allocation of suitable wood raw materials to mills, processes and products is crucial for the sustainability of the forestry wood chains, influencing product quality, production economy, environment and society. For this, information is needed about what properties of wood and fibres are needed or preferred for the production of different forest-based products, as well as the properties and volumes of wood available within the forest resource.

In some cases certain wood properties are imperative for the production of a specific product. In most cases, it is, however, difficult or impossible to define general threshold values for the required properties of the raw materials for products and processes. Investments may have been made in process equipment to manage otherwise sub-optimal raw materials, but at an extra cost. Therefore, the description above of property demands has to be indicative rather than absolute for many types of products.

6.1 Overall analysis from forest to recycled product

Sustainability has to be assessed from an overall perspective and include all steps from the forest to the used and recycled or disposed of products, including operations in forest management, production, logistics, etc. An alternative which saves materials and energy in the primary production steps but can not be recycled might be less sustainable. This need for a broad perspective is in many cases also valid for successful design of products, their production, distribution, and marketing. It is good if an innovation results in decreased energy use in the pulp mill, but even better if it also results in benefits for converters and end-users. Alternatives may often involve changes in more than one part of the chain, sometimes combinations of positive and negative effects. This makes it very complex to compare different alternatives.

The principle objective of the EFORWOOD project has been the development of ToSIA (Tool for Sustainability Impact Assessment) to support these kinds of overall analyses. It is a tool for chains to be analysed from forest to recycled products, to analyse individual or interacting chains, and for the calculation of “sustainability indicators” for various types of effects on sustainability (Lindner et al. 2007; Rametsteiner et al. 2006). Indicators related to environment, economy and society are included such as employment, production costs, greenhouse gases, etc. The indicator values may then be aggregated to provide an overall perspective on sustainability. A number of case studies have been performed and scenarios have been compared from a sustainability perspective. A large part of the collective work effort has been devoted to the collection of data for the calculation of indictors related to different types of processes and typical conditions in different European regions.

6.2 Analysing sustainability of allocation alternatives

An overall perspective is obviously necessary also when analysing and comparing different allocation alternatives from a sustainability point of view. Factors like available raw materials and product and process demands have to be combined with consequences and opportunities occurring all along the chain to the used and recycled/deposited product. The solution is to combine expertise from different fields along the whole chain and define alternatives from a broad perspective, including all effects of allocation from harvesting via transportation to processing in different product chains, distribution and use. These broad perspective alternatives are then simulated within ToSIA. Sustainability indicators are calculated and compared for the whole or part chain.

If available, a “Forest Resource Databases” is an efficient way to search for and define a number of allocation alternatives based on the available resource (Lundqvist, Grahn 2008). Each alternative is obtained by application of a set of search criteria on the database. Each selection can be based on properties of stands, trees, logs, knots, wood or fibres included in the database. The result of each selection will be a set of raw material classes, which may be dedicated to the production of different key products of the three types of chains (fibres, solid wood, bio-energy). For each class, the volume (or dry mass) and the key properties are known. The volumes and properties may serve as the basis for allocation of wood flows to different production chains considering the product and process requirements defined in this report. The properties constraint how the material may be processed, the costs involved, etc., along the chain as far as is relevant for the particular case.

A practical way to carry out such an allocation study is to define a reference case including all the relevant parts of the chain. The reference case is evaluated in order to ensure that the results are reasonable. The experts then define which products can be produced and in what way if the wood classes of the reference case are allocated in other ways. They also define the expected consequences for yield, consumption of energy, chemicals and person-hours, etc. as well as for product quality, the need for transportation, etc. The different alternatives designed are then simulated within ToSIA or other tools to clarify how sensitive individual and aggregated sustainability indicators are to reasonable allocation alternatives, including also the consequences of each alternative along all the chain. This initial step provides information about which changes in allocation (flows to various chains), processes, product properties and uses, etc. have the strongest effects and thus should be given most attention in the investigation of various alternatives.

The alternatives are then refined by the experts and further simulated. The results are compared with respect to quantity and properties of products produced and their properties as well as to their effects on environmental, social and economic sustainability indicators. In this way, the different demands on raw material properties of various key products of the forest-based industries may be incorporated into the analysis of sustainability, including the entire chain from tree to recycled product, and incorporating the economic benefits of the different alternatives. Examples are given in (Lundqvist et al 2010), describing two case studies: one related to a fibre-based chain and one related to a solid wood and bioenergy chains.

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8 Innventia Database information

Title

Key products of the forest-based industries and their demands on wood raw material properties

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Abstract

The allocation of wood raw materials with suitable materials to mills, processes and products is crucial for the sustainability of the forestry wood chains. For this, information is needed about what properties of wood and fibres are needed or preferred for the production of different products. The objective of this report is to express these demands on wood and fibres in terms of raw material properties for major types of forest-based products, divided into the products of solid wood chains, fibre chains and bio-energy chains. For each type of chain, sets of key product types have been identified. In most cases, it is difficult or impossible to define generally applicable threshold values for the required properties of raw materials for products and processes. In these cases the property demands are expressed in indicative rather than absolute terms.

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