Mechanical processing for improved products made from Swedish hardwood
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Jimmy Johansson

Växjö University Press
Abstract


Swedish hardwood is today used in the energy, pulp and mechanical hardwood industries. Only very small volumes of Swedish hardwood are, however, consumed by the mechanical industry that normally pays the highest timber price. The smallness of the volumes used for mechanical refinement is a result both of forestry not focusing on the production of hardwood for these uses, and of the fact that the mechanical hardwood industry, particularly the sawing industry, is not designed to process the existing raw material in an optimal manner. This thesis discusses the possibilities of improving the conditions for the mechanical refinement of hardwood. The aim of the work has been to investigate the possibilities of developing products and methods for processing of Swedish hardwood.

The thesis proposes a new manufacturing system for Swedish hardwood to better utilize the inherent properties of the wood material. The system is based on the so-called PrimWood Method and the star-sawing concept. Compared to normally sawn wood, the sawing concept utilizes the raw material more efficiently with regard to volume yield, and increases the distance between knots in the sawn wood. The material produced has vertical annual rings which give the wood smaller movements as a result of moisture variations and a different textural appearance. Using the PrimWood Method for hardwood would make it possible to more closely match customer requirements regarding hardwood products.

Since Swedish hardwood is nowadays mainly used indoors, a possible way of expanding the market would be to increase the outdoor use of the material. Here the durability is of great importance, and one important factor is then the capillary characteristics of the material. The thesis therefore focuses on the characterisation of the capillarity in wood for the future improvement of its durability. It is shown that with the material produced by the proposed manufacturing system, i.e. wood with vertical annual rings, the possibility of using hardwood outdoors increases, because the susceptibility to cracking decreases.

Keywords: capillarity, capillary transport, customer requirements, ecoeffectiveness, sawing pattern, star-sawing, the PrimWood Method, timber products, volume yield, water transport, wood products

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Preface

This research has been carried out at Växjö University, the Department of Forest and Wood Technology, and has been financed by the Centre of Industrial Competitiveness, Växjö University. The Knowledge Foundation has also financed the research through the projects *Wood manufacturing and hardwood - the quality of hardwood* (2002/009) and *The influence of moisture on shape stability of bent wood products* (2003/0237). Carl Fredrik von Horn’s foundation through The Royal Swedish Academy of Agriculture and Forestry is acknowledged for financing of the research reported in Paper 1. VINNOVA has financed the project and will continue to finance the author’s future research within the project *Business system for competitive and customer-oriented birch wood production for furniture manufacture* (2007/01651).

I would like to express my sincere gratitude to my supervisors Assistant Professor Dick Sandberg and Professor Thomas Thörnqvist. Dick Sandberg is also the co-author of Papers 4, 5, 6 and 7. Professor Ove Söderström at KTH building materials is acknowledged for co-supervising the part of the project concerning capillarity. I would also like to thank my co-authors, Assistant Professor Åsa Gustafsson, Paper 2 and Assistant Professor Girma Kifetew, Paper 3. Many thanks are extended to Professor Reine Karlsson at TEM at Lund University and to Assistant Professor Lotta Woxblom at Swedish University of Agricultural Sciences, who are colleagues within the VINNOVA research project mentioned above. The staff of Nässjö Träcentrum and Susanne Johansson at Woodcraft Network are acknowledged for fruitful collaboration. Dennis Johansson, Birger Marklund and Professor Tom Morén at LTU are acknowledged for help in conducting the work reported in Paper 3. Finally the author wishes to thanks all the staff of the School of Technology and Design and especially the colleagues at the research group of wood science, family and friends.
The thesis is based on the seven appended papers listed below. The work has, however, included important work presented in conference articles, technical reports etc. where the author of this thesis has been the main or a co-author. A list of such publications is presented in appendix 1.


Author's Contribution to the work in appended papers with divided authorship

**Paper 2:** Johansson initiated the work and collected most of the data. The authors performed the analysis and wrote the paper together.

**Paper 3:** Johansson initiated the work, collected the material and performed the analysis. The authors wrote the paper together.

**Paper 4:** Sandberg initiated the work and collected the material. The authors performed the analysis and wrote the paper together.

**Paper 5:** Sandberg initiated the work and the authors wrote the paper together.

**Paper 6:** Sandberg initiated the work and the authors wrote the paper together.

**Paper 7:** Johansson initiated the work, collected the material and performed the analysis. The authors wrote the paper together.
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1 Introduction

1.1 Hardwood in Sweden

Hardwood is much appreciated as a feature of the forest and as a material in various types of products. Today, the Swedish forest consists of 17% deciduous trees. This means that there are approximately 500 million m³ of deciduous trees with an annual growth of 23 million m³. The most common hardwood species are birch (Betula pubescens Ehrh., Betula pendula Roth.), aspen (Populus tremula L.), alder (Alnus glutinosa L.), oak (Quercus robur L.) and beech (Fagus sylvatica L.) (Swedish National Forest Inventory, 2008), Figure 1.

![Figure 1. Volumetric species distribution of the Swedish deciduous forest.](image)

Interest in hardwood has been at a low level since the 1950s. Deciduous thickets and undergrowth were in fact sprayed with the so-called ‘Agent Orange’ biocide in the 1960s and 1970s, so that the conifer saplings would not succumb to competition (Heräjärvi, 2002). Historically, however, deciduous trees have always been considered valuable. From the 17th century until the end of the 19th century, the oak in particular has been protected from felling in a variety of ways. Oak timber was used primarily for the production of naval vessels. New plantings of oak forest were also carried out in the first half of the 19th century,
e.g. on Visingsö, to safeguard the future supplies of oak timber for shipbuilding (Kardell, 2003). The belief that deciduous forestry is now unprofitable is a result of the fact that forestry has become focused on conifers together with the limited market for hardwood (Almgren, 1990; Nylinder and Woxblom, 2005). At the same time, governmental targets have been set up to increase the proportion of deciduous forest for environmental reasons (SOU, 2000; SUS, 2001; SOU, 2005; SOU, 2006). Deciduous forests show several positive environmental effects through an increased biological manifoldness and a much appreciated environment for recreation and outdoor life (SOU, 2000). From the perspective of the forest owner, a deciduous forest is advantageous as a diversifier of risks, since the felling can be guided according to the prevailing timber price picture and, according to Persson and Rytter (1998), the wood species are also influenced differently regarding damage during growth owing to e.g. storms.

To make deciduous forestry attractive, a profitable market for the wood is required. Today, hardwood as a material is used mainly in the production of energy, pulp, sawn wood and for veneer manufacture. According to Nylinder et al. (2006), the industrial use amounts to approximately 8.0 million m³ per year. The use of hardwood for fuel which is estimated to be 3.5-6 million m³ per year is not included. Approximately 400 000 m³ per year is used for saw logs, 40 000 m³ per year for the manufacture of matches and less than 8 000 m³ per year for veneer manufacture. In industrial use, birch accounts for 75 % of the total hardwood consumption. The Swedish hardwood sawmill industry constitutes only about 5 % of the industrially used volume, in contrast to the situation regarding softwood, where the sawmills stand for the consumption of about half the felled volume.

The prices of hardwood vary with a number of factors such as the species of wood and the quality, dimensions, delivery method and felling time. The small volumes and the few buying/selling situations mean that it is difficult to define the market price of many Swedish hardwood species. Table 1 gives roughly approximated prices for ash, beech, birch and oak. These are the main species which are traded in large volumes. The prices of veneer logs are difficult to determine because of a small market with uncertain demand and because of low availability of logs for this purpose. The prices are in the interval two to three times the prices of the saw logs. The use of Swedish hardwood for veneer production is mainly limited to oak.

To use the forest for recreation etc. is something which several forest owners encourage by offering different types of experiences in and in connection with the forest. The value of the forest as a recreation environment is nevertheless difficult to assess. Preliminary results from the deciduous forest program (Löf, 2006) indicate that the deciduous forest and excursions to them are highly valued (value or price/forest visit). An increased area of deciduous forest in the south of

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1 m³Sub – Cubic metre solid wood excluding bark.
Sweden would also generate a higher value compared with the presently available deciduous forest area. In total, the annual recreation value would probably correspond to the value generated by the timber products from the forest (Boman and Mattsson, 2006).

<table>
<thead>
<tr>
<th>Species</th>
<th>Energy wood</th>
<th>Pulp wood</th>
<th>Saw logs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>22</td>
<td></td>
<td>28-110</td>
</tr>
<tr>
<td>Beech</td>
<td>22</td>
<td>32</td>
<td>63-73</td>
</tr>
<tr>
<td>Birch</td>
<td>13-16</td>
<td>26–30</td>
<td>42-90</td>
</tr>
<tr>
<td>Oak</td>
<td>22</td>
<td></td>
<td>30-230</td>
</tr>
</tbody>
</table>

Persson and Rytter (1998) say that there are critical diameter limits, above which the value of the individual tree increases strongly. These limits coincide with the limits for sawable logs and with logs for veneer manufacture.

Persson and Rytter (1998) say that a high value of the trees in the hardwood forest and thereby a higher profitability for hardwood forestry is best created by maximising the volume of thick trees in the final felling. This is best done through repeated thinning. The Swedish hardwood forests are not however usually managed in this way. Pure hardwood forest stands are unusual in Sweden; the deciduous trees are more often to be found in mixed stands with conifers. This means that the deciduous trees are normally felled in the first thinning to favour the growth of the conifers. The dimensions of the felled deciduous trees are consequently small and the wood can be used only in the pulp industry and for energy purposes. Since hardwood thinner than 17-18 cm in top diameter is not sawn, the volumes of sawable hardwood obtained in the felling are small, and this is a problem with current ways of transporting timber. A large amount of sawable hardwood timber thus becomes pulp wood, according to Bylund and Rytter (1997), who have shown that 15 % of the wood delivered as pulp wood may in fact consist of sawable timber. The deciduous trees which are left in the forest after thinning are often allowed to remain until the conifers are finally felled. The deciduous trees are then too old and have a poorer quality (Heräjärvi, 2002). In addition, a lot of the standing deciduous forest in Sweden is judged to be of poor quality with respect to e.g. knots and crookedness. This can be considered to be the result of poorly managed deciduous forest stands with a slow growth (Rytter and Werner, 2000).

The small volumes of sawable timber together with the quality deficiencies mean that the mechanical hardwood industry (here defined as sawmills, board factories, the veneer industry and the subsequent processing by the building, furniture, flooring and joinery industries) finds it difficult to secure a balanced flow of Swedish hardwood raw material. From the perspective of the hardwood sawmills, the processing also results in products with different qualities which in certain cases lack a sufficiently profitable market. The sawmill’s customers usually require products with few knots and a minimum of textural effects (Johansson, 2003).
The products which the mechanical hardwood industry manufactures are used primarily for interior use within the furniture, flooring and joinery industries (Paper 1; Nylinder and Woxblom, 2005; Nylinder et al., 2006). These industries are important employers in Sweden with about 20 000 direct employees (TMF, 2008). At the present time, most of the hardwood timber used by these industries is imported (Nylinder et al., 2006). The domestic wood species used by the mechanical hardwood industry are chiefly birch, oak, beech and ash, and also aspen for the manufacture of matches. With regard to volume, birch and oak are the major species. Thus, the volumes used do not correspond to the availability in the forest, where aspen and alder are available in greater volumes than ash, oak and beech.

The present refinement chain for hardwood in Sweden is thus unbalanced, with a forestry industry which does not optimize the yield of deciduous trees by focusing on the wood required by the mechanical hardwood industry. This industry is in turn not able to take care of the existing raw material in an optimal way by creating the profitable products from the raw material requested by the customers.

For a long-term functioning refinement chain, profitability is required in each stage. In the refinement chain, the forest should in a short-term perspective be regarded as a constant with respect to the availability of raw material, since any change in the forest takes a long time. For this reason, the development of the mechanical hardwood industry is thus a first requirement. This should take place through the development of both the manufacturing process and the products produced, (Johansson, 2005). Through the development of the manufacturing process and of the products, the material can be used more efficiently and it can become possible to broaden the use towards new products on new markets. The market for hardwood is currently largely limited to interior use. A possible development would thus be to broaden the market towards a more extensive exterior use. This market would set other requirements on visual effects such as e.g. knots and colour. However, outdoor use makes demands on a high durability of the material.

In this study, the mechanical hardwood industry has therefore been studied with respect to the more efficient use of the material. The work has focused on the development of the manufacturing system for sawing, on a better use of the existing raw material and on the development of products with a higher value.
1.2 Research questions

This main problem relates to the concept of product and manufacturing systems development. Johansson (2005) suggests that the Swedish mechanical hardwood industry must differentiate its products from those of its competitors i.e. industries in other countries and substitute materials. This means developing the manufacturing system to more clearly focus on the market requirements and at the same time to put effort into utilising the inherent properties of the existing raw material stock. An improvement in the way of producing products may also result in new or improved products from the manufacturing process. This means that there is also a need to focus on finding new markets for the material produced. New markets may then set other quality demands. This may be a way of expanding the range of demanded qualities of the sawn wood.

The focus here is on the production of sawn wood starting from sawmilling, followed by value adding processes. This is because the production of sawn wood is judged to better suit the existing raw material base in Sweden, compared to e.g. veneer production. The division of the log into sawn wood, traditionally carried out in sawmills, is also a refinement stage that has a large impact on the quality, and thereby the price, of the final wood products.

This project has therefore studied how wood products and manufacturing systems can be improved so that the volume and quality of the hardwood forests in Sweden are properly exploited. The main question addressed may be summarized as:

*How is it possible to develop hardwood products and the mechanical manufacturing process for an improved utilisation of Swedish hardwood?*

Knowledge of the customers' requirements and how the products must be designed to satisfy the customers' needs is the most important parameter to consider during product development. Therefore a strong focus during this project has been to identify customer requirements and to consider how to adjust the production process to create products that fulfil those requirements.

The main research question may then be divided into two research questions (RQ:s). These are:

RQ 1. *What requirements do the customers set on hardwood products?*

RQ 2. *How is it possible to improve the manufacturing process for better utilisation of the raw material and to improve the characteristics of the products produced?*
1.3 Objectives

The study investigates the possibilities of improving the products and manufacturing process for Swedish hardwood, through a better utilisation of the existing raw material and through the creation of products with greater degree of fulfilment of the customer requirements.

The following are the two main objectives of the work described in this thesis:

- To propose a new industrial manufacturing system with a better utilisation of the existing Swedish hardwood
- To propose products of hardwood with characteristics more attractive to the customers

1.4 Vision

The vision of the thesis is that the improvement in products and manufacturing system utilising existing raw materials should increase the profitability of the industry. It should also reduce the need for imports and mean that the Swedish forest owners would receive a better yield on the timber from their forests. At the same time new attractive products would be added to the market.

The vision is also to create a change of attitude within the Swedish forest and wood industry towards Swedish sawn hardwood. Hardwood as a material should be seen as a useful, industrial material. More specifically, the material should to a large extent be produced with the proposed production system in order to more effectively utilise the benefits of the material. This should lead to a will and courage to invest in hardwood within both forestry and the mechanical hardwood industry. This will lead to a greater biological diversity and the increased competitiveness of the Swedish forest and wood industry.
1.5 Presentation of the appended papers

This thesis is based on the work described in the appended papers and to some extent on conference papers and reports not appended. This section gives the reader an insight into the basic ideas of each of the appended papers, and how they contribute to the fulfilment of the overall objectives.

**Paper 1:** When starting this research, it was noticed that an overview of today’s Swedish hardwood sawmill industry was lacking. Therefore, Paper 1 explains the structure of the industry and discusses its future. It should be noticed that this research was conducted immediately after a devastating hurricane that struck southern parts of Sweden in January 2005. This affected the study, since many of the companies within the study lacked raw material to saw during the spring of 2005, since all resources available in the forest were focused on saving and handling the fallen softwood trees.

**Paper 2:** A major issue for hardwood sawmills is the problem of receiving value from all the sawn products with different qualities. Expanding the market for the products to areas that may set other requirements on the sawn wood would open the way to opportunities of finding profitable markets for all the sawn wood products produced by the sawmill. Paper 2 therefore deals with the customer requirements of wood, especially related to the requirements of the house-building industry. Paper 2 also relates an increased use of hardwood to the impact on the environment, and describes hardwood as an eco-effective material.

**Paper 3:** A possible way of expanding the market for sawn hardwood products would be to use more hardwood outdoors. When using hardwoods outdoors, the durability is a critical factor. This means that the capillary characteristics may be a problem, since most degradation in wood structures occurs close to the end-grain surface as a result of capillary water absorption (see section 4.6). The phenomenon of capillary water absorption and its effect on the material is not quite clear. Paper 3 seeks to provide knowledge of the basic principles of capillarity in different wood species, and to show the differences between wood species with regard to their capillary structure.

**Paper 4:** The quality of wood products has been shown to depend strongly on the selected sawing pattern. In order to be able to evaluate the effectiveness of a sawing pattern, it is necessary to develop a method for comparison. Paper 4 compares star-sawing (section 5.2) and square-sawing in relation to the occurrence of knots in sawn wood. The study in Paper 4 was conducted on pine, since data for hardwood was not available at this time.

**Papers 5-7:** In the papers 5-7 a manufacturing system for hardwood is presented. The system is based on the so-called PrimWood Method (section 5.2) and the
star-sawing concept. Most of this research involved the application of an idea developed for the sawing of pine, which also shows very promising results for hardwoods. The manufacturing system utilises the raw material more efficiently, with regard to both volume yield and especially the value of the material. Using the PrimWood Method for hardwood would make it possible to match more closely the customer requirements regarding wood products. Through the PrimWood Method, wood with vertical annual rings is produced, defined in section 4.3, which presents several benefits compared to the traditionally sawn wood.

1.6 Delimitations

This work has as its theoretical and practical framework sawing and further processing of hardwood. The study does not involve the question the procurement of raw material to the sawmills except that we conclude that there should be sufficient standing volume in the forests for today’s sawing and even an expansion of the sawmill industry. The study does not consider how the products should be presented on the market.
2 Methodology

2.1 Methodological approach

The hardwood field in Sweden may be categorized as being quite unexplored, so that a wide research approach is necessary to gain knowledge of the problem areas in the field. This work has therefore been both quantitative through experiments and qualitative through interviews and observations.

As pointed out by Johansson (2005), it is important to establish a connection between the market, i.e. the customer requirements, and the raw material base available in order to be able to create a long-term durable situation. This must also be put in relation to the economic situation and available manufacturing systems. In this thesis, the new products and the proposed expansion of the market are put in relation to the raw material base and the customer requirements. The market must be expanded to better utilise the raw material base and new products must focus on the critical factors governing the customers’ selection of material for their products, as shown in Figure 2.

![Diagram](image)

Figure 2. Model illustrating the factors that affect the products and manufacturing systems studied within the project.

The elements in Figure 2 are strongly related to the research questions (RQs) (see section 1.2) where RQ 1 deals with the customer requirements, and RQ 2 deal with product development and process development in relation to the customer requirements and the raw material base, here assumed to be static.
2.2 Research, science and development

Most of this work focuses on the development of hardwood, with reference to the manufacturing process, the products and the basic material properties. Working with product or material development often includes a stepwise scheme which ensures the quality of the research and the selection of appropriate methods to use. According to Ullman (1997) this process may be summarized as follows:

1. Establish – establish the need on the market and the problem that needs to be solved.

2. Plan – Plan how the problem should be solved

3. Understand – Establish requirements and benchmark considering solutions to similar problems

4. Generate – Different solutions and concepts

5. Evaluate – compare different solutions towards requirements and towards each other

6. Select – what or which solutions that might work

In the same way, science is a process for gaining knowledge. Christensen (2004) defines the method of science, i.e. research, in the following five steps,

1. Identifying the problem

2. Designing the experiment

3. Conducting the experiment

4. Analysing the data

5. Communicating the research results.

The main differences between the scientific process and the development process are then related to the communication of the results. Science is about creating knowledge and the communication of this knowledge to a broader audience, whereas the development process mostly is interested in the actual results. However, a process always is cyclical, i.e it is constantly repeating, so that we can learn from one cycle to the next (Bergman and Klevsjö, 1995). These schemes together then create the research process in this thesis work, as shown
in Figure 3. The research process is here seen as a cyclical process where each project leads forward, bringing up new questions and ideas. It should also be noticed that the process is rarely perfectly cyclical. It is often necessary to take a step backwards during the process in order to perform new experiments or make new theoretical studies. The experience is also that these steps backward, or to the side often lead to knowledge creation.

Figure 3. The research process in this study is seen as a cyclical process from idea to the communications of the results.

2.3 Research quality

The quality of research is often determined by the two concepts, validity and reliability. Validity mainly describes whether the research measures the right parameter and reliability determines the consistency, stability and repeatability of the measurements. This means that, if the same study were performed again the results should be the same (cf. Yin, 2003). In the present study a problem with regard to reliability is that many of the results have a limited life-time, for instance the work conducted in Papers 1 and 2, because of changing conditions in the hardwood sawmill industry.

Validity is divided by Yin (2003) into three parts, the construct validity, the internal validity and the external validity. Construct validity measures whether the selected measurement tool is appropriate to measure the studied item. Internal validity refers to causal relationships, i.e. whether the investigator incorrectly concludes that there is a relationship between two factors without knowing that a third factor has influenced the system and caused the false relationship. External validity determines whether the study’s findings may be generalized to a broader perspective.
These aspects are discussed in each of the appended papers in this thesis. However, a few remarks deserve to be made. Papers 1 and 2 are based on interviews and observations at companies. It may be discussed whether this is the right method to use. For instance, using a questionnaire to be answered in writing might then have been an alternative. However the personal meeting was considered to be favourable, even though it was time-consuming and costly, since it gave the opportunity to discuss aspects beyond the initially formulated questions. It also gave the author a lot of knowledge to see the business in full action. The follow-up study in Paper 2 through a phone survey was an efficient way to quickly collect data, at the same time as it gave the opportunity to explain questions to the respondents if something was misunderstood.

In Paper 3 there is a question related to the validity with regard to the precision of the measurement technique. We were searching for a method to study the capillary transport from cell to cell within the wood specimens. The CT-scanning technique is a good starting point but it would be advantageous in further studies to find a measurement tool with even higher resolution.

2.4 Methodological criticism

During the research, the author has encountered several difficulties that may have affected the results of the research. During this time, it has been demonstrated that the refinement chain of hardwood is highly vulnerable. Twice during the period of research, the Southern parts of Sweden, where most hardwood sawmills are located, have been struck by severe storms. At the time of the first storm, the research for Paper 1 was planned and conducted. This may have affected the results. The second storm affected the research in Paper 7 since the test sawing was planned but largely delayed because the promised raw material could not be felled due to a lack of felling resources. The research in Paper 7 was also planned to be conducted much earlier during this research time. However, since no sawmill had at that time adopted the PrimWood Method, a laboratory sawing had to be conducted, which would have been very time- and money-consuming. At the same time, there were plans to start a sawmill utilising the PrimWood Method. A decision was therefore made to wait until the industrial production was running.
3 Customer requirements on hardwood

Ashby and Johnson (2003) divide the requirements of a successful product into three stages, functionality, usability and satisfaction. A product must work and be easy to understand and use, and it must enhance the life of its user. The choice of material affects all three factors. The material helps the product to function properly and it affects the usability through both visual and tactile features. The main aspect of the material selection is however related to user satisfaction created through aesthetics and the perception of the products. Lenau (2002) states that products are sold on the basis of the image it convey to the consumers. The identity is also important considering the user’s conception of the product. The material in the product plays a significant role in creating the conception of quality of the product.

The most important properties required of the wood in wood products are described by e.g. Wiklund (1991), Sandberg (1998) and Sandberg and Johansson (2005) as:

- Aesthetics and tactile properties
- Accuracy in dimensions and geometry
- Material free from cracks
- Controlled movements in the wood material with changing humidity
- Strength and hardness
- Above-ground durability (considering mainly weathering and biological attack)

In hardwoods, the emphasis is often on the appearance whereas in softwood the focus is on strength properties since the largest volumes of softwood are used in load-bearing constructions. It is shown in Paper 2 that the market for hardwood products sets high requirements related to both service and product. The service requirements are related, for instance, to the availability of the products at the right time and rapid deliveries.
The customers for hardwood products are described by Paper 1, where the furniture, flooring and carpentry industries are seen to be the most important users of sawn hardwood. An expansion of the market for hardwood products may be directed towards building and outdoor applications in the future (Paper 3).

A special aspect of the use of wood in products is that the materials differ in value in relation to their use. Ashby and Johnson (2003) states:

Wood in fine furniture suggests craftsmanship, but in a packing case, cheap utility (pp. 30).

The value is thus often related to the amount of work put into the product. In Sweden, there is a strong relationship between number of jobs and volume of used wood. 3 500 m³ wood in the forest will generate one job and the same volume sent to the sawmill and planing industry will generate 1.4 jobs. In the further processing, excluding furniture production, this volume of wood will generate 14 jobs. In furniture production, where the wood is an important raw material 3 500 m³ wood will generate 200 jobs (The Ministry of Industry, Employment and Communications, 2004; SVO, 2008).

In the development of products, the material characteristics must be considered in relation to both technical manufacturing aspects and design (Lenau, 2002). A good product design utilises the potential to shape and manufacture a specific material. Design is an aspect that is valued very highly for the consumer of wood products, for instance regarding furniture (e.g. Michalec and Strnad, 2008). According to Scholz and Decker (2007), the wood species used in a furniture product has a strong impact on consumer preferences. Wood affects the overall product assessment from material performance to style and design. The consumer also associates different aspects with different wood species (see e.g. Bowe and Bumgardner, 2004; Scholz and Decker, 2007). Oak signals for instance durability whereas cherry suggests elegance and costliness (Scholz and Decker, 2007).

Sundberg (1999) also points out that customers are often driven by fashion and trends. In the selection of materials for products the designers and architects become important. Lenau (2002) say that it is not always clear to these occupational groups how different materials should be used. This is especially important in the case of new materials. This implies a need for information considering material use (cf. Wiklund, 1991, 1992; Baudin, 1999). Lenau (2002) also states that, already in the design stage, the material should be considered as a part of the product in order to avoid costly changes in later stages of the development process and also to inspire the use of new technological possibilities. Knowledge of material properties then becomes essential, and a close cooperation between the hardwood producer and the design stage is necessary in order to reach the market.
A critical issue considering the use of Swedish hardwood concerns the use of all available wood species. Today, the use of the Swedish hardwood species for sawing is concentrated towards birch and oak and to some extent beech. The trend during recent years has been directed especially towards oak (UNECE/FAO, 2008). Beech was earlier a much utilised and popular wood species for sawing, but the market for sawn beech is today at a low level (Hapla and Ohnesorge, 2005). In Sweden, sawmills focusing on beech sawing have even been closed down.

The consumption of beech for saw logs has, according to Nylinder and Woxblom (2005), decreased by 60% from 2000 to 2005. According to Ekström (1990), the Swedish sawmill industry consumed 44 000 m³ Sub in 1989 and, according to Paper 1, the consumption in 2005 was 27 000 m³ Sub. China is however a new market for beech logs and there is now a large export of beech to China. In 2007, the export of beech logs from Europe was 5.4 million m³, compared to 3.8 million m³ in 2005 (UNECE/FAO, 2008).

In the case of other available wood species such as aspen and alder, no large volumes are sawn in Sweden. Several products such as clogs, brushes and turning products that used to be made of alder are now made of other materials or are replaced by other products. Aspen is used mainly for the production of matches, but this production in Sweden is very small and consumes approximately 40 000 m³ Sub timber per year (Nylinder et al., 2006). Aspen has also been favourable in saunas, but this application is also limited in size. For these species new products for new markets therefore must be found. The work reported in Paper 3 was therefore undertaken in order to study the possibilities of increasing the use of hardwoods in outdoor applications. Here aspen in particular may find a potential market since there are examples from other countries where aspen is used outdoors with good results.
4 Important hardwood product characteristics

Aesthetic aspects (knot-freeness, absence of the red heartwood, texture etc.), the moisture-related behaviour (shape stability) and the durability (crack-freeness, biological decay etc.) are important features in hardwood more thoroughly discussed in this section.

4.1 Red heartwood

Red (or brown) heartwood (Figure 4) is one of the most important value-decreasing wood features in, for instance beech (Hapla and Ohnesorge, 2005). However, there is a growing trend towards a more “natural appearance of the wood, utilised for instance by several flooring companies that manufacture floors with a ‘rustic’ or ‘wild’ look. This change, where a demand is created for this type of wood, may lead to a change in the quality language that normally equates high-quality with a lack of knots and evenness in texture.

Red heartwood is a phenomenon that many hardwood species develop. The main problem seems to be the difficulty of distinguishing between the red heartwood and decay (Pape, 2002). Few studies have been directed towards mechanical properties, strength etc. There seems however to be no great differences between red heartwood and clear wood regarding strength properties, according to Enquist and Petersson (2000) and Pöhler et al. (2006). Pöhler et al. (2006) show that the differences in colour between clear wood and red heartwood is reduced when the wood is exposed to UV-light. They propose that this aspect may be utilised in production in order to achieve a more colour-homogeneous wood product containing both clear wood and red heartwood.
4.2 Knots in wood

Knots in wood result in a lower strength, make the processing more difficult, make the surface treatment more difficult and affect the visual appearance. It is common to differ between fresh, dry and black knots. In sawn wood knots are an undesired feature and in the manufacture of wood products, attempts are made to minimize the number of knots in the products.

Heräjärvi (2002) studied birch, both Betula pubescens Ehrh. and Betula pendula Roth. Butt logs from the stump up to 6 metres in Betula pendula and butt logs from the stump up to 4 metres in Betula pubescens contained mainly knot-free boards from a distance of 75 mm from the pith outwards, when the logs were sawn through-and-through. At the same heights, boards from the inner part of the tree closer than 75 mm to the pith were evenly distributed in three quality classes. Class 1 contained at the most 1 knot (diameter \( \geq 5 \) mm)/2 m; class 2 contained at least 2 dead knots (diameter \( \geq 5 \) mm)/2 m regardless of the other knots; and class 3 contained the rest of the boards, i.e. mainly fresh knotted boards. Overall logs higher up in the trees contained an increased proportion of class 3 boards.
The knots start from the pith and extend towards the bark with increasing diameter. This means that the shape of the knots in the sawn wood surface is dependent on how the wood is sawn. The sawing pattern affects the knot appearance and also the distances between knots. For instance, star-sawing results in longer distances between knots than through-and-through-sawing (Papers 4, 7), although the star-sawing leads to many splay knots (Paper 7, Sandberg, 1998).

4.3 Annual ring orientation

Panshin and De Zeeuw (1980) state that the grain pattern and colour markings on the longitudinal sides together with its physical properties make wood unique as a construction material. It is common to distinguish between the tangential surface, called plain or flat-sawn wood and the radial surface called quarter sawn. These two types of wood surfaces differ in many aspects with regard to both visual textural and physical properties. The main physical effects are differences in swelling and shrinkage of the wood in relation to the annual ring orientation. Wood shrinks more in the tangential than in the radial direction. The shrinkage and swelling of some common wood species in relation to the annual ring orientation is described in Paper 5. In wood with a tangential surface, the annual rings are horizontal, and in wood with a radial surface, they are vertical. The definition of vertical annual rings used in this thesis is shown in Figure 5 and in Papers 5 and 6, Johansson (2005) and Sandberg (1998).

Figure 5. In this thesis vertical annual rings in wood are defined as annual rings at an angle of 60-90° in the cross-section in relation to the flat side of the sawn wood (CEN, 1995).
4.4 Textural characteristics

In wood with vertical annual rings, the ray tissue is exposed in the surface. In oak, where the rays are larger in size, this leads to a characteristic visual effect called ray flecks (Panshin and De Zeeuw, 1980), Figure 6. Which surface preferable is of course a matter of customer taste. However, as described for instance by Johansson and Sandberg (2005) and Johansson and Sandberg (2008), vertical annual rings have been historically favoured in many products. Many well-known designers and architects has also favoured and promoted the use of vertical annual rings in their products.

![Figure 6. Vertical annual rings expose the rays in the wood. In some wood species, in this case oak, this is apparent as ray-flecks.](image)

A particular phenomenon affecting the textural appearance of sawn wood in many hardwood species is curly or wavy grain. This phenomenon occurs because of a change in fibre directions in certain areas in the wood (Panshin and De Zeeuw, 1980; Harris, 1988). In Swedish wood species, the phenomenon is most frequent in birch and especially in silver birch (*Betula pendula* Roth) (Ståhl and Pettersson, 2007). When the waves are very narrow and abrupt, the phenomenon is called fiddleback because a common use of maple with this kind of figure is for violin decks (Panshin and De Zeeuw, 1980). In today’s sawmill industry, the wavy formation is, however, seen as a quality-degrading factor, due mainly to difficulties in planing the wood to a smooth surface without torn grain.

A common phenomenon visible particularly on the surface of birch wood is small (5-25 mm long) black or dark brown streaks following the fibre direction. These streaks are caused by the birch cambium fly.
A specific requirement regarding hardwood is the colour. The colour of the wood naturally varies from different parts in the log, particularly from the outer to the inner part of the log, for instance in birch. The placement of a board in the cross-section therefore may be necessary to note. In many species there is also a difference between the colour of the sapwood and of the heartwood. A uniform colour is usually desired in the wood. The colour nuance of the sawn wood often changes during the drying of the wood, and the sawmills want to be able to control the colour by the selection of drying parameter (Stenudd, 2002).

4.5 Environmental friendliness

Wood is, as described in Paper 2, considered to be an environmental-friendly and sustainable material. Concern about our environment and ethical issues has led to different kinds of products being marketed for instance as fair-trade products, organic products, products free from child labour, or labelled with country of origin etc.

Several studies on wood products have been published concerning the consumers’ willingness to pay a slightly higher price if the product carries some kind of environmental certification (see for instance Hansmann et al., 2006 and Aguilar and Vlosky, 2007). This willingness to pay more for these products has also increased during recent years according to Aguilar and Vlosky (2007). De Pelsmacker et al. (2005) suggest, however, that even if the consumers say they would be willing to pay more for these products they will unfortunately react in a different manner in the actual purchase situation. For instance, exporters of hardwood from the U.S. say that very few of their customers are willing to pay extra for certified wood. The customers place a low value on an eco-label and few of the exporters’ customers are asking for certified wood (Hrabovsky and Armstrong, 2005). There is a large group of consumers, however, who indicate a positive approach towards fair-trade labels etc. Even if they are not necessarily willing to pay much more for the products, they favour these products over others (see for instance Pakarinen, 1999; Pakarinen and Asikainen, 2001; De Pelsmacker et al., 2005). This indicates that environmental issues and an ethical approach to wood products may be used as marketing factors in order to give trademarks a positive value.

4.6 Capillary characteristics of wood

Suchsland (2004) indicates that nine out of ten problems with wood products in service are related to swelling and shrinkage because of moisture absorption or desorption. Especially important, considering wood and water, are the capillary characteristics of the material. As described in Paper 3, Stamm (1964) states that most of the problems related to wood and water in outdoor constructions are
related to water rising in the capillary structure of the material. The capillary characteristics of wood are studied in Paper 3. Capillarity has been the focus in this thesis since capillary absorption may be the most severe factor leading to damage in wood constructions. Capillary characteristics are also important with regard to other aspects of wood utilisation, e.g. collapse during drying, impregnation, gluing properties etc. (cf. Stamm, 1964).

In general capillarity means that the surface of a liquid will rise or fall when it comes into contact with a solid. The phenomenon appears due to surface tension forces in the contact between a liquid and a solid. Capillary rise occurs if the forces of adhesion between the liquid and the solid are greater than the forces of cohesion among the different liquid molecules (Massey, 1998). A liquid in a cylindrical capillary tube with one end inserted in water will form a meniscus, illustrated by Figure 7, with a contact angle $\theta$ between the liquid and the solid. A liquid will rise in a capillary if $\theta$ is between $0^\circ$ and $90^\circ$. Water in contact with most common building materials, for example wood, will lead to capillary rise (Nevander and Elmarsson, 2006). The fundamentals of capillarity are thoroughly described e.g. by Siau (1984, 1995). The capillary rise in the steady state is then described by the expression:

$$z = \frac{2\gamma \cos \theta}{R \rho_w g}$$

where:
- $z =$ capillary rise [m]
- $R =$ capillary radius [m]
- $\gamma =$ surface tension [Ns/m²]
- $\rho_w =$ density of the liquid [kg/m³]
- $g =$ acceleration due to gravity [m/s²]
- $\theta =$ contact angle [degrees]

*Figure 7. A liquid surface in a capillary forms a meniscus that either rises or falls in the capillary depending on the contact angle. The water rises as long as the contact angle is below $90^\circ$.***
Capillary absorption in wood is relatively slow compared to that in, for instance, glass capillary tubes. The dynamic capillary moisture transport is based on the Newton dynamic equations described in Paper 3. When water comes into contact with wood the liquid absorption is described as a three stage process (Stamm, 1964). First the water wets the surface; thereafter it is taken up by the wood through capillary forces; finally it diffuses from the cellular voids into the cell walls themselves. In Paper 3, the first and final stages are included in stage two, i.e. the wetting and diffusion are treated as capillary absorption.

In the model presented in Paper 3, it is assumed that the fibres may be seen as a bundle of tubes with circular cross-sections, although this is not strictly true. There are many models to describe the structure of wood, for instance the Comstock model (Comstock, 1970), in which the fibres have a hexagonal shape in the longitudinal-tangential plane, and a rectangular cross-section. However, the use of such a model to describe the capillary flow makes the calculations very complicated and time-consuming, and the circular tube model was therefore used in Paper 3.

In wood the capillarity is affected by the cavity radii of the different cell types in the material; also by the transport of water from one capillary to the next through the pits, whether or not the pits are aspirated, and the presence of extractives and tyloses within the wood structure and sapwood/heartwood formation. In Paper 3, this is described as a resistance in the wood structure.

As seen in Paper 3, aspen absorbs substantial amount of capillary water. There are however examples where aspen has been used in outdoor application with successful results. This means that the capillary water uptake alone is not sufficient to determine the suitability for outdoor use of any particular wood species. It is also important that the wood is able to dry out between the wetting cycles in order to maintain its function (Flæte and Eikenes, 2000).

A critical aspect of the capillarity in wood is the transport of liquid from one cell to the next, associated with the transport of liquid through the pits and, in many cases, a transverse transport of liquid. This means that it may be necessary for the capillary meniscus in a water-filled tube to break at the top of the tube in order to enter another tube. There are other examples of applications where this capillary breakage is interesting; for instance, wet films on the top of building materials because of capillary suction through the material. To study the capillary breakage phenomenon, glass tubes with an inner diameter of 0.5±0.01mm were dipped with one end in water. It was shown that the capillary broke at the top of these glass tubes when the tubes were shorter than 22 mm. Figure 8 shows the result of a simulation of this phenomenon for capillaries with varying inner radii. (cf. Söderström, 2005; Bryne and Johansson, 2007). The capillary meniscus breaks when the speed of the rising liquid water column is greater than zero (the continuous line below the dotted line) when the contact angle $\theta$ exceeds a certain limit. In this case, the limit is assumed to be roughly 180°.
4.7 Crack formation in wood

When wood is exposed outdoors, the material is affected by a varying environment regarding temperature, moisture, wind and sun, and this leads to different kinds of degradation in the material (e.g. Sandberg, 1994). There are three main types of degradation: biological degradation, mechanical degradation and photochemical degradation. These are all severe, depending on the response variable, but a more serious problem is that the different types of degradation cooperate. For instance, the photochemical and mechanical degradation resulting in visible cracks may speed up the biological degradation. This is because moisture traps are created, leading to a greater risk that water enters the wood (cf. Sandberg and Söderström, 2006).

Cracks in wood are a phenomenon with a great impact on the quality conception of a wood product. The cracks affect both the mechanical and the aesthetical aspects of the wood utilisation. According to Flæte et al. (2000), measurements of differences in crack formation in aspen and Norwegian spruce exposed to artificial weathering indicate a difference in crack formation between the species. Aspen tends to have more but shorter cracks, whereas spruce develops fewer but longer and more injurious cracks. For instance Sandberg and Söderström (2006) also describe a relationship between crack propagation and the annual ring.
orientation. Wood with horizontal annual rings tends to be more susceptible to crack propagation in the surface than wood with vertical annual rings when exposed to variation in climate.

To further study the crack formation in hardwoods, a cyclical capillary wetting and drying test in different wood species was performed. The aim was to study the impact of the annual ring orientation on the crack formation in wood exposed to capillary water suction. 120 specimens with a size of 22x70x300 mm³ of six wood species were prepared and conditioned at a temperature (T) of 20°C and a relative humidity (RH) of 65 %. The tested species were alder (Alnus glutinosa L.), aspen (Populus tremula L.), hybrid-aspen (a crossbreeding of Populus tremula L. and Populus tremuloides L.), Birch (Betula pendula Roth.), Oak (Quercus robur L.) and Poplar (Populus alba L.). Ten specimens with horizontal annual rings and ten specimens with vertical annual rings were prepared from each species. The specimens were placed with one end-grain surface in contact with a water surface for 72 hours. The specimens were immersed in approximately 5 mm of water. The specimens were thereafter placed vertically for drying for 72 hours, and then again placed in water for 72 hours. The specimens were then dried for a longer time period, 20-30 days. This wetting and drying cycle was repeated six times until most of the specimens showed clear evidence of visible crack formations. The surrounding climate was also changed to be more and more harsh, i.e. dryer and warmer (T ranging from 20 to 40°C and RH ranging from 20 to 65 %), during the testing procedure. The last wetting/drying cycle was performed after the specimens had been conditioned to approximate equilibrium moisture content in the original surrounding climate (T = 20°C, RH = 65 %).

In Figure 9 the total visible crack lengths on the longitudinal sides of the specimens for the different species are shown. It has been shown that experimental data from crack formations on wood are not normally distributed (cf. Sandberg and Söderström (2006). For this reason a non-parametric test was used for evaluation. It is shown that there is a significant difference between specimens with different annual ring orientation. Specimens with vertical annual rings tend to develop shorter visible total crack length than specimens with horizontal annual rings.
Figure 9. Crack lengths for the specimens exposed to capillary wetting cycles. H = Horizontal annual rings, V = Vertical annual rings.
5 Mechanical manufacturing of hardwood products

5.1 Value yield

The development of wood products and the development of the mechanical production process aim at adding value to the sawn wood. According to Williston (1991), value-added products can be any products that somehow lead to an increased return to the business. This may be associated with drastic changes in production or with ways of increasing the proportion of wood in a quality class with a higher price without increasing the production cost. Value-addition may also be related to the refinement of the product for instance by cross-cutting the wood to blanks or planing the wood.

An important aspect of value-addition is the understanding of customer requirements. A failure to understand the customers' needs and demands has been a decisive reason why the introduction of new products onto the market has failed (cf. Bergman and Klevsjö, 1995; Ulrich and Eppinger, 2000). Patrick (1997) showed, for example, that more than 90% of all launchings of technical products onto the market are considered to have failed. Ljungberg and Edwards (2003) claim that this occurs even though the product itself exhibits technically good properties with regard to e.g. function and material. In these cases, the products have not been fully accepted by the customers who need to understand and accept both the technical and non-technical functions of the product.

Johannesson et al. (2004) state that the market should be considered as setting high requirements with regard to customer adjustment, quality and short product-life cycles. During product development, the time from idea to product launch becomes critical and demands a fast and reliable process. Ulrich and Eppinger (2000) point out that the work of developing a product is not related solely to a marketing problem, a design problem or a manufacturing problem. Product development is a cross-functional activity involving all these aspects.

One aspect to be considered in the development process is the relation between a developed and improved feature and the cost (Ulrich and Eppinger, 2000). In some cases development leads to a lower cost, but in other cases the development leads to higher costs of for instance production and it will then be difficult
to know whether the new development is something that the customers value and are willing to pay a higher price for. Knowing whether value-addition is achieved then becomes difficult

5.2 Sawing patterns

Ferrante et al. (2000) consider how the use of a specific material affects the production process, and they emphasize that it is necessary to select material and process options in relation to each other.

The quality and value of the sawn wood are to a large extent determined in the sawing process, and the sawing pattern provides the basis for a profitable and successful wood production. The sawing pattern affects the yield from the log, the grade of the sawn wood and the productivity of the sawmill. When developing and modifying the equipment and concepts of sawing operations, the sawing pattern should be one of the first things to consider in order to optimize yield (Denig, 1993).

In the case of hardwoods, sawing pattern should be selected in order to maximize the volume of clear wood, i.e. wood essentially free from the low valued red heartwood (e.g. Flann, 1978), and this is something that many Swedish hardwood sawmills do indeed practice (see Paper 1). The sawing patterns normally used in hardwood sawmills are the through-and-through sawing pattern, the square-sawing pattern or the sawing-around pattern, Figure 10, see also Paper 1.

According to Denig and Wengert (2005) the through-and-through-sawing pattern result in a high volume yield for small logs and produces a relatively high percentage of wood with vertical annual rings. The disadvantages are that middle
pieces from the logs mix the high-grade material in the outer parts of the logs together with the low-grade heart centre of the log.

The square-sawing pattern utilises the fact that the outer parts of the logs normally consist of higher grade material than the centre of the log. The centre pieces also become edged directly in the primary log-breakdown process. The disadvantage may be that, for large high quality hardwood logs, the centre piece may contain high quality material that is not utilised in the further breakdown (Denig and Wengert, 2005).

The sawing-around pattern starts by sawing boards from the bark towards the pith. The pattern utilises as much high-grade material as possible from the outer parts of the logs before the centre piece is used. The pattern requires that the logs are turned several times and results in many saw kerfs and this means volume losses. The remaining centre piece will normally be of a very low-grade (Denig and Wengert, 2005).

As described in section 4.3, vertical annual rings in wood are preferable in many cases. Vertical annual rings are traditionally produced according to the sawing pattern shown in Figure 11a-c, so called quarter sawing. This way of producing sawn wood is however inefficient because of the low volume yield and it involves high production costs (Paulsson, 1938; Desch and Dinwoodie, 1996). Figure 11d describes another common way of producing wood with vertical annual ring by sawing the log with a pith catcher and Figure 11e illustrates the production of wood for components with vertical annual rings used by e.g. the window industry.

![Figure 11. Sawing patterns that generate wood with vertical annual rings. a-c) quarter-sawing, d) 3-ex-log, e) Monolit-sawing, f) star-sawing.](image-url)
Star-sawing presented by Figure 11f is a way of producing wood with vertical annual rings. The star-sawing pattern is utilised by the PrimWood Method where the sawn wood is processed into knot-free and defect-free wood products with vertical annual rings, Figure 12. The products obtained with the method are:

- Sawn rectangles and triangles which will be further processed.
- Knot-free rectangles.
- Knot-free glued triangles with either a rectangular or a rhombic cross-section.

The method gives a volume yield in the production of knot-free boards and panels which is much higher than that reached by conventional sawing and post-sawing processes (Papers 4-7, Sandberg, 1998; Sandberg, 2005; Johansson and Sandberg, 2005).

If adopting the PrimWood Method there are certain requirements of the raw material. The top diameter of the logs must exceed 28 cm to receive products of acceptable widths. The length of the logs should further not exceed 4.5 m, because of the negative influence of the tapering on the volume yield. Large ovality and crook should be avoided in order to minimize the effects of reaction wood and negative influence on the volume yield. Knots in the logs will not be a large problem when utilising the method since they are cut-off.

So far, the PrimWood Method has, on an industrial scale, been limited to the processing of pine (Pinus sylvéstris L.). For an industrial production of hardwood the raw material conditions, considering availability, quality and species dependent properties, require development of the processing system. Paper 7 therefore presents a processing system for the PrimWood Method applied to hardwood. The system is based on a fixed vertical band saw with a carriage. The carriage is equipped with both attachment and alignment devices for the log and
its sawn parts. The carriage can be tilted at ± 30° from the horizontal plane to be able to saw the different rectangles and triangles. Besides the actual sawing unit, the installation includes the further processing of the dried wood into knot-free components with vertical annual rings. This version of the PrimWood Method is intended for annual production of 5–6 000 m³. The size of the system is set in relation to the existing raw material supply and the size of the existing mechanical hardwood industry. With the planned size of the production system it is assumed that it is possible to obtain a balanced and secured raw material flow.

Today, most hardwood sawmills in Sweden are using timber with top diameter of 18–20 cm (Johansson 2005). The dimensional requirement (at least 28 cm in top diameter) for the PrimWood Method makes the volumes of Swedish hardwood timber strongly limited. The total stand of deciduous trees in Götaland, where the largest volumes of deciduous trees with breast height diameter exceeding 30 cm are found, is approximately 64 million m³ (Swedish National Forest Inventory, 2008). If the growth of this volume was made available for saw timber production, this would result in considerable volumes, approximately 2 million m³ (if the growth is assumed to follow an average stand growth in Sweden for all species of approximately 3 %). It should be noted that some volumes of deciduous trees are found in areas where harvesting is restricted or where the trees are for other reasons not available for saw timber production.

Since the Swedish deciduous trees were earlier considered unprofitable, they are often found in unmanaged stands and the trees may therefore often not be straight. Crookedness will be a problem in the sawing process and the effect of crookedness in the PrimWood Method should be studied further. Williston (1991) maintains that crooked timber may be sawn in shorter lengths to reduce the effect of crookedness on the volume yield. This method is practiced for instance when sawing birch in Canada (Clément et al., 2005). It may therefore be necessary to adjust the PrimWood Method in order to be able to handle short logs.

Using the PrimWood Method on hardwood will result in several benefits, including for instance knottiness as described in Paper 4 and 7. Star-sawing will, however yield splay-knots, and cross-cutting followed by finger-jointing is recommended. Star-sawing means that red heartwood is always oriented towards one edge side of the board, which is beneficial since it then is possible to utilise the red heartwood in order to create special patterns in panels as seen in Figure 13. The knot-free and defect-free products generated by the PrimWood Method have a market segment in the market for traditional sawn hardwood. Hardwood is today used mainly for furniture, carpentry and floors (Paper 1). For these products mainly knot-free wood, even in colour and texture are demanded.
Figure 13. Table surface of ash (Fraxinus excelsior L.) with brown-heartwood.
6 Conclusions

In this thesis, problems related to the development of product and manufacturing systems for the improved utilisation of Swedish hardwood for sawing purposes are identified and discussed. The manufacturing process should aim at adding as much value as possible to the raw material, because of the limited available volumes for sawing. This requires a flexible production aimed at satisfying each customer’s needs and requirements. The customers’ requirements regarding the products are related to aesthetical and tactile requirements together with moisture related issues. The customers indicate that both product requirements and service requirements are important. Utilising the PrimWood Method for hardwood sawing may be one way of increasing the yield from each log regarding both volume and value. This is important from both a profitability perspective as well as an eco-effectiveness perspective. The PrimWood Method is shown to result in a higher volume yield and longer knot-free pieces than traditional ways of producing sawn wood. The method also results in an attractive texture, and offers a possibility to make use of the red-heartwood. The method however requires large, straight logs, and the sawn wood will contain a large amount of splay knots. It is recommended that the sawn wood is refined through cross-cutting and finger-jointing to receive a completely defect-free wood.

An important factor considering a greater utilisation of hardwood is the possibility of using hardwood in outdoor applications. The focus of this work has been on capillary absorption, since this is important for the durability and service-life of the material. Through the thesis a model is developed to describe the capillary phenomenon in different wood species. A structural resistance together with the number of conducting cells determines the capillary characteristics of any particular wood species. It is also shown that there is a relationship between the annual ring orientation and the durability with respect to crack formation. Capillary wetting and drying will speed up the propagation of cracks, and this means that the annual ring orientation is extremely important. Using sawn wood with vertical annual rings may be seen as a first step towards making it possible to use more hardwoods outdoors.
Further research is required within several subjects related to hardwood. The material produced by the PrimWood Method must be studied in order to find profitable uses in both indoor and outdoor markets.

The capillary characteristics must be altered to improve the material’s resistance to moisture uptake. The capillary characteristics must be further studied at a micro-level.

A sawmill has recently started to utilise the PrimWood Method for sawing of pine. In cooperation with this sawmill further studies will be carried out in order to utilise the method for hardwoods. This will consider both production and marketing possibilities. The PrimWood Method this must be studied with regard to several wood species and further processing through drying, cross-cutting, gluing etc. must be developed for different wood species. The drying process is particularly critical, and it must be further developed since this is a time-consuming and expensive production step in hardwood processing.

It is also necessary to work on the development of the material usage, considering value-adding of the low-valued wood, containing knots, red heartwood etc. and wood species with a small market today, particularly alder, aspen and beech. This means improving the production process with better control of the products, for instance through automatic sorting of the wood and through product and material development.

To further study the possibility of utilising hardwood in outdoor applications, a study has been prepared in which boards from 9 common Swedish wood species are exposed outdoors. 20 specimens of each wood species are included in the test and each wood species is divided into two groups, one with horizontal annual rings and one with vertical annual rings. Figure 14 shows the experimental setup. The wood species included in the study are alder (Alnus glutinosa Gaertner), aspen (Populus tremula L.), beech (Fagus sylvatica L.), birch (Betula pubescens Ehrh.), oak (Quercus robur L.), pine (Pinus sylvestris L.), white poplar (Populus alba L.) and spruce (Picea abies Karst.). The test was started in November 2007 and will be evaluated first during the spring of 2009. The main response variables that will be evaluated are crack formation and microbial discoloration.
Another important issue is the function of the existing refinement chain of hardwood in Sweden. To improve this value-chain, a project was initiated in 2007 called ‘Business system of competitive birch component production for the furniture industry’. This project involves 10 companies, 3 Universities and 1 Institute. The aim is to focus on some critical aspects in the value-chain and to collaborate to find ways of handling these issues. The main aspects so far consider a mutual quality language, logistics solutions in the forestry and technological improvements involving automation of the process of sorting the sawn wood.
8 References


Appendix 1. Other relevant publications not included in the thesis


