Colour Response in Drying of Nordic Hardwoods
COLOUR RESPONSE IN DRYING OF NORDIC HARDWOODS

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Abstract


Colour and appearance of hardwood are of great importance for the interior and furniture industry. The widespread use of transparent surface treatment and a fashion that prescribe light colour on many species, means that deviation from the ideal have considerable impact on the industrial operations. Kiln drying is generally regarded as the process that has the greatest impact on the colour of Nordic hardwood species. The lack of satisfactory explanation models for many types of discoloration, however, complicates the control of the drying process.

This thesis is an attempt to increase the knowledge of which factors that control the appearance of some commonly found discolorations associated with drying of beech, birch and oak. The main focus is on convection drying but also the influence of timber storage, pre-steaming and press drying has been investigated for individual species. The studies have been conducted as comparative studies based on design of experiments in which the colour was determined using a colorimeter.

Results show that reddish and dark discoloration of beech and birch during convective drying is mainly dependent on the temperature and time of exposure when the local moisture content exceeds the fibre saturation point. The conversion of naturally occurring substances in birch into coloured compounds is not due to active precursors created at high moisture content levels during the subsequent drying at low moisture content levels. Interior grey stain in beech is caused by slow initial drying at low temperatures. Log storage in cold winter and spring climate does not cause discoloration in beech. Birch becomes lighter when press-dried at high temperatures, resulting in a colour comparable to that of traditionally kiln dried wood. Steaming of oak before kiln drying reduce the presence of brown discoloration, a general darkening of the wood occurs at temperatures above 50°C.

Key words: beech, Betula pendula, birch, CIELAB, discolouration, drying, Fagus sylvatica, log storage, oak, press drying, wood colour, Quercus robur.
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Key words: beech, *Betula pendula*, birch, CIELAB, discoloration, drying, *Fagus sylvatica*, log storage, oak, press drying, wood colour, *Quercus robur*.

Denna avhandling är ett försök i att öka kunskapen om faktorer som styr uppkomsten av några vanliga typer av missfärgningar hos björk, bok och ek. Främst behandlas konventionell luftväxlingstorkning men även inverkan av timmerlagring, ångbasning och presstorkning har undersökt för enskilda träslag. Studierna har bedrivits som jämförande studier baserade på statistisk försöksplanering där färgen bestäms med hjälp av färgmätare.

Resultaten visar att ljushetsförlust och rödfärgning hos björk och bok vid konventionell torkning främst styrs av den temperatur och tid som träet exponeras för i fuktigt tillstånd. Färg förändringen orsakas av naturligt förekommande ämnen i veden och kan uppkomma inom några få timmar. Den inre grå missfärgning som ibland förekommer på obasad bok orsakas främst av långsam torkning vid låg temperatur. Stocklagring under den kalla årstiden har ingen märkbar inverkan på färgen hos bok. Björk blir ljusare då temperaturen ökar vid presstorkning, färgen kan jämföras med konventionellt kammartorkat virke. Ångbasning före kammartorkning minska förekomsten av missfärgande strimmor och fläckar hos ek och gör dessutom veden något ljusare. Mörkfärgningen hos ek ökar snabbt när temperaturen överstiger 50°C.

Sammanfattning


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ACKNOWLEDGMENT

This thesis is the result of a journey that started at the end of the 90s when I joined the newly founded Swedish Hardwood Institute. At this time, drying was a process that many hardwood industries struggled with and several industry members of the institute expressed a need to improve this process. In an effort to help the industry Scandinavia's grand old man in hardwood drying, Thomas Thomassen, was engaged by the institute, and I got the task of assisting him. Together we visited sawmills and timber drying industries in different parts of Scandinavia. During our travels Thomas became my mentor as he invited me into the intriguing world of wood drying. Early on in our work it became clear that part of the problems of hardwood drying was a lack of satisfying answers, in particular with discoloration. Here research was needed. This project is thus a result of a need from the industry in which the Hardwood Institute and Linköpings University collaborated. Due to changes in Swedish research policy the project moved to Växjö University in 2003 where I became part of a larger research group specialised in wood science. When the Hardwood Institute was re-organised in 2004 I joined IKEA's industry group Swedwood. Here, I got the opportunity to implement some of my research findings on an industrial scale. This work gave me a profound insight into how challenging industrialisation can be. It also gave me the special satisfaction that one gets when laboratory findings come to practical use improving the production of an entire factory.

Over the years I have had the fortune to co-operate with many stimulating people both in the research community as well as in the industry. I therefore would like to express my gratitude to everyone who has helped me on this journey, you know who you are. In addition I would like to mention a few persons whose efforts have been essential for this work. First of all, I would like to thank my two supervisors Thomas Thörnqvist and Dick Sandberg at Linnaeus University (LnU) for all the help you have given me, without your support, this journey would never have reached its destination. Secondly, I would like to thank my late mentor Thomas Thomassen, without whom this journey never would have begun. At the same time I would like to express my...
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gratitude towards my former manager at the Hardwood Institute Ingemar Överberg and Per Larsson at Linköping University (LiU) who lay the foundations for this journey.

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Mölndal, on a summer day in September 2013.

Stefan Stenudd
LIST OF PAPERS

The following papers are appended and referred to by their numbers in the text. Paper (I) has been corrected for printing errors. Papers (VI) is submitted for journal publication.


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1 INTRODUCTION

1.1 Background

Wood is an organic material that if derived from reafforested areas is a sustainable and renewable material for construction and energy use. It is a natural composite material of cellulose fibres embedded in a lignin matrix (Hon & Shiraishi 1991). Transforming living trees into wooden products involves several process stages where drying is an essential step in the value-added chain, turning sensitive organic material into a stable construction material ready for further processing. Like other organic materials wood is biodegradable and would naturally deteriorate and turn into soil with the help of i.e. micro-organisms if the process were not delayed (Zabel & Morrel 1992). One way to inhibit the decay is to remove water from the wood (Zabel & Morrel 1992). Green wood from the forest contains large quantities of water, making it unsuitable for many applications since the material properties change and the shape transforms as the wood dries (Denig et al. 2000). Drying comes naturally as the moisture content (MC)\(^1\) in the wood strives to achieve equilibrium with the surrounding air below the fibre saturation point (Siau 1995).

The demand for hardwood by the pulp industry in Sweden has increased, as has the interest in increasing biodiversity in the forest, and this has resulted in a growing interest in sustainable management of deciduous forests (Woxblom & Nylinder 2010). For the forest owner the sale of saw logs is of particular interest since the revenue is higher, but less than 5% of the volume is used by the sawmills (Johansson 2003). Wood from deciduous trees have long been appreciated for its strength, hardness and visual appearance. Several of the common hardwood species found in Northern Europe like beech, birch and oak are much appreciated for their light colour and they are frequently used in carpentry, flooring and furniture applications (Dahlgren et al. 1996, Möttönen 2005). The common usage of transparent surface coatings put focus

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\(^1\) In this thesis the moisture content (MC) of wood is defined as the mass of moisture in the wood expressed as the percentage of the oven dry (wood) mass (Kollmann & Côté 1984, Siau 1995).
on the colour of these hardwoods. Since colour changes outside the living tree are strongly related to the drying process, the industry has adapted its drying processes to meet the new market demands (Stenudd 2002, Möttönen 2005). The downside has been that processing times may be prolonged by 20-30% and that production costs are consequently increased, and these costs are hard to make up for the industry on a highly competitive world market where light coloured European hardwoods are facing competition from other wood species as well as substitute materials such as foiled or laminated board. To strengthen hardwood based production in the Nordic countries is it therefore important to improve the drying technology and hereby improve conditions for biodiversity in the forest.

1.2 Challenges to the industry

Drying hardwood timber offers many challenges to the industrial user besides the main objective of controlling the moisture content of the wood. Several problems like distortion, checking and discoloration may arise during the process, each capable of causing quality losses and subsequent financial losses (Simpson 1991). For beech and birch, discoloration and distortion are major drying-related challenges while oak is also facing difficulties with checking (Stenudd 2002). The causes of deformation and checking are fairly well known, but this is not true of all types of discoloration. Colour changes are in some cases also species-specific (Hon & Shiraishi 1991), making generalisation difficult. The industry is not without advice on ways to limit undesired colour changes (Bois 1970, McMillen 1975, Simpson 1991) but most techniques are expensive to implement.

Hardwood is frequently used in applications with a transparent surface treatment, so that discoloration is a major defect causing downgrading and substantial losses in timber value (Burtin et al. 1998), and the market for low-grade timber is limited with low prices (Elowsson 1989, Heräjärvi 2002). Industrial drying is typically a batch operation where up to 300 m$^3$ of timber is processed in each batch. Since the value of the timber may be as high as EUR 50,000 per batch and there is a potential risk of total downgrading, may process development using an trial-and-error approach be less attractive. As a consequence, drying schedules developed during the 1950’s are still being used for the drying of hardwoods, and the hardwood industry has not benefitted from later developments in e.g. computer-aided control systems in the same way as the softwood industry.

The increasing use of automatic quality inspection systems for grading and sorting in the wood industry has increased the interest in quantifiable and comparable colour measurements. As optical systems take over from subjective viewing by the human eye in quality inspection, there is an increasing need to understand how to control the colouring processes and to
reduce undesirable colour variation in these processes. From an industrial point of view it is desirable to be able to select wood colour beforehand and to produce it on demand. Before being able to do so, a deeper understanding is needed of how the different controllable process parameters in a kiln influence the colour of dry wood.

1.3 Aim

The aim of the work described in this thesis has been to increase the understanding of how log storage and process parameters during timber drying influence the colour of beech, birch and oak. The focus has been on identifying critical parameters and on understanding how these parameters influence the colour of the wood during convection-type batch drying.

1.4 Limitations

This study focuses mainly on colour changes in relation to traditional convection kiln drying at low to moderate temperatures as illustrated in Figure 1.

![Figure 1: Investigated temperature intervals for the appended papers.](image)

The influence of log storage have been studied only on beech, as beech is recognised by the Swedish hardwood industry to be the most sensitive of the three investigated wood species regarding storage conditions. The influence of air velocity has not been included in this study. Many hardwood kilns have limited resources concerning air velocity. Speeds between 0.5 and 3 m/s are commonly found. Long drying cycle times in combination with high and increasing electricity costs to power the fans excluded the air velocity from this study.
Attempts have been made to minimise the influence of external factors such as tree provenance, individual trees, location in the stem and laboratory equipment by careful sampling, handling and experimental design.

1.5 Methodological reflections

Conducting research on a diverse organic material such as wood is always challenging. In particular the study of small colour variations as a result of minor differences in process settings makes sample selection a critical matter. Due to genetic variation in the forest, the generalisation of the results to wood from neighbouring regions in Sweden, Finland, Norway, Denmark, Russia and the Baltic states may only be suggested. However results from other studies concerning colour changes in relation to drying indicate that the results may be generally valid (Charrier et al. 1992, Luostarinen et al. 2002, Möttönen 2005).

The methods of sampling, handling and storing the samples developed over time to meet the needs of the experimental design and access to drying facilities. In order to avoid uncontrolled drying during transport, samples were always stacked tightly, the perimeters of the stack being protected by wet wood from the same batch and everything being wrapped in plastic foil. Protecting fresh samples by freezing proved to be a good solution when the number of drying settings exceeded the number of laboratory kilns. Sample preparations for example resizing was in most cases conducted on frozen material. Since colour measurements were made on new surfaces created after the drying, variation due to sample handling are expected to be small.

Results from test dryings in laboratory kilns and climate chambers may be generalised for wood of similar cross sections with the exception of these in paper II, where axial length must also be considered. Climate settings were selected in order to explore the effect of drying on the colour of the dry wood in multiple dimensions simultaneously. Boundaries for each factor, temperature, relative humidity and MC, were chosen to be both explorative and representative for the industry, at the same time as the underlying objective has been to generate knowledge that may be industrially utilised. Results of drying in small scale laboratory kilns may not always be applicable in large industrial applications as a result of variation induced by limitations in the industrial equipment. Industrial drying in the Nordic countries typically uses time-based schedules where the climate settings are based on the initial MC and estimated development of the MC at given times during the process. Applying results from this study to the industry therefore requires further trials to convert sample board MC readings into timetables at the same time as technical limitations of the kiln are evaluated.

How post-drying treatment, machining of the surfaces, before colour measurements are made is also important for the reliability of this study.
Consequently, all samples were handled in the same way, although the methodology differed between studies depending on sample size and the purpose of each investigation. Colour recordings were made using a tristimulus colorimeter (Minolta CR 310 and 410) with a standardized light source and measuring distance, wide-area-illumination, 0° viewing angle over a circular area 50 mm in diameter and the meter was always calibrated before the start of each measurement session.

Colour readings using three different colour meters, all of the same type and brand, on the same sample showed good reproducibility. The recordings were statistically analysed and in many cases based on multiple readings from the same sample, avoiding any local characteristics e.g. knots if they existed. Statistically significant colour differences were not always distinguishable, by the naked eye, as the structure also influences the human perception of colour.

In this type of study, where the effects of multiple factors and their interactions are explored, design of experiments DoE (Box et al. 1978) have been shown to be a successful way of investigating this type of process-related question in a time- and cost-efficient way (Bergman 1992). Full factorial $2^k$ and fractional factorial experiments $2^{k-p}$ are well suited techniques for screening purposes when identifying which factors are influential and which are not for a specific process (Box et al. 1978). Identification of active effects may be done using analysis of variance (ANOVA) or graphically using normal probability plots (Daniel 1976). This plot is based on the idea that contrasts of non-influential factors cluster around zero, approximately belonging to the same normal distribution (Daniel 1976). A line that approximately represents this distribution may be fitted and contrasts that deviate from this line may be judged as active, representing an influential factor or interaction of factors (Daniel 1976). This technique requires relatively few experimental runs per factor while still indicating major trends in a wide region (Box et al. 1978).

### 1.6 Structure of this thesis

This thesis consists of this introductory part and six appended papers. In the introductory part, an introduction to the topic along with aim, limitation and some methodology is presented in Chapter 1. A summary of the appended papers is given in Chapter 2. Following this, Chapter 3 gives an introduction and overview to the subjects of colour in hardwoods, drying technology, economics of drying and colour measurement. In Chapter 3, the appearance of several non-drying related colour changing in beech, birch and oak are presented. Following this, Chapter 4 presents the main results of the present work related to colour changes in connection with drying. Chapter 5 concludes the over-all findings of the presented work and also presents some industrial applications that derives from these findings. Finally, Chapter 6 lists references cited in the introductory part.
2 SUMMARY OF PAPERS

2.1 Paper I

*Colour changes in birch and beech during kiln drying.*

This study investigates the colour changes in Silver Birch (*Betula pendula* Roth.) and Beech (*Fagus sylvatica* L.) during conventional kiln-drying under industrial conditions. The effects of drying temperature, relative humidity, initial moisture content and board thickness on wood colour were investigated.

Beech and birch samples 240×80×16/10 mm were dried in a climate chamber according to a full $2^4$ factorial designed plan. Results were analysed using normal probability plots and graphic presentations.

The results showed that the drying temperature is the most important factor for the colour response in the investigated intervals for both birch and beech. The second most important factor for both species was the thickness of the wood and the relative humidity was the third most important factor. Both species reacted in a similar way to increasing temperature, thicker dimensions and a higher relative humidity. The wood colour became darker, more saturated and redder than that of the reference material. The colour response effects were larger in birch than in beech.

2.2 Paper II

*Colour response of Silver birch to press drying.*

This study explored the possible use of a rapid press drying technique for silver birch. Press drying is recognized in the flooring industry to cause discoloration in some wood species. Since the colour of birch is of great importance to the industry, the colour response in the core of 36 mm birch samples to the plate temperature, plate pressure, air pressure and to the initial moisture content was investigated.

Birch samples 300/240×80×36 mm were dried in an electrically heated laboratory press according to a full $2^3$ factorial designed plan. Some samples
were dried in a vacuum chamber placed in between the heated press plats. Results were analysed using normal probability plots.

The plate temperature was found to be the most influential process variable controlling the wood colour. A higher temperature results in a brighter more yellowish colour and a shorter drying time. Other process and material variables also influence the final colour but their contributions are smaller. Press drying of green wood at 170°C under normal atmospheric air pressure gave a wood colour resembling that of conventionally kiln-dried birch wood, but which was slightly darker and more reddish. The study indicates that press drying of Silver birch is possible from a colour perspective if the process parameters are carefully selected.

2.3 Paper III.

**Color response in Silver birch during kiln drying.**

This study investigated the colour response of birch to initial moisture content, climate and time during convection drying.

Small birch samples 300/240×80×36 mm were dried in a climate chamber according to a full $2^4$ factorial plan and larger samples 700×100×20 mm in convection type laboratory kilns, with a loading capacity of approximately 0.2 m$^3$. Results were analysed based one-way ANOVA and regression analysis using Minitab 10 software.

Results show that during the capillary drying phase time is more important than temperature. Rapid initial drying even at elevated temperatures increases the lightness and reduces the colour saturation. The major colour changes occur later, during the diffusive drying phase from 30-20 % moisture content. Here the combination of temperature, time and initial moisture content is decisive for the final wood colour. Swift drying in both stages at even moderately elevated temperatures results in a highly desirable brighter colour.

2.4 Paper IV

**Influence of pre-heating on brown discoloration when drying oak heartwood.**

This study investigated the influence of drying temperature and the pre-heating of oak heartwood prior to conventional kiln drying and its influence on the colour of the dry wood as well as the occurrence of brown discoloration.

Oak samples 750×81×30 mm were dried in convection type laboratory kilns, with a loading capacity of approximately 0.2 m$^3$. Before the drying process started half of the samples were pre-treated using saturated steam for 2 hours. Smaller matched samples 70×70×10 mm were dried in a climate
chamber. The general colour was measured using a colorimeter and the occurrence of spots and stripes was manually evaluated. Results were analysed graphically using Minitab 14 software.

The pre-heating significantly reduced the level of local brown discolouring streaks and spots and also slightly increased the general lightness. Drying temperature has a major impact on the development of local brown discoloration, and a higher temperature cause more discoloration. The thermal effect on general lightness is less distinct and a critical point seems to exist in the 40-50°C range, above which the lightness is distinctly reduced.

2.5 Paper V.

*The influences of log storage and kiln drying climate on the colour of non-steamed beech (Fagus sylvatica L.) wood.*

In this study, the influences of log storage time and kiln drying climate on the colour of non-steamed sawn beech have been investigated and quantified.

From the logs in the storage test were 420×87×27 mm samples cut and dried in an industrial kiln. Later, another set of 750×87×27 mm samples were dried in convection type laboratory kilns, with a loading capacity of approximately 0.2 m³. Results were analysed based one-way ANOVA and regression analysis using Minitab 14 software.

Log storage for 13 weeks at a low temperature had no visible effect. The reddish discoloration was mainly temperature-related while the greyish discoloration was mainly dependent on the equilibrium moisture content (EMC) during the initial drying phase. Within the investigated climate interval, the EMC was twice as important for the final colour as the temperature. Regression models developed show that, as long as the EMC is kept below 15%, a temperature of up to 37°C can be allowed without any visually detectable discoloration.

2.6 Paper VI.

*Influence of moisture content, temperature and air humidity during kiln drying on the lightness of Silver birch (Betula pendula Roth.).*

This study explored how temperature, equilibrium moisture content (EMC) and MC influence silver birch lightness using small matched samples.

Matched birch samples 70×70×10 mm were dried in climate chambers according to two multi-level experimental plans and one fractional factorial 2^5-1 experimental plan. Results were analysed based on normal probability plots and regression analysis using Minitab 14 software.

The darkening was mainly controlled by temperature and drying time as long as the local moisture content (MC) exceeds the fibre saturation point.
(FSP). High temperature and slow drying at high EMC levels lower the lightness. Darkening may also occur below the FSP but at a significantly lower rate. Naturally occurring wood constituents are transformed to coloured substances within hours and this does not appear to be caused by precursors created during one MC interval and developing during subsequent MC intervals if special conditions apply. Regression models revealed a quadratic effect of EMC on birch lightness, possible because it influences both drying time and wood temperature at high MC levels. This study showed that darkening occurred in samples with a local MC exceeding the FSP when they were exposed to drying temperatures higher than 40°C in combination with EMC levels above 15%.
3 COLOUR IN HARDWOODS

Wood comes in a variety of colours. Species with green, red, yellow and blue hues can be found and the lightness may vary from almost white to ebony black. The basic colours of hardwood species in northern Europe range from almost white to yellow, red and brown shades.

As wood is a biological material, the environment influences it when it is alive in the forest, after felling, during processing and in its further product life as e.g. furniture. Wood is decomposed by micro-organisms and reacts chemically with different substances such as metal ions, acid and alkali. Wood is also affected by heat and light, the latter resulting in a photo-yellowing of the surface (Hon & Shiraishi 1991).

Colour changes in wood are sometimes appreciated. Pre-steaming of beech and walnut is a traditional way of intentionally modifying the colour without using chemical stains or dye. Another method is post-drying heat treatment, a field which has attracted much research in recent years (Viitaniemi & Jämsä 1996, Johansson 2008). Other examples of intentionally stained woods include blue stain and white-rot infections sometimes utilized in artistic and handicraft items (Myhra et al. 1997).

Although colour changes during kiln drying have no practical influence on the strength or durability of the wood, the aesthetic appearance of the wood surface plays an important role for the woodworking industry, strongly influencing the economic value. Different species are appreciated for their different colours and textures. While natural variation in wood colour is sometimes appreciated, artificially introduced variations are usually not. The industry desires, in many cases, a uniform colour in accordance with present designer trends.

3.1 Colouring components in wood

Of the basic components in wood, cellulose, hemicelluloses and lignin, it is mainly lignin which absorbs certain wavelengths in the visible region and thus appears as coloured (Hon & Shiraishi 1991). The origin of the natural
yellow-white colour of many wood species is probably lignin (Hon & Shiraishi 1991). Light absorption in lignin peaks at wavelengths around 300 nm with a wide tail extending to 400-500 nm (Gould 1982). Absorption of wavelengths longer than 300 nm is believed to be the result of an accumulated photochemical modification of the lignin polymer (Gould 1982). Since lignin absorbs light in the blue region of the visible spectrum, it is perceived to have a yellowish colour. Native lignin mildly extracted mechanically and chemically is pale yellow in colour (Hon & Shiraishi 1991). Cellulose and hemicelluloses do not absorb but merely scatter light and therefore have only a greyish appearance (Hon & Shiraishi 1991).

In addition to cellulose, hemicellulose and lignin, wood consists of other compounds such as pectins, starch, inorganic material and extractives in lesser and varying quantities (Hon & Shiraishi 1991). Normally wood contains small quantities of polysaccharides such as pectins, typically less than 1% and even smaller quantities of starch (Fengel & Wegener 1984). Ash-forming inorganic compounds such as silicates, carbonates and metal ions usually make up less than 0.5% of wood (Fengel & Wegener 1984, Hon & Shiraishi 1991). Extractives i.e. low molecular weight components soluble in water or organic solvents, typically make up a few percentage of the wood. The concentration is usually higher in heartwood than in sapwood and in branch bases and roots (Fengel & Wegener 1984). While the cellulose content is common there are only small variations in the hemicellulose and lignin contents between different hardwoods, the extractives are recognised to differ between genus, families and even species (Hillis 1971, Hon & Shiraishi 1991). While extractives contribute to properties such as colour, odour and durability, they are not generally considered to contribute to the mechanical properties of wood (Fengel & Wegener 1984). Extractives can be divided into polyphenols, terpenoids and other compounds such as sugars, fatty acids and alkaloids (Hon & Shiraishi 1991) and they are concentrated in resin canals and parenchyma cells in the wood (Fengel & Wegener 1984). The phenols include several types of compound such as lignans, flavonoids, tannins, stilbenes and quinines, some which form coloured compounds in wood (Hon & Shiraishi 1991).

The coloured compounds found in brown, black, purple, red and orange heartwood are associated with polymeric reactions involving phenolic substances during the heartwood formation (Hillis 1968, Charrier et al. 1995, Burtin et al. 1998). Introducing metal ions (Bauch 1984) or modifying the pH value are other means of catalyzing the formation of coloured substances from extractives (Starck et al. 1984, Bauch et al. 1985, Yazaki et al. 1985). There is a lack of a detailed understanding of the chemical processes behind colour changes in wood during drying at low to moderate temperatures (Luostarinen 2006), but oxidative and hydrolytic reactions involving phenolic extractives are generally considered to be the cause (McMillen 1975, Forsyth & Amburgey 1991, Charrier et al. 1995, Burtin et al. 2000,
Koch et al. 2003). It is suggested that the formation of non-soluble phenolic compounds in the wood is the result of the plant’s defence against dehydration (Miller et al. 1990).

The formation of a thin dark layer on cell walls in discoloured birch, limited to ray and axial parenchyma cells, where the discoloured cells tested positive for phenols have been reported by Luostarinen (2006). Microscopic studies have revealed crystalline and amorphous substances in the parenchyma cells of discoloured wood of several species (Bois 1970, McMillen 1975, Forsyth & Amburgey 1991, Koch et al. 2003, Straze et al. 2003). Scanning electron microscopy studies on grey stained beech revealed similar structures in the parenchyma cells of discoloured wood in paper V, Figure 2. Microscopic studies of sapwood from red oak (*Quercus falcate*), ash (*Fraxinus spp.*), and hard maple (*Acer saccharum* L.) revealed brown globules in the parenchyma cells of the discoloured wood which were not present in normal coloured wood, and which were presumably the result of an enzyme-mediated oxidation of wood constituents (Forsyth & Amburgey 1991, Smith & Herdman 1996). The influence of living parenchyma cells on non-microbial enzymatic discoloration in logs and wet timber during storage has been shown by studies were chemical inactivation of parenchyma cells has protected the sapwood of several hardwoods from discolouration (Bailey 1911, Amburgey et al. 1996, Schmidt & Amburgey 1997). However, birch wood without living parenchyma cells darkens almost as fresh wood during drying (Loustarinen et al. 2002, Loustarinen & Möttönen 2004b).

Living parenchyma cells do not appear to be susceptible to colour changes related to kiln brown stain (Kreber et al. 1994) or brown discoloration of oak heartwood, Paper IV. Kollmann et al. (1951) have also

![Figure 2 SEM micrograph of discolouring globules in ray parenchyma cells from grey-discoloured beech wood (*Fagus sylvatica* L.), paper V.](image)

13
shown that re-wetted hardwood veneers were discoloured if the temperature was raised under humid conditions.

Sap extracted from Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* Karst.) darkens and turns reddish over time when exposed to elevated temperatures (Sehlstedt-Persson 2003). Nutritive components e.g. simple sugars and amino acids may accumulate some 0.5-1.5 mm from the board surface during thermal treatment and drying (Terziev et al. 1993, Terziev 1995,) and may form coloured compounds (Millett 1952, Sehlstedt-Persson 1995, McDonald et al. 2000). The concentration of such components beneath the surface is known to cause kiln brown stain (KBS) in several softwood species (Miller et al. 1983, Kreber & Byrne 1996, Kreber & Haslett 1997, Avramidis et al. 1993). The moisture flux in Silver birch (*Betula pendula* Roth.) is reported to be more dependent on axial migration rather than cross sectional migration in contrast to Scots pine (*Pinus sylvestis* L.) (Möttönen & Kärki 2010), and this might offer an explanation of why KBS is not found in birch wood.

At high temperatures, other components than the extractives, e.g. hemicelluloses and lignin, may play a role in the formation of coloured substances in the wood (McDonald et al. 2000, Navi & Sandberg 2012). Pre-steaming, press drying and other high temperature drying as well as heat treatment of the dry wood are examples of such processes.

A macroscopic colour change may also be introduced by the propagation of micro-organisms, coloured fungus e.g. sapstains, penetrating deep into the wooden structure resulting in what appears to be a discoloration of the wood (McMillen 1975, Simpson 1991).

### 3.2 Tree provenance

It is commonly recognised in the timber trade that wood of the same species originating from different areas sometimes differs in appearance, possibly because of genetic variations (Mosedale et al. 1996) or differences in growing conditions (Wilkins & Stamp 1990). Investigations on Black walnut (*Juglans nigra*) in the US, comparing dry wood grown in the states of Indiana and Missouri, showed a statistically significant, but hardly recognisable, difference in lightness. It was also possible to relate the differences to soil composition (Nelson et al. 1969, Hiller et al. 1972).

Similar results have been reported for silver birch (*Betula pendula*) by Luostarinen et al. (2002) where fresh and kiln-dried wood from medium fertile soil were found to be lighter and less saturated than to wood originating from low fertile soil. The difference was statistically significant but not distinguishable by the naked eye (Luostarinen et al. 2002). Small differences between regions were noted in Mid-Sweden for birch (Karlmats & Tegelmark 2004). The difference between birch species, *Betula pendula*
and *B. pubescens* from the same stands was greater than the provenance (Karlmats & Tegelmark 2004). Different species may offer one explanation of why persons in the timber trade recognise that birch quality has regional differences (Esping 1996) as birch is marketed as a single species in the Nordic countries. McMillen (1975) did not identify regional differences concerning sticker marks in hard maple in the US.

### 3.3 Tree age

The age of a tree is important for the colour. Studies on European oak (*Quercus robur, Q. petreas*) have shown that tree age as well as wood age, i.e. distance from the pith, influence the colour. Aged oak heartwood tends to be darker and more reddish (Klumpers & Janin 1992). Similar findings have been reported on birch (*Betula pendula*) by Sundqvist (2002b) who identified board side, pith or bark side, as a factor influencing lightness. Lustarinen et al. 2002 also reported that redness in kiln-dried birch was influenced by the radial location in the stem, more reddish wood being found closer to the pith. Axial location in the stem is reported to influence the colour of birch (*Betula pendula, B. pubescens*), the first metre from the butt end tending to be darker than wood higher up in the stem (Tegelmark & Karlmats 2004). Another investigation by Lustarinen et al. (2002) recognised only small differences in yellowness between butt and top end of birch wood after drying.

### 3.4 Heartwood formation

#### 3.4.1 True heartwood

Heartwood may be defined as the inner layers of a growing tree stem which have ceased to contain living cells and where reserve materials like starch have been removed or converted into heartwood substance (Hillis 1971), Figure 3. Heartwood typically contains high levels of extractives deposited within cell walls or cell lumina (Shigo & Hillis 1973, Bauch 1980). The extractives which may be present in large amounts are usually toxic and have an antimicrobial effect (Bauch 1980). Tyloses a common morphological protective action by living tissue under attack limiting permeability is also commonly found in the heartwood of many hardwoods (Shigo & Hillis 1973, Bauch 1980). Physical restrictions, limited access to nutrition and antimicrobial compounds in the wood result in increased resistance against decay to heartwood than to sapwood, but in the living tree the sapwood is commonly more resistance to fungal decay than the heartwood, thanks to its active defence (Shigo & Hillis 1973, Pearce 1996). However some active parenchyma cells have also been reported in heartwood and these may contribute to its active defence (Pearce 1996). In addition, enzyme activity
persists in the walls of heartwood including phenol-oxidizing enzymes and peroxides (Shigo & Hillis 1973, Ebermann & Stich 1982) which might catalyse the transformation of heartwood constituents as a response to microbial attack. Heartwood may be discoloured by microbial attack even though this may be difficult to see (Shigo & Hillis 1973). Transformation of sapwood into heartwood typically takes 2-3 years (Hon & Shiraishi 1991).

![Crosscut section of oak (Quercus robur L.) stem illustrating; (1) bark, (2) sapwood and (3) heartwood.](image)

**Figure 3** Crosscut section of oak (*Quercus robur* L.) stem illustrating; (1) bark, (2) sapwood and (3) heartwood.

### 3.4.2 False heartwood

False heartwood is distinguished from heartwood in the way in which the heartwood substances are stored on the outside or inside of the parenchyma rather than inside the cell walls (Shigo & Hillis 1973). Red-heart, a commonly occurring discoloration in many hardwoods, e.g. ash (*Fraxinus*), beech (*Fagus*), birch (*Betula*) and maple (*Acer*) is an example of false heartwood development in the living tree (Bauch 1984). An example of discoloured red-heart in birch can be seen in Figure 4. The discoloured area does not always follow the annual rings, nor is it limited to the centre of the stem but may have a cloud like shape (Shigo & Hillis 1973, Bauch 1984). The presence of red-heart in the stem increases with age, but it does not always develop (Shigo & Hillis 1973). Studies in former Yugoslavia show red-heart development after some 80 years in the lower parts of beech stems growing on fertile land, and after approximately 150 years in trees growing more slowly under less favourable conditions (Torelli 1984). The discoloration is caused by coloured extractives in the parenchyma cells (Pape 2002). The total concentration of phenolic extractives is reported to be lower in discoloured red-heart than in normal beech wood, which suggests that the phenols are involved in the formation of coloured substances (Albert et al. 2003). Red-heart development is assumed to be caused by physical or biological stress to the tree, possibly by injury or dying branches (Shigo &
Red-heart wood in birch is characterised by an increasing presence of non-decomposing microbes in the wood (Hallaksela & Niemistö 1998, Pape 2002), but neither fungus nor bacteria were found to be necessary for the development of red-heart in birch (Hallaksela & Niemistö 1998, Pape 2002). Similar results have been reported for sugar maple (Basham & Taylor 1965). The mechanical properties of birch red-heart are similar to these of non-discoloured wood (Enquist & Petersson 2000).

![Figure 4 Red-heart in silver birch (Betula pendula Roth.).](image)

### 3.5 Protective actions by the living tree

Sapwood comprises both living and non-living cells and as a result the sapwood is capable of an active response towards microbial infection and damage (Pearce 1996). Here living cells in axial and the radial parenchyma play a key role in the plant’s defence towards pathogen interaction. Several host-pathogen models describing the dynamic development of decay in living trees have been presented (Pearce 1996). The models describe zones of wood transforming in an effort to stop or slow down the progress of the infection, commonly accompanied by colour changes (Shigo & Hillis 1973, Shigo 1976, Bauch 1980, Torelli 1984). Hardwoods appear to accumulate water in the protective reaction zone between decayed and healthy tissue in an effort to minimize the access of oxygen in an effort to make the environment less favourable for the attacker (Pearce et al. 1994). Cell walls in the reaction zone undergo functional and biochemical alterations including suberization, the development of antimicrobial compounds and cell necrosis (Pearce 1996). In birch, the vessels are not obstructed by extractives which results in an extended axial spread of the attack and discoloration (Bauch 1980, Rademacher et al. 1984). In some species, e.g. beech and oak, the
reaction zone is assisted by tyloses which develop from xylem parenchyma and grow through pits to seal the lumen of vessels (von Aufsesse 1984, Rademacher et al. 1984). Suberization, the development of cork tissue, is reported to be extensive in oak and beech sapwood but absent in some species. Tyloses are commonly suberi zed (Pearce 1996). Together with gummosis, i.e. gummy deposits formed by polymerization of phenolic compounds in the sapwood, tyloses may block the axial spread of pathogens along the vessels (Rioux el al. 1995). During active growth suberization is reported to develop within 1-6 weeks while no response was reported after 6 weeks during the dormant season (Biggs 1987, Schmitt & Liese 1993). Necrotic reaction tissue is characterised in many trees by cell wall transformation and the accumulation of coloured pholyphenolic deposits which fill up vessels and cell lumina, appearing 1-2 weeks after the attack (Pearce & Woodward 1986, Pearce et al. 1994).

### 3.6 Seasonal effects

It has been suggested that seasonal variations in the living influence the colour of wood (Luostarinen et al. 2002). The concentration and levels of extractives in wood vary over the year (Törnqvist 1987, Mononen et al. 2002, Loustarinen & Möttönen 2004a). Luostarinen et al. (2002) and Mononen et al. (2002) reported that spring-harvested silver birch (*Betula pendula*) wood was slightly darker than autumn-, winter- and summer-harvested both in fresh and dried timber. Comparative studies investigating the influence of season on hard maple (*Acer saccharum* L.) by Smith & Herdman (1996) and Scots pine by Terziev & Boutelje (1998) have not identified season to be a factor of practical importance for the colour of dry sawn timber. The individual variations between trees from the same stand and felling season can be rather large for birch (Karlmats & Tegelmark 2004).

Nowadays, deciduous trees are harvested in all the seasons of the year in Sweden. In particular mixed stands of conifer and deciduous trees with alder, aspen and birch are handled in this way as a result of the pulp industry’s need for fresh fibre material. However, the majority of the logging is done during the dormant period, particularly in monocultural stands (Esping 1996).

### 3.7 Logging and log storage

Timber harvesting and log handling are generally considered to be important for the properties of wooden products (Törnqvist 1987, Denig et al. 2000). Discoloration caused by mould, sapstain or internal grey stain and darkening of exposed end surfaces may be the result of storage (Koch & Bauch 2000).
Protective action by living cells may also play a role in the formation of coloured compounds and tyloses in the wood after logging. Various enzymes participate in metabolic systems in the living tree and some are also active after felling. Enzymes often participate in discoloring the surface of wood when freshly sawn green wood comes into contact with oxygen (Hon & Shiraishi 1991). The reaction can be reduced by dipping the wood in chemical antioxidants (Hrutfiord & Luthi 1981, Forsythe & Amburgey 1992b). Another way to prevent this type of discoloration is to deactivate the parenchyma cells. Some suggested methods to do this are thermal treatment by steam or boiling (Bailey 1911, McMillen 1976), chemical treatment by e.g. methyl bromide or mechanical compression of the green wood (Kreber et al. 1994, Schmidt & Amburgey 1994).

One example of biochemical reactions is the red surface discoloration on Alder (Alnus ruba and Alnus hirsute), that develops after sawing and darkens during storage due to the interaction between oxidizing enzymes and wood extractives (Hrutfiord & Luthi 1981, Terazava et al. 1984). The influence of living parenchyma cells on non-microbial enzymatic discoloration in logs and wet timber during storage has been shown by killing the parenchyma cells using methyl bromide, which protects the sapwood of several hardwoods: red oak, alder, ash and maple from discoloration (Amburgey et al. 1996, Schmidt & Amburgey 1994). Trials using more environmentally friendly and less poisonous chemicals, e.g. the antioxidant sodium bisulfit reduced but did not completely protect the wood from discoloration (Forsyth & Amburgey 1991, 1992b, Schmidt et al. 2001). Inactivating parenchyma cells using methyl bromide was not successful in controlling kiln-brown stain (Kreber et al. 1994).

Hardwood logs are commonly stored in the forest and at sawmills for several weeks or even months before sawing (Esping 1996, Tegelmark & Karlmats 2004, Jonsson 2013). Oak logs may sometimes be stored for years. Storage of hardwood logs in a warm climate increases the risk of wood discoloration regardless of the kiln schedule used in the US (Smith & Herdman 1996, Simpson 1991). End discoloration of birch and beech is recognised by the sawmill industry to be a summer problem (Koch & Bauch 2000) accelerating from June in Sweden (Esping 1996). End discoloration starts from log ends as well as other damage to the bark and propagates mainly axially as the wood dries in an uneven pattern (Verkasalo 1993, Jonsson 2013). While clearly visible on wet timber, the colour difference is less prominent after drying, but the border between the discoloured and non-discoloured wood is typically visible giving a striped appearance (Corbo et al. 2001). A hardly detectable reduction in lightness of birch boards was noted after up to 15 weeks of log storage during the spring and summer (Tegelmark & Karlmats 2004). Darkening first occurs on log ends and is less visible on the dried wood (Tegelmark & Karlmats 2004). More than 4 months storage of birch logs during the summer and autumn period in Sweden led to an intense discoloration.
of the complete log (Tegelmark & Karlmats 2004). Only mild deterioration was reported in birch logs stored in the forest during the first summer; stains were limited to log ends and insect damage just beneath the bark, but after a second summer the logs were ruined (Verkasalo 1993). Water sprinkling significantly reduced the end discoloration of winter- and spring-felled birch logs during 12 weeks in the summer compared to dry storage (Jonsson 2013). Studies on birch by Luostarinen et al. (2002) and Möttönen (2005) did not recognise a storage time up to 10 weeks to have a negative influence on the colour of silver birch after drying. Studies on beech (Paper V) did not find any significant influence by storage on the colour of the wood after 13 weeks of storage during February to May in Southern Sweden. Storage of hard maple logs in northern U.S. from December to June led to darkening and increased reddishness (McMillen 1975). Inactivation of parenchyma cells in sugar hackberry (Celtis laevigata) logs using methyl bromide successfully protected the wood from end discoloration during 6 weeks of log storage in warm Southern U.S. climate (Schmidt & Amburgey 1994).

### 3.7.1 Microbial discoloration

The natural decomposition of wood which typically involves bacterial and mould infections is an ever present risk to the material which may cause discoloration. Fungi attack may be divided into moulds, sapstains and rots (Bergström & Blom 2005). While spores from moulds, Figure 5, only discolour the surface, blue, green or black pigmented hyphea of sapstain fungus can penetrate deep into the wood, sometimes discoloring the whole of the sapwood (Fengel & Wegener 1984, Törnqvist 1987, Nylinder et al. 2001, Nylinder et al. 2003). Rot, on the other hand, is fungus that decomposes cell walls influencing both colour and structure (Törnqvist 1987, Nylinder et al. 2003).

![Figure 5](image_url) **Figure 5** Mould growth on beech (Fagus sylvatica L.) components, 52x32 mm in cross section.
Under favourable humid and moderately tempered conditions, sapstain may develop within days while rot requires a longer period of time (Kollmann & Côté 1984, Hon & Shiraishi 1991). The risk for mould or sapstain, Figure 6, attack is enhanced on wood with a moisture content exceeding 20-25 % (Esping 1992, Bergström & Blom 2005). Birch is less sensitive towards sapstain than softwoods (Esping 1996).

Figure 6: Blue stain fungi hyphea in beech (Fagus sylvatica L.) vessel.

Some heartwood discolorations are also known to be caused by fungal attack. One example is the yellow discoloration, Figure 7, that occurs on European oaks particularly under the stickers (Bauch et al. 1991, Gustafsson & Lundqvist-Gustafsson 2008). This development is favoured by low air speeds, and by wet and wide stickers (Peck 1956, Smith & Herdman 1996). The actual colouring process is assumed to be the result of a reaction between the fungi metabolism and wood extractives (Bauch et al. 1991).

Figure 7: Yellow sticker mark on oak (Quercus robur L.).
Fungi and bacteria may indirectly cause discoloration of wood by reactions which in their turn result in new discolouring reactions e.g. by changing the pH-level in the wood (Bauch et al. 1991). Discoloration caused by microorganisms can be prevented by removing one of the essential growth factors: water, oxygen, moderate temperature or nutrients, or by the addition of a chemical growth inhibitor (Bauch et al. 1991).

Sawmills which mainly acquire logs from private forest owners tend to build up large stocks during the spring period (Esping 1996, Jonsson 2013) and they are subsequently forced to prioritise their sawing operations. The priority order in which the different species and log qualities are processed typically depends on the risk of storage damage, on the value of the wood and of course on orders from customers. Storage-sensitive high-value species like beech and ash are typically first priority. Thereafter come birch, black alder and aspen in this order depending on the value of the timber. The highest valued timber, oak, is sometimes handled differently. Although the wood is sensitive to checking, the risk of discoloration of the heartwood during storage is lower, and logs may therefore be stored for up to 2 years (Esping 1996). Only in the case of discoloration of the sapwood is this disregarded i.e. if the final product is produced solely from oak heartwood.

Industrially implemented techniques to reduce log storage damage on hardwoods in Sweden are water spraying, snow storage and end-sealing in combination with log pile orientation (Törnqvist 1987, Corbo et al. 2001). Spraying water on log piles to reduce surface drying and limit oxygen access is a well-known technology practised on both soft- and hardwoods (Törnqvist 1987, Söderström 1986, Jonsson 2013). Prolonged water storage may however increase the risk of microbe invasion causing severe discoloration (Kreber & Byrne 1996). Snow storage is sometimes used where the winter conditions are favourable. High-value veneer logs in particular are treated with this method (Corbo et al. 2001). Snow storage is also industrially practised on hard- and softwood saw-logs in e.g. Russia and Finland. Covering a pile of logs with snow and bark provides an excellent protection of the wood for several months. The log quality is good and no problems with discoloration have been reported (Corbo et al. 2001). A basic means of reducing storage damage is to keep the bark intact and to orient the log piles at the sawmill in a north – south direction in order to reduce the exposure of the log ends to the strongest mid-day sun. Covering log ends with a wax-based coating is sometimes also adopted, a technique which offers some protection against log end drying (Simpson 1991). However this method has not been reported to protect birch from end discoloration during log storage (Tegelmark & Karlsmats 2004). Storage of beech and birch logs in an oxygen-free environment to protect the logs from discoloration have been reported to be successful (Corbo et al. 2001, Maier 2005). The technique, encapsulating logs in air-tight plastic bags, is however labour-intensive and sensitive to damage in the plastic film.
Table 1: Practical defence strategies for avoiding microbial discoloration of logs and green timber.

<table>
<thead>
<tr>
<th>Action</th>
<th>Logs</th>
<th>Timber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowering the temperature</td>
<td>Snow storage</td>
<td>-</td>
</tr>
<tr>
<td>Removing moisture</td>
<td>Summer felling</td>
<td>Air or kiln drying</td>
</tr>
<tr>
<td>Reducing oxygen access</td>
<td>Water sprinkling</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Fermentation in sealed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>package</td>
<td></td>
</tr>
<tr>
<td>Mechanical protection</td>
<td>Keeping the bark intact</td>
<td>End sealing</td>
</tr>
<tr>
<td></td>
<td>End sealing</td>
<td></td>
</tr>
<tr>
<td>Reduce the nutrient source for micro-organisms</td>
<td>-</td>
<td>Clean boards from sawdust</td>
</tr>
<tr>
<td>Kill the micro-organisms</td>
<td>Chemical inhibitors</td>
<td>Chemical inhibitors</td>
</tr>
</tbody>
</table>

3.8 Storage of sawn wood/timber

Storage of green sawn timber before drying may result in the same problems regarding discoloration as the storage of logs prior to sawing. It is recommended that the time between sawing and drying is minimized as soon as the wood temperature exceeds 0°C (Esping 1988).

As a result of the sawing process, the surface area is dramatically increased and the risk of surface-related discoloration is consequently increased. On the other hand the increased surface-to-volume ratio will speed up air-drying and this will help to protect the surfaces from fungal infection. A drawback of air drying is the increased risk of surface checking (Esping 1988). Freshly sawn timber may be protected by water sprinkling during storage before drying in order to avoid uncontrolled surface drying (Simpson 1991).

The bulk storage of wet timber without stickers before drying, particularly of water-stored logs, in a tempered climate is reported to increase the risk of non-microbial gray-stain in red oak (*Quercus ssp.*) (Forsyth & Amburgey 1992a). The wood can be protected against surface discoloration by dipping in an anti-oxidant solution before bulk stacking (Forsyth & Amburgey 1992a).

3.8.1 Weathering

Most unprotected materials exposed to the weather will slowly degrade in a process called weathering (Williams 2005). In wood, the smooth original surface becomes rough when grains rise, boards deform and checks develop as the weather cycles between sun radiation and rain (Feist & Hon 1984).
The surface changes colour as a result of photo-induced discoloration, mould may grow and dirt gather on the roughened surface (Feist & Hon 1984). Softer parts of the surface structure may later be rinsed away by rain water leaving the surface with a silver greyish appearance (Anon. 1975) as illustrated in Figure 8. It is a surface phenomena, but since cracks may develop and propagate as a consequence of repeated shrinkage and swelling in the material, dark coloured materials may also collect in small cracks deeper in the boards, creating undesirable streaks in the material.

3.9 Pre-steaming

Pre-steaming is a heat-treatment process under moist conditions used to artificially modify the colour of wood (Wagner 1917), particularly applied on hardwood species like beech and walnut.

Figure 9: Beech (Fagus sylvatica L.) 70×70×10 mm samples after 1 mm surfacing, a) after 1 hour pre-steaming in saturate steam at 100°C, b) after 96 hour pre-drying in 60°C and 60% RH, c) Untreated reference. All the samples were dried in 23°C and 50% RH with 2 m/s air speed to 9% moisture content after pre-treatment before surfacing.
In beech, the technique is used to reduce the natural colour variation of the timber by giving it a slightly pink tint (Burtin et al. 2000, Trübswetter 2006), Figure 9, and matching the colour of solid wood with that of traditional beech veneers which has this colour as a result of the veneer log softening process. In walnut, the technique is used to reduce the colour variation between heartwood and sapwood (Chen & Workman 1980).

The procedure is commonly conducted on fresh, newly sawn timber which is exposed to saturated steam under atmospheric pressure at 95-100% relative humidity (RH) and 80-105°C for a few hours in a specially designed steaming chamber or drying-kiln (Trübswetter 2006). The colour change intensifies with temperature and time of exposure and works only on wet wood (Brauner & Loos 1968, Chen & Workman 1980, Burtin et al. 2000). Besides colour changes related to extractives, illustrated in Figure 10, the presence of simple sugars in the condensate from the pre-steaming treatment of beech indicates the decomposition of hemicellulose (Burtin et al. 2000, Irmouli et al. 2002). It has also been suggested that chemical modifications of lignin occurs at temperatures exceeding 80°C (Kollmann et al. 1951, Koch & Bauch 2000).

![Figure 10: Micrograph of radial parenchyma in steamed beech (Fagus sylvatica L.).](image)

In order to obtain an even colour throughout the cross section, the treatment must be performed on wet non-frozen timber. An uneven discoloration of the wood may nevertheless develop as a result the of migration and condensation of water-soluble compounds in the wood close to the surface during pre-steaming. Small sawmills typically uses steaming chambers with a capacity of a few packages per batch and pre-steam as they saw, later drying timber from several pre-steamed batches in the same kiln. After pre-steaming, beech timber appears to be more susceptible to mould growth than untreated timber, and mould-inhibiting pesticides are sometimes
used if the timber is air dried. Similar findings have been reported for Douglas fir (Miller et al. 1983). An uniform colouration of beech can also be achieved if newly sawn timber is kiln-dried at temperatures higher than those conventionally used (Pratt 1986, Thomassen 1998). Initiating drying at temperatures exceeding 55°C leads to a similar reddish colour to the timber as pre-steaming, but it shortens the drying time and makes pre-steaming obsolete, thereby reducing operating costs. Today, beech veneers are also produced without the traditional red colour and the demand for natural non-steamed beech timber has subsequently increased.

3.10 Chemical contact stains

Chemical contact stains are colour changes in wood caused by contact between wood and chemical substances such as metal ions, acid or alkali (Hon & Shiraishi 1991). Since wood is a porous material, water-soluble substances and salts may be deposited in the voids during growth or after logging, and this may cause colour changes. This type of discoloration is typically limited to the surface layer.

3.10.1 Iron stain

Chemical reactions between metals and some woods are known to result in dark discoloration. When wet wood with a high tannin content, e.g. oak, chestnut or walnut, comes into direct contact with iron, a black coloured substance develops (Bauch 1984, Simpson 1991), as shown in Figure 11. Iron ions are formed when iron is dissolved in water and ionization is accelerated by the acidic wood. Iron ions react with the hydroxyl groups in phenolic substances in the wood and form black substances, the process being accelerated by oxygen (Hon & Shiraishi 1991).

![Figure 11: Iron stain on oak (Quercus robur L.), a sample of dimension: 60x60x8 mm after exposure for 12 hours of rewetted wood in room climate.](image)

Figure 11: Iron stain on oak (Quercus robur L.), a sample of dimension: 60x60x8 mm after exposure for 12 hours of rewetted wood in room climate.
High moisture content above the fibre saturation point, high relative humidity, time and increased temperature and oxygen levels enhance the discoloration process (Hon & Shiraishi 1991). Iron stain on the surface can be removed mechanically by sanding or chemically using e.g. oxalic acid (Hon & Shiraishi 1991).

3.10.2 Acidic reactions

Acidic substances such as glue and paint may interact with wood and cause discoloration, so-called acid stains (Hon & Shiraishi 1991). Several species exposed to low pH values, below 1.5 are reported to cause strong red or reddish-purple staining, while higher pH values resulted in changes invisible to the naked eye (Hon & Shiraishi 1991). Oxygen does not participate in this stain development which is accelerated by UV-radiation. The source of acid staining is believed to be the phenolic extractives and not lignin (Hon & Shiraishi 1991). Of the investigated species, only beech showed a clear visible response to a strong acid solution, Figure 12.

![Figure 12: a) Beech, b) birch and c) oak after exposure to acid conditions (top), control (below). Wet samples immersed in hydrochloric acid at pH 1.0 for 7 days and exposed to indoor light, samples dried at 23°C and 50% climate.](image)

3.10.3 Alkaline reactions

Alkaline stain is the discoloration caused by exposure of wood to alkaline chemicals. If wood comes into contact with e.g. concrete in the presence of water, alkaline stains may develop, a problem recognised in the flooring industry (Simpson 1991). Little staining is reported under pH 11.4, but above this value a rapid reddish-brown to bluish discoloration has been reported (Hon & Shiraishi 1991). The discoloration process is believed to be caused mainly by oxidative polymerisation of water-soluble phenolic components, but lignin also participates (Hon & Shiraishi 1991). All three species were immediately discoloured when exposed to an alkaline solution, Figure 13.
Bacteria have been found to be involved in the discoloration of Ilomba (Pycnanthus angolensis) (Yazaki et al. 1985, Schmidt & Liese 1994). Similar bacteria, as found in Ilomba, which were incubated on beech led to brown discoloration in some days. The bacteria produced ammonia which increased the pH to 7.3. The alkalinity caused oxidation and polymerisation of phenolic compounds, resulting in brown deposits (Schmidt & Liese 1994).

### 3.11 Photo-induced discoloration

Both visible light and UV-radiation may cause photo-induced discoloration (Hon & Shiraishi 1991). All woods change colour when exposed to light, in ways which vary with species. Many species lose in lightness and become more colour-saturated. Other species fade, increasing in lightness and losing in colour-saturation or turning towards yellow (Hon & Shiraishi 1991). Light-coloured species typically turn yellow or darken while dark species more frequently fade (Anon. 1975). The beige-white colour of natural beech tends to darken and become more reddish. Steamed beech with its slightly orange-pink colour tends to become more golden. The creamy white colour of birch develops into a yellow-reddish colour and the light brown of oak develops into an amber-like colour, as illustrated in Figure 14.
Figure 14: a) Oak, b) birch and c) steamed beech exposed to UV-radiation by a Xenon lamp for 48 hours. Lower sections; unexposed wood protected by aluminium foil.

3.12 Drying

Wood starts to dry immediately after being cut in the forest in a process that proceeds until the wood is in equilibrium with the surrounding environment. The stem wood of a living tree may have a moisture content of 30-150% while the equilibrium moisture content in the surrounding environment is 16-22% outdoors depending on the season, and 6-12% indoors (Esping 1992, Thomassen 1998).

The visual appearance of wooden material in its equilibrium state often depends on how it got there, i.e. on the way in which the wood was processed and dried. As already stated in chapter 3.1-3.10, it is known that several processes in the value adding chain from the living tree to the dry construction material influence the final colour of the wood. Their influence on the colour is however much less than the effect of drying (Loustarinen et al. 2000, Rappold & Smith 2004).

Colour changes occurring during drying depend on the conditions to which the wood is exposed. Factors such as time, temperature, humidity and MC may influence how the wood colour reacts during the drying process. There are several ways to dry wood industrially, and each technique has its advantages and drawbacks. The most commonly used techniques for drying Nordic hardwoods are presented below.

3.12.1 Air-drying

The historical way of drying sawn timber is by air-drying (Wagner 1917), a technique that is still used industrially on a large scale for hardwoods (Esping 1996, Stenudd 2002). Here, newly sawn boards are piled up in
packages, as shown in Figure 15. A space is created by stickers separating each layer of boards in the package to allow the wind to create an air flow through the package (Peck 1956). Heat from the sun is transferred by the air flow to the wood allowing the evaporation of moisture from the timber surfaces to continue. Simultaneously, the same air-stream removes moist air from the vicinity of the boards keeping the local vapour pressure low enough for evaporation to continue. The drying rate is slow and depends not only on the species, dimension and final MC but also on the climate (Peck 1956, Rietz & Page 1971). The active drying season is during the spring, summer and early fall period. Outside this period, the drying rate is low, the process may take 3-12 months (Esping 1996).

Figure 15: Air-drying of birch in the timber yard of a Swedish sawmill.

While air drying have some benefits, such as no energy costs and very low investment requirements, the technique does have some drawbacks. Not only does it tie up capital for a considerable period of time, but there are two additional issues of major concern. Firstly, the technique is suitable only for pre-drying to approximately 15-22 % MC (Esping 1996). Final drying to a lower moisture content level for furniture and carpentry applications, 8-10 % MC, requires additional techniques. Secondly, air-drying is an uncontrolled process were the risk of defects by discoloration and checking is significant (Peck 1956). Air drying increases the risk of sticker marks, dark discoloration of the wood directly beneath the stickers. Wide and wet stickers increase the risk of sticker marks in maple (Smith & Herdman 1996, Wengert 1997) and there is also seasonal dependence (Peck 1956). There are ways of improving the basic concept of air drying, speeding up the process and reducing the risk of discoloration. Improved air drying typically involves
artificial movement of the air through the wood stacks using fans e.g. forced air-drying or forced air-shed drying (Thomassen 1969, Rietz & Page 1971, Stenudd 2000). Protecting the timber from rain and snow by roofing, selecting windy locations on well drained ground, keeping the ground surface free from vegetation, using high foundation piles, using dry and profiled stickers are other means of improving air drying and reducing the risk of discoloration (Peck 1956, Wengert 1997).

3.12.2 Heat and vent batch kiln drying

While air drying is still common practice as a mean of pre-drying, most timber is now being dried in batch kilns (Esping 1996, Stenudd 2002), either of the heat and vent or the dehumidification type. In batch kiln drying, packages with sawn boards are loaded into a compartment or chamber. The basic concept of drying is the same as for air drying, but the process is here controlled according to special schedules adapted to the species, dimensions and end usage. The climate, temperature and relative humidity inside the chamber are regulated by supplying thermal energy, removing moist air through ventilation or supplying humidity according to the needs. The equilibrium moisture content of the wood can thus be set to any level along to the sorption – desorption isotherm. Air is artificially forced through the space created by the stickers, passing above and below the boards. Air velocities used in hardwood drying typically range from 1.5 to 3 m/s (Pratt 1986, Thomassen 1998, Trübswetter 2006), while softwood kilns typically uses 3-5 m/s for the same applications (Esping 1996, Sahlin 2001). For beech and birch, the low air velocities are mainly an economic concession. Long drying cycles give limited room for investments in powerful fans. The electrical energy consumption is rapidly increased with increasing air speeds (Sahlin 2001, Sandland et al. 2010). Consequently the air speed is kept as low as possible and a reduction in RH sometimes used as compensation to achieve the same drying rate. Drying hardwood timber to a moisture content of 8-10% typically requires anything from a couple of days up to three months depending on species, dimension and final quality demands (Pratt 1986, Thomassen 1998, Trübswetter 2006). Heat and vent convection kilns use natural or powered venting to replace some of the hot humid air inside the chamber with an equal amount of cold air from the outside with lower absolute humidity, as illustrated in Figure 16. It is the difference in absolute humidity which makes this type of kiln work, in most cases, it requires a higher temperature inside the chamber than outside.
Heat is transferred from the heating coils (1) to the wood (2) by the circulating fans (3). The relative humidity is increased by water spray or steam and lowered by evacuation through the ventilation outlets and allowing make-up air to enter through the ventilation inlets (4). The climate is usually monitored and controlled by a computer-based system using psychrometers or comparable sensors for temperature and relative humidity (5) inside the chamber, Figure 16.

General recommendations for how to avoid discoloration during kiln drying typically involve the immediate stacking of the boards on dry profiled stickers after sawing, initiating a rapid drying process in a low temperature and low humidity climate after a short heating period, and reversing the air flow frequently (Wengert 1997).

Similar pre-treatments as for logs and wet timber storage have been suggested as protective measures against discoloration during kiln drying. But neither freezing, compression, acoustic sound, microwaving or electric discharges were successful in protecting soft maple (*Acer rubrum* L.) from discoloration during kiln drying, only exposure to sulphur dioxide gas managed to restrict but not eliminate the grey discoloration (Wiemann et al. 2009).

### 3.12.3 Batch kiln drying using a dehumidifier

Dehumidifying kilns closely resemble the convection-type chamber kilns. The difference is the way in which moisture is removed from the circulating air-vapour mixture inside the chamber (Simpson 1991). Condensation kilns use a heat pump to dewater the air circulating inside the sealed chamber (Esping 1996) rather than by venting out the moist air. The energy efficiency of the system is improved by recovering the latent heat of vaporisation and avoiding heating up cold replacement air (Anon. 2007).

In the process part of the hot humid air inside the chamber is forced to pass the cold evaporator of the dehumidification unit where condensation
occurs as the moist air is cooled below the dew point, Figure 17. The cold humid air stream is subsequently reheated by the condenser unit making it hot and dry before returning to the chamber (Simpson 1991, Esping 1996). Besides being more energy efficient than a convection kiln, the dehumidification kiln does not require a boiler. The main drawbacks of this system are its limited maximum operating temperature, which leads to longer processing times, and the dependence on electrical energy (Simpson 1991, Anon. 2007).

Both convection and dehumidification kilns are used to dry hardwoods. Due to considerably higher costs for electrical than thermal energy, there is a tendency for larger kiln operations to use convection kilns while smaller operators may benefit from the fact that no boiler is required for the condensation kilns (Esping 1996).

![Figure 17: Working principle of a condensation dehumidification unit.](image)

### 3.12.4 Progressive drying kilns

Progressive kiln drying, also known as tunnel drying, is drying in a kiln where the timber is moving through the chamber and is thus exposed to various drying climates depending on the physical location of each board inside the kiln (Esping 1996, Anon. 2007), Figure 18. Common progressive kiln designs are: FB (Feedback) with counter air flow, OTC (Optimized two-stage) with the air flow along the moving direction of the timber in the first zone, in addition there is also cross flow drying kilns (Esping 1996, Anon. 2007). Progressive kilns may consist of one or more zones in which the climate in individually controlled. The multi-zone kiln design combined with elevated temperatures in recent years has also allowed drying of furniture-grade timber. Except for the cross flow kiln, progressive kilns are mainly used for the drying of softwoods.
3.12.5 Vacuum drying

Vacuum drying is a fast drying technique where the ambient pressure is lowered in an autoclave to reduce the boiling point of water (Anon. 2007), Figure 19. The wood is heated to a temperature exceeding the boiling point at the chosen pressure level (Thomassen 1998, Anon. 2007). An internal over-pressure builds up which assists moisture flux from the interior to the surface of the board (Källander 2000). Large-scale commercial vacuum drying in Europe is nowadays based mainly on low-temperature super-saturated steam-drying technology (Trübswetter 2006) where the wood is dried in a continuous process typically exposing the wood to a temperature of 40-80°C and a vapour pressure of 5-40 kPa (Källander 2000). Alternative vacuum drying technologies include discontinuous processes where the wood is convectively heated at atmospheric pressure and dried under vacuum, conduction heating using heated plates (Paper III) or dielectric heating using high frequency radio waves (Avramidis & Zwick 1996, Resch 2006).

Figure 18: Progressive tunnel kiln, 2-zone FB type.

![Progressive tunnel kiln](image)

Figure 19: Convection-type vacuum kiln using low-pressure super-saturated steam as heat transfer medium.
Heat is transferred from the heating coils to the wood by high-speed circulating fans. Moisture is evacuated from the low-pressure chamber as steam by a condenser and vacuum pump in collaboration. Moisture may be added to the wood by injecting steam. The climate is monitored and controlled by a computer-based system using temperature and pressure sensors.

If the air is replaced with water vapour some types of oxidative discolouring processes can be reduced or avoided (Thomassen 1998, Källander 2000). Vacuum drying is reported to cause less colour changes in some hardwoods (Charrier et al. 1992, Welling & Wöstheinrich 1995, Joyet & Meunier 1996) despite the higher temperatures in the vacuum kiln. However the colour-protecting effect does not appear to apply for birch (Luostarinen et al. 2002). Despite the positive effect on colour, a lower total energy consumption and a 3-4 times faster drying than the conventional heat and vent technology (Källander 2000), the use of vacuum drying is still limited in Europe. This may be due to the high investment cost and the fact that the process is sensitive to process disturbances, for example larger moisture content variation have been reported (Källander 2000, Ledig & Militzer 2000). Drying of thick 50 mm oak without checking is also reported to be difficult (Joyet & Meunier 1996). Increasing electrical costs during recent years has also made this technology less favourable. Vacuum drying consumes more electrical energy than conventional kiln drying (Esping 1996).

### 3.12.6 Press drying

A very fast but less frequently used drying technique in the Nordic countries is press drying. A variant of the technique has been used by Junckers Industrier A/S in Denmark for the production of solid beech flooring since 1959 (Schmidt 1967). Freshly sawn beech components, 32 mm thick and approximately 600 mm long, are dried from fresh to approximately 1-3% MC in some 2 hours. The drying apparatus consists of a 20 layer plate press heated to 165°C where the wood is subjected to a pressure of 1.2 MPa (Schmidt 1967, Esping 1996). After cooling and one week of storage in a conditioning hall, the wood is re-moisturised using saturated steam in an autoclave to regain moisture and thereafter left to equalize for another 2-3 weeks before processing (Schmidt 1967). The process leads to a darker and more reddish colour of the wood than conventionally kiln dried beech. Higher temperatures lead to a strong brown coloration of the interior wood as a result of hydrolyse as well as a marked tendency for collapse and internal checking (Schmidt 1967). The process is best suited for species with high permeability (Hittmeire et al. 1968, Esping 1996). Press drying of beech is sensitive to the development of tyloses in the wood so that pre-steaming was introduced as a method of protection (Schmidt 1967).
Press-steam drying caused darkening of red oak (*Quercus rubra* L.) and maple (*Acer saccharinum* L.) compared to the result of air- and kiln-dried timber (McGinnes & Rosen 1984), but Chen (1980) only noted surface discoloration in yellow poplar (*Liriodendron tulipifera* L.) and American beech (*Fagus americana* Ehrh.).

Another example of commercial press drying is an installation in Finland where full length boards of birch and aspen are dried in a machine that uses hollow and porous aluminium plates. The press plates are heated by hot air circulating inside the hollow plates in a process that resembles convection drying but where the wood surfaces are protected from the hot air and the heat is transferred from the plates to the wood by conduction. Here the wood is dried at 100-130°C for 6-72 hours at a pressure of 0.15-0.3 MPa (Hottinen & Hottinen 2005, Heräjärvi 2009).

Benefits of press drying are fast processing, reduced energy consumption, reduced deformation and, in some cases, improved dimensional stability (Schmidt 1967, Hittmeire et al. 1968). Besides the risk of colour changes, the major challenges in the press drying of timber are checking and honeycombing, in particular for species with heartwood like oaks (Hittmeire et al. 1968).

Press drying is dependent on capillary moisture movement (Schmidt 1967). Trial drying of 2.6 metre boards of birch using the results from paper II failed, as the middle parts of the boards became discoloured. Steep moisture gradients from the end to the middle of the boards was noted and the drying time got considerably longer.

*Figure 20: Laboratory-scale electrically heated hydraulic press, used for the press drying tests in Paper II.*
3.13 Economics of hardwood drying

The purpose of business is to make a profit. Consequently drying operations must be optimized to generate the highest possible profit for the processing company, but studies of the economics of drying are rarely found (Olek et al. 2002). Profits from drying depend on whether or not the drying process is a bottle-neck in the total production (Riley & Sargent 2010). If the drying capacity exceeds the need i.e. drying is not a bottle-neck, the profits are maximized by minimizing the costs. The costs of drying can be divided into fixed and variable operating costs and the cost of poor quality (CoPQ) caused by the drying process.

\[ \text{Profit} = \text{Annual throughput} \times (\text{Sales price} - \text{Wet timber value} - \text{Fixed costs} - \text{Variable costs} - \text{COPQ}) \]

If the drying capacity is a bottle-neck increasing the throughput must also be taken into consideration when optimizing the profit (Goldrat & Cox 1984). Drying operations then become a balancing act between increased production volumes and increased quality losses as a result of the faster processing.

3.13.1 Fixed costs

Fixed drying operation costs (Thomassen 1998, Olek et al. 2002, Trübswetter 2006) include:

- Capital costs for kiln, equipment and stickers
- Maintenance costs
- Operators costs
- Work in progress
- Insurance costs
- Administration costs
- Land and property tax
- Facility energy costs (lighting, circulation pumps, freeze protection etc.)

Fixed costs are in general independent of how the kiln is being used and can be calculated as a fixed cost per hour of operation (Riley & Sargent 2010). The major cost drivers behind the fixed cost are the depreciation and interest on the investment, as indicated in Table 2. A shorter cycle time and high utilization are efficient means of reducing the fixed costs.
3.13.2 Variable costs
Variable costs for drying operations includes costs for:

- Electrical energy
- Heat energy
- Timber handling

Variable costs depend on the design and efficiency of the technology used in a specific kiln, on the duration of the processing and on the timber being processed. Electrical consumption in a given kiln depends primarily on: air velocity, air density and time (Riley & Haslett 1996). In addition, some electricity is used to power pumps, valves and controls. The electrical consumption by a fan is proportional to the air density and to the cube of the velocity (Esping 1992, Riley & Haslett 1996). Air density is determined by the air pressure and to a lesser extent by the temperature and RH (Esping 1992). Reducing the air speed in the later stages of the drying process is a cost-efficient way of reducing the electricity consumption (Salin 2001, Steiner et al. 2010). The initial air speed in industrially drying is typically 2-3 m/s, for the investigated species (Thomassen 1998).

Heat consumption in a specific kiln depends on: initial moisture content, final moisture content, density, evacuation losses, transmission losses and time. The mass transfer of water inside and evaporation from the surface of each piece of wood determines the basic thermal energy consumption (Salin 2001). Evacuation losses depend on the mass transfer as well as on the enthalpy (i) and specific humidity (x) differences between the climate inside the kiln and the surrounding external air. Evacuation losses increase at low wet bulb temperatures as the di/dx quotient increases. Transmission losses through walls, roofs and floor of the kiln increase with temperature and time (Esping 1996). The specific heat energy consumption per unit of water removed when drying hardwoods may be 2.0-2.3 kWh/kg (Esping 1996, Thomassen 1998) as a result of the low temperature and long processing times.

Handling is a semi-flexible cost that comes once per treatment covering labour and operating costs for loading/unloading, stacking and forklifts (Thomassen 1998).

3.13.3 Cost of poor quality
Cost of poor quality (COPQ) are costs related to defects in a product caused by the processing and costs related to identifying and correcting such defects (Bergman & Klefsjö 1995). In timber drying, COPQ is related to issues such as incorrect moisture content, case-hardening and processing defects such as distortion, checking and discoloration.
Considering only yield losses caused by the drying process when estimating the costs of drying is a simplification that tends to under-estimate costs related to quality losses for wood that is further processed into high value products such as furniture. A sawmill performing a drying operation will probably have to cover, at least in part, the costs generated by yield losses in further processing, lost production or claims from the final customer as part of an on-going business relation between the sawmill and its customers. Failure to comply with the customer’s specification regarding colour is a major defect for many hardwoods and the price loss is substantial as the market for low grade-hardwood timber is limited. Discoloration of hardwoods typically leads to downgrading to the lowest C-quality for use in hidden or fully painted applications. Low quality hardwood is sometimes referred to as frame-grade when used in upholstered furniture for its technical properties e.g. bending strength and nail-holding capacity. The value lost by discoloration can be up to 75% of the value of non-discoloured wood of the same timber quality.

3.13.4 Kiln drying cost calculation example
In this example, a birch sawmill is producing 10 000 m3 sawn timber annually and the total volume is kiln-dried to 8% MC, suitable for products for indoor use. Logs are sawn to 50 mm planks and 25 mm boards, distribution being 75/25% for the respective dimensions, in accordance with Elowsson (1989). The initial MC was set to 70%, in accordance with Jørgensen et al. (1995). Drying times for the two dimensions are 576 and 240 hours. In order to process the total volume 6 kilns, each with a 107/87m3 loading capacity are needed with an estimated investment cost of SEK 1 000 000 each. The value of non-dried timber and the sales price of a mixed A/B grade and C- or frame grade, the latter allowing discoloured wood, are based on price indications given by hardwood sawmills in Sweden in December 2012. Cost indications for other direct and indirect costs e.g. heat, electricity, maintenance and salaries were also given by the industry. The initial air speed for both dimensions was 3.5 m/s, reduced to 2.5 m/s in the later stages of the process in order to reduce the electrical energy consumption.
Table 2: Drying cost calculation example for a hardwood sawmill in Sweden producing 10,000m³ kiln-dried sawn birch timber annually.

<table>
<thead>
<tr>
<th>Conditions</th>
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<tbody>
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<td>Insurance, admin., tax</td>
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\[102\text{ SEK/m}^3\]
### Variable costs

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<td>Cost Of Poor Quality*</td>
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<td><strong>Sum of variable costs</strong></td>
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</tbody>
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*Downgrading 5% from A/B to C-grade

### Total drying costs

<table>
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<tr>
<th>Description</th>
<th>Cost (SEK/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed costs</td>
<td>102</td>
</tr>
<tr>
<td>Electrical energy</td>
<td>71</td>
</tr>
<tr>
<td>Heat energy</td>
<td>161</td>
</tr>
<tr>
<td>Timber handling</td>
<td>33</td>
</tr>
<tr>
<td>Cost Of Poor Quality</td>
<td>95</td>
</tr>
<tr>
<td><strong>Total cost of drying</strong></td>
<td><strong>463</strong></td>
</tr>
</tbody>
</table>

Table 2 shows that the heat energy cost followed by fixed costs and quality losses are the major costs related to hardwood drying in this example, which is in agreement with what others report (Olek et al. 2002). The majority of the fixed costs are related to capital costs for the kiln installation. Costs of electricity may be higher if higher air speeds are used or if the fans are not powered down in the later diffusion stage of the drying process. The example emphasises that quality losses may become very high if the timber is discoloured as a result of the drying process or timber handling. The fact that process development through trial and error involves a potential risk of losing up to SEK 190 000 for each kiln batch, if the timber is discoloured, has restricted such process developments in the industry.

### 3.14 Colour measurement of wood

Colour is an attribute of human perception resulting from electromagnetic radiation in the visible wavelength spectrum, approximately 380–780 nm, (Hunt 1998), Figure 21. In humans, there are three types of colour receptors in the eye giving rise to trichromatic colour vision. Other animals may have more or fewer types of receptors and may therefore observe the world monochromatically or including parts of the ultra-violet and infra-red regions.

When visible light strikes an object the light is typically absorbed, scattered or reflected. If all the visible light is reflected, the object appears to be white and if all the light is absorbed the object will be completely black. If
no scattering occurs, the surface acts as a mirror. It is the wavelengths of the diffusely reflected light from an object that the eye observes and perceives as a specific colour. This means that our common blond woods with a yellow tint absorb radiation at wavelengths in the blue and violet regions. If the wood turns reddish this means that radiation in the green region is being absorbed.

Figure 21: The visible region of the electromagnetic spectrum.

3.14.1 CIE colour space

Colour is a subjective experience in the viewer’s brain. To define colours, the International Commission of Illumination, CIE (Commission Internationale de l’Eclairage) has since 1931 developed models which describe the human perception of colour in a standardised way. Based on studies of how numerous individuals match different colours with mixtures of three primaries and spectrometric recordings of the wavelength distributions connected to these colours, CIE has developed spectral sensitivity curves corresponding to the human eye, also known as standard observers. Colour perception is also dependent on the light source (illuminant). Since different light sources have different spectral distributions, a standardized source of illumination must be used in order to obtain comparable recordings.

The tristimulus colorimetric analysis of the colour of an object is based on the spectral power distribution of a standard illuminant, the spectral distribution of the light reflected from the object and a standard observer colour matching function. The product generate XYZ tristimulus values which can be transformed into the chosen colour space (Anon. 1993).
3.14.2 CIELAB colour space

The L*a*b* colour space, also known as CIELAB, was introduced in 1976 as an approximately uniform colour space to be used for general purposes were colour values could easily be compared. In this system, a colour is represented by three coordinates L*, a* and b* and the distance between two points in the colour space corresponds well with the visual colour difference between the two samples.

Figure 22: CIELAB colour space, lightness (L*), yellow-blue component (b*), green-red component (a*).

The L* axis which runs from top to bottom represents lightness which is quantified at the position on the dark L* = 0 to light L* = 100 scale. Colours in this system is quantified based on the opponent colour vision theory where a colour cannot be perceived as both yellow and blue or as both green and red at the same time. The component on the green-red axis is represented by a* where negative (–a*) values represents green and positive (+a*) values red. The b* axis represents blue at negative (–b*) and yellow at positive (+b*) values. There are no theoretical maximum values of a* and b*. Colours for which a* and b* are zero are neutral grey colours. (Anon. 1993).

The total colour difference (\(\Delta E_{ab}\)) between two samples can be calculated as the Euclidian distance between two points in the L*a*b* colour space. This expression gives the value but not the direction of the difference, thus a red and a blue sample can have the same value of \(\Delta E_{ab}\) when compared with a grey reference. The colour difference is defined by equation 1 (Hunt 1995), where \(\Delta L^*, \Delta a^*, \Delta b^*\) represent the differences between the sample and the reference on the different coordinates. Differences \(\Delta E_{ab} > 3\) are generally regarded as being easily noticeable by the naked eye. Visually
distinguishable colour differences between samples have been reported for \( \Delta E_{ab}^* > 2 \) (Terziev & Boutelje 1998, Mononen et al. 2002). Möttönen & Luostarinen (2004) reported that colour differences \( \Delta E_{ab}^* > 1.8 \) were distinct for birch. In Paper VI it was possible to distinguish the colour difference between birch samples, with a uniform grain structure, for which \( \Delta E_{ab}^* > 1.5 \).

\[
\Delta E_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad [1]
\]

### 3.14.3 CIELCh colour space

The CIELCh colour space is the cylindrical transformation of the L*a*b* colour space. Lightness L* is represented as in the L*a*b* colour space, but the a* and b* coordinates are transformed into the new coordinate C* and the colour angle h, equations 2–3 (Hunt 1995), where C* stands for chroma or saturation from \( C^* = 0 \) representing greyish colours to a vivid saturated colour. The colour hue or angle h is represented in degrees from 0 to 360°, where 0° or 360° represents red, 90° yellow, 180° green and 270° blue (Anon. 1993). The use of CIE L*C*h coordinates, Figure 22, makes it easier to express the colour of wood since only one coordinate is used to describe a change in e.g. hue (Sundqvist 2000).

\[
a^* = C^* \times \cos(h) \quad [2]
\]
\[
b^* = C^* \times \sin(h) \quad [3]
\]

### 3.14.4 CIE illuminants

CIE has defined a set of standard illuminates to facilitate colour measurements. Illuminants A, B and C were introduced in 1931 to represent average incandescent light, direct sunlight and average sunlight respectively and illuminants D, E and F were later introduced to represent natural daylight, equal-energy illumination and fluorescent lamps respectively.

Commonly used illuminants for colour measurement on wood are illuminants C and D\(_{65}\) (Smith & Herdman 1996, Möttönen & Luostarinen 2004, Sehlstedt-Persson 2008). Illuminant C represents average daylight with a correlated colour temperature (CCT) of 6774\(^\circ\)K and contains little ultra violet radiation. Illuminant D\(_{65}\) represents natural daylight including ultra violet radiation and has a CCT of 6504\(^\circ\)K.

Illuminant C was selected for all studies since one of the industrial partners already used this illuminante in their measuring equipment which was used in papers IV and V.
3.14.5 Surface effects
The surface structure affects the perceived colour of wood. When light strikes a wooden surface the light is reflected, absorbed, scattered or transmitted (Hagman 1996), depending on the surface texture, fibre orientation and scattering effects of the wood cells.

The surface texture depends on the machining technique e.g. sawing, planing or sanding. These processes destroy the fibres in different ways which affect the way light is reflected or absorbed by the surface. It is therefore important to treat all the samples in the same way when conducting comparative tests.

Fibre orientation also influences the way light is reflected. The greatest difference is between surfaces viewed parallel to and perpendicular to the grain. Lightness is highest when the material is view crosswise to the fibre orientation since the quantity of light that is reflected and scattered without penetration into the cell walls is greatest. The effect on saturation is the opposite (Stokke et al. 1995, Hon & Shiraishi 1991).

The scattering effect of a tracheid has no major effect in this type of large area measurement. It is more interesting when narrow areas are scanned or lasers are used (Hagman 1996). On the other hand, scattering caused by moisture may influence the colour. When cell cavities are filled with water light can be transmitted deeper into the cells, scattering into the cell walls and resulting in the so-called wetting colour (Hon & Shiraishi 2001).
4 COLOUR CHANGES DURING DRYING

For the industry, the drying of hardwood is a matter of supplying dry timber fulfilling a quality specification at minimum expense. Since visual appearance, in particular colour, is a key quality feature for many hardwood products, special attention must be given to ensuring that the desired colour is achieved in a reliable and repetitive way. In order to achieve this the industry needs to understand how the drying process influences the colour of the wood. Many factors have been reported to influence the colour of wood during drying (Wengert 1997, Luostarinen et al. 2002, Sundqvist 2004, Möttönen 2005), and these factors can be divided into process parameters and material characteristics:

1. Temperature
2. Moisture content
3. Relative humidity
4. Time
5. Air pressure

Several of the process parameters, e.g. temperature and humidity are directly controllable in a conventional heat and vent drying kiln. Others are indirectly determined by other factors or an interaction of factors like drying time, while some parameters e.g. air pressure cannot be controlled in this type of kiln.

In this chapter, the findings in papers I-VI and results from some additional studies are presented, showing the influence on the colour of dry beech, birch and oak of process parameters and the interaction of process parameters.
4.1 Temperature

Temperature is a process parameter which it is possible to set in a kiln. In larger industrial kilns, the actual temperature of the wood will vary depending on conditions such as the board location and the uniformity of air flow. Artificial hardwood drying typically operates in the low-moderate temperature range of 25-80°C, starting at temperatures as low as 25-40°C and finishing at 65-80°C. The final operating temperature commonly depends more on the technical equipment used in the kiln, particularly fan motors, than on the timber being processed. Initial temperatures are on the other hand mainly limited by the risk of discoloration.

Wood changes colour as a result of being exposed to elevated temperatures, sometimes referred to as heat discoloration (Hon & Shiraishi 1991). Exposure to a high temperature for a long time will turn most wood species brown (Hon & Shiraishi 1991). A higher drying temperature generally results in a reduction of lightness, increased saturation and increased reddishness in all the investigated species of this study, beech, birch and oak (Paper I, III, IV, V, VI). Even relatively small changes in temperature may cause excessive colour changes.

Temperature influences the processing time in a direct way, and an increased temperature shortens the processing time. Temperature is also negatively related to the development of drying tensions which may result in case-hardening and possibly surface checking. The latter does not apply for oak, where the low permeability of the heartwood makes it impossible to dry at elevated temperatures. If heat discoloration is acceptable for the timber, beech and birch readily be dried at initial temperatures exceeding 55°C without any risk of checking, and this shortens the processing time.

Birch wood turns darker with increasing drying temperature, and the effect appears to level out first at temperatures below 30°C, Figure 23, but according to findings in paper VI the darkening was hardly detectable by the naked eye as long as the temperature was kept below 40°C in combination with an EMC level below 15%. Similar results have been reported for hard maple, where 40 to 43°C is reported to be a critical temperature above which core darkening can be expected (Yeo & Smith 2004, Liu 2011), and for beech were 37°C appeared to be a critical level (Paper V).
Discoloration by temperature is commonly an evenly distributed phenomenon in beech and birch, where the colour gradually changes with no distinct borders between different areas in the wood. The core of a board is typically darker than the outer rims, possibly as a result of longer exposure under moist conditions and gradually elevated temperatures as the drying process progresses. Temperature-related discolouration of European oak (*Quercus robur* L., *Q. petrea* Liebl.) is on the other hand characterised by irregular brown spots and stripes which penetrate from the surface and board ends (Schmidt 1986, Wassipaul et al. 1987, Fortuin et al. 1988a,b), Figure 24. This macroscopic discoloration, referred to as brown discoloration, is caused by water-insoluble dark brown substances in the parenchyma cells assumed to be the result of polymerisation of wood extractives, particularly ellagitannins (Wegener & Fengel 1987). The process is enhanced by a higher temperature and a high oxygen level and can occur without the involvement of enzymes (Charrier et al. 1995).

*Figure 23: Influence of drying temperature on the change in lightness, ΔL*, of 70×70×10 mm samples at 5 mm distance from the surface, papers IV and VI.*
Figure 24: Brown discoloured oak heartwood (*Quercus robur* L.) 30×81×325 mm flooring component, sampled after 21 days of drying at 50°C and 85% RH with air speed of less than 0.5 m/s, average MC 25%. Samples sliced perpendicular to the grain in 20 mm increments from the unprotected end-surface (right) to the centre (left), MC in bright sections 30%. Paper IV.

4.1.1 High-temperature press drying

High-temperature drying, at temperatures exceeding 100°C, influences all wood components where losses in mass and strength as well as changes in sorption behaviour start to occur (Košiková et al. 1999). At temperatures above 150°C, major changes also occur in the wooden component (Sundqvist 2004).

Figure 25: Press-dried Silver birch (*Betula pendular Roth.*) components 300×80×36 mm dried from green to 10%. Centre control dried in a room climate, Paper II.
The colour response of birch to hydrothermal high-temperature treatment is dependent on the temperature as well as the time. At temperatures between 95 and 200°C, the same lightness level can be achieved by selecting suitable treatment time (Sundqvist 2004). The level of saturation of the surrounding steam has also been reported to influence the colour of birch, increased saturation turns the wood darker (Torniainen el al. 2011). Colour changes at high temperatures may involve other wood constituents than the extractives (Kollmann & Fengel 1965, Tjeerdsma et al. 1998).

Temperature is the factor that have the greatest influence on the colour of birch when press drying at temperatures between 105 and 250°C, Figure 25, paper II. Fast drying at high temperatures results in a brighter colour. Similar findings have been reported for the microwave drying of birch (Antti 1999). The press plate temperature is mainly decisive for the rate of heat transfer. The interior of the wood stays below 100°C for a considerable part of the drying process until the mass transfer is reduced as the wood dries below the fibre saturation point (Hittmeier et al. 1968, Wang & Beall 1975). The formation of a discoloured layer 1 mm below the surface was noted when birch was press-dried at a temperatures of 250°C Paper II, similar in appearance to kiln brown stain. Specks of what appeared to be caramelised sugar were also noticed on these samples.

4.2 Relative humidity

Relative humidity (RH) is a directly controllable parameter, but there are practical limitations in industrial drying. In kilns where the drying air passes over several boards before being regenerated, the timber is exposed to different RH levels depending on the location of the board in the kiln. This effect is enhanced when low air speeds are used, which is common practice in hardwood drying.

The relative humidity in the kiln drying process parameter influences the colour of dry wood where relative humidity reduces the lightness of the dry wood (Kollmann et al. 1951). Relative humidity is negatively correlated to the speed of drying and the development of drying stresses in the wood. Drying beech, birch and oak in a high RH and high temperature climate results in a general loss of lightness and the development of a more reddish in colour, Figure 26.
Drying hardwood at very low temperatures initially, in order to avoid a reddish discolouration, may result in another type of discoloration if the relative humidity is kept too high; an internal grey stain, Figure 27. This type of discoloration typically appears in the centre of a board resulting in brighter outer parts and darker core giving a striped appearance in the finished end product (Paper V). Internal grey stain is a common problem in the beech wood industry in connection with poor air drying or kiln drying in kilns not specially designed for drying below 40°C. Similar results have been reported by Forsyth and Amburgey (1991), who suggested that the discolouring globules found in the parenchyma cells are the result of non-microbial enzyme-mediated chemical processes naturally occurring in the wood.
Figure 27: Interior surfaces of beech (Fagus sylvatica L.) from 420×84×27 mm samples. Left: Samples dried in 26°C and 74% RH climate from fresh to 30% MC. Right: Samples dried in 26°C and 92% RH climate from fresh to 30% MC. Paper V.

Relative humidity is a parameter which influences other process parameters e.g. drying time. The temperature of the wood during the initial stages of drying also depends on the relative humidity, since the wood temperature is closer to the wet bulb temperature than to the temperature of the air. Drying speed, in particular above the fibre saturation point, is to a large extent controlled by the RH inside the kiln. Initial drying at temperatures below 35°C when the moisture-carrying capacity of the air is low can also be difficult to handle industrially. The drying air may become saturated too quickly, after passing only a few packages, and no drying will occur in the remaining packages in the kiln load. Likewise, the moisture removing capacity of the ventilation system is greatly reduced at low temperatures.

4.3 Moisture content

The initial moisture content (IMC) of the wood is a material characteristic depending on several factors such as: species, heartwood ratio, radial and axial location in the stem, logging season and pre-drying during log and timber storage. Only when the pre-dried timber is dried to a lower final MC can the IMC be controlled. The moisture content inside each board varies as a result of the initial conditions and the drying process itself. In many applications, the board dimension set limitations to the drying process from both a checking and a colour perspective. The risk of large MC gradients causing drying stresses which result in defects like checking and honeycombing are particularly great in the case of oak. Beech and birch are less sensitive to checking (Pratt 1986). Even so, drying timber with a steep MC gradient may
still be difficult. The phenomenon is particularly visible on thick boards where the outer rim typically has a lighter colour than the inner sections of the same board after drying (Thomassen 1986). In particular, the transition period, i.e. after the capillary transfer system has collapsed and before all the sections drop below the fibre saturation point (Wiberg & Morén 1999), is a period when colour changes develop asymmetrically.

The colour of dry wood, below 15-20% MC, shows little response to environmental parameters used in conventional kiln drying. In general, the moisture content is negatively correlated to the lightness of dry wood for the investigated species, as illustrated by birch in Figure 28. Thus, a low IMC results in lighter colours than a high IMC if the wood is exposed to the same climate conditions (Paper III).

![Figure 28: Lightness plotted against Initial Moisture Content for air-dried 20×100×700 mm birch samples dried to 15 % MC at 51°C and 75 % RH during 68 hours, paper III.](image)

### 4.4 Drying time

Drying time is the result of process parameters and material characteristics. Temperature, air speed and relative humidity are process parameters that influence the speed of drying. Material characteristics like board dimension, initial moisture content and species specific properties like permeability and density are also decisive for the processing time.
Time is negatively correlated to the lightness of dry wood for the investigated species, i.e. rapid drying reduces the risk of discoloration, Figure 29. The effect of time appears to be second only to that of temperature (Paper I, VI) but since it cannot be independently controlled it is of limited practical use for most applications. If the application of the wood allows for small dimensions, in particular regarding thickness, the effect of time can be efficiently utilized as for example in the drying of veneer. Air speed offers another way of controlling the time, at least in theory. High air speeds reduce the time of drying in the capillary phase. For most purposes however it mainly is a question of avoiding very low or uneven air speeds which increase the risk for discoloration by mould and blue-stain (Bauch et al. 1991) as well as grey stain in beech (Paper V) as a result of a local micro-climate with high relative humidity levels. A time influence is expected since time and temperature typically have an impact on chemical reactions. The effect is obvious on thick boards which usually have a different colour in the centre than close to the surface. Prolonged drying usually enhances any type of discoloration, whether it be caused by invading micro-organisms or a process-related transformation of natural constituents in the wood. Internal colour changes, detectable by a colour meter, were reported on 10 mm thick birch samples within hours of exposure to moderate temperatures, paper VI.
4.5 Air pressure

Air pressure is a controllable process parameter for industrial kilns only in vacuum chambers. In other types of kiln the air pressure or oxygen concentration is not regulated. During vacuum drying, most of the air is initially removed and most of the remaining air is later replaced by steam from the evaporation. The effect on the colour of hardwood of limited oxygen access during vacuum drying is not conclusive. Little or no discoloration has been reported for oak (Charrier et al. 1992), discoloration did occur in birch (Luostarinen et al. 2002). Arguments that sufficient oxygen sources exist inside the wood for oxidation to occur (Hon & Shiraishi 1991) may offer an explanation of these results. Results from high temperature press-drying of birch, comparing very rapid drying in partial vacuum and under normal air pressure, show that reduced air pressure led to lighter colours, Figure 30. Compared to controls dried in a room climate, did however, all samples became darker (Paper II).

![Graph showing lightness plotted against air pressure for 300/240×80×36 mm birch samples press dried at 120/170°C from fresh to 10% MC in less than 5 hours, paper II.]

**Figure 30:** Lightness plotted against air pressure for 300/240×80×36 mm birch samples press dried at 120/170°C from fresh to 10% MC in less than 5 hours, paper II.

4.6 Temperature, relative humidity and time

Temperature, relative humidity and moisture content have all been pointed out as important parameters affecting the colour of wood in connection with drying (Kollmann et al. 1951).
As for many of the suggested colour-controlling factors (McMillen 1976, Luostarinen & Loustarinen 2002, Yeo & Smith 2004), the combination of the different process parameters has the major influence on the end result.

As earlier mentioned, temperature has a great influence, particularly if combined with high RH which reduces the speed of drying and thereby increases the time the wood spends in the sensitive MC interval. Even moderate temperatures of 40°C may lead to darkening and reddish discoloration in beech and birch if combined with a high RH, as illustrated for beech in Figure 31. Drying at very low temperatures, below 30°C, in combination with high RH provides no protection against discoloration however, Figure 31. Similar findings have been reported for other hardwoods (McMillen 1976, Straze et al. 2003). During the experimental drying in papers I and III, it was noticed that reference samples dried slowly in a room climate became darker than several of the samples dried at higher temperatures. This indicates that drying time under some conditions, even at low temperatures, may have more effect on the colour than the temperature. Findings in paper V confirmed this, when beech dried at 26°C and 92% RH from green, average IMC 76%, to 30% MC developed a dull grey appearance.

**Figure 31:** Colour response to the drying climate; temperature and equilibrium moisture content (EMC) of 27×87×750 mm beech wood samples dried from green to 30% MC in a constant climate, Paper V.
Results from papers V and VI indicate that, if the EMC is kept below 15%, beech can be dried at temperatures up to 37°C and birch up to 40°C without any visually detectable discoloration to the wood, Figure 32. McMillen (1976) suggested a similar strategy for avoiding discoloration on hard maple. An EMC level of 15% corresponds to approximately 80% RH which is an initial drying humidity that many hardwood species of conventional timber dimensions may withstand without high risk of checking, with the exception of thick oak. Moderate temperatures in combination with low RH will also result in shorter processing time and thus reduced operating costs.

### 4.7 Temperature, time and moisture content

The effect of temperature on the colour is relatively limited at low MC levels (McMillen 1976), although the same temperature would lead to severe discoloration at high MC levels. In paper I, the drying temperature was identified as the major factor controlling the lightness, saturation and hue, rather than the IMC, RH and drying time under the investigated conditions. An increase in temperature resulted in a loss of lightness and the colour became more saturated and reddish in both beech and birch, Figure 33.
While temperature was the primary factor, time, represented by the sample thickness, was found to be the second most influential factor contributing in a similar way but with less than 50% of the effect of temperature in paper I. Both beech and birch respond in a similar way to the respective process parameters. In paper I, the initial moisture content had a rather small effect on the final colour, indicating that major colour changes occur in the 20-30% MC interval, supporting earlier findings by Thomassen (1986) and Loustarinen et al. (2002).

Further investigations on birch in paper III using commercial board dimensions with considerably longer drying times show that elevated temperatures in the capillary drying phase 80-55% MC led to an increase in the lightness $\Delta L^* = 1.6$, Figure 34, presumably a result of the 27% shorter drying time at a 10°C higher temperature and supporting findings by Sundqvist (2002a) who identified time as being more important than temperature in the capillary drying phase in the 70-90°C interval.

In the mixed and diffusion stages of the drying process, the influence of sample MC on lightness increased. High temperature in combination with elevated MC in the 20-55% MC interval increased the risk of a lightness reduction, paper III. Colour change at MC levels below 15-20% are limited (Loustarinen & Loustarinen 2001), but this is valid for the local MC not the average MC. Depending on the MC gradient, where the MC increases from the surface towards the middle of the board, different separate layers of the same board react differently depending on their distance from the surface. As soon as a layer close to the surface has dried below the FSP, the colour changing reactions slow down dramatically, as illustrated in Figure 35 where wood at a depth of 1 mm below the surface shows little response to elevated temperatures when the average sample MC has fallen below 30%, paper VI.
Figure 34: Lightness after kiln-drying plotted against temperature in the capillary phase for 32×100mm birch samples, average values indicated by horizontal bars, paper III.

At the same time, the core of the sample, where the local MC exceeds the FSP is still sensitive to increasing temperature, as illustrated at a depth of 5 mm in Figure 35. Results in paper VI indicate that lightness-reducing in birch mainly develop when the local MC exceeds the FSP.

Figure 35: Influence on lightness reduction of exposure to a drying temperature of 50°C drying temperature in distinct moisture content intervals during drying of 70×70×10 mm birch samples at 9% EMC, Paper VI.
This appears not to be due to the transformation of uncoloured precursors, created at high MC levels e.g. by enzymatic activities, that may later develop into coloured substances in the wood through oxidation in lower MC intervals if the temperature is increased (Smith & Herdman 1996, Wengert 1997, Möttönen & Luostarinen 2005). Darkening of birch appear rather to develop within hours if the wood is exposed to elevated temperature in the 50-25% MC interval, paper VI.
5 CONCLUSIONS

The main purpose of this work has been to increase the understanding of when and how colour changes occur during the drying of beech, birch and oak. The ambition is to utilize this knowledge, together with other related studies, to generate strategies and methods for how to control the colour during drying and in the end to give hands-on advice to the industry. The main conclusions of this study are that:

• Winter and spring storage of logs is not a major risk factor for the hardwood industries in the Nordic countries. Supply chain optimization may consequently be done without risk of obsolescence during the cold season.

• Slow drying, as a result of high relative humidity or poor air flow, even at very low temperatures shall be avoided in order to minimize the risk of dark interior discoloration. This applies both for air and artificial drying.

• The risk of dark and reddish discoloration of beech and birch is imminent as long as the MC exceeds 20%. The best way to avoid this is swift drying, using low RH, at a low to moderate temperature. The drying climate must be balanced with timber and kiln properties a low temperatures alone is not the most cost-efficient way. Drying temperatures up to 37°C in beech and 40°C in birch may be applied without notable discoloration if the equilibrium moisture content of the air is kept below 15%.

• If a reddish colour is desirable for beech and birch the drying process may be initiated and conducted at a high temperature level which shortens the process time and save the costs of pre-steaming.

• Pre-steaming of oak reduces the risk of dark-brown discoloration, but the method does not offer a general solution to the problem. However since the treatment also reduces the risk of end checking, the method is recommended when drying oak components.
• If a light colour is desirable for oak heartwood shall low temperatures be used during the initial drying stages, a general darkening of the wood can be expected at temperatures above 50°C.

• The macroscopic colour changes in birch, caused by the conversion of naturally occurring substances in the wood into coloured compounds is not due to the active precursors created at high MC levels during the subsequent drying at lower MC levels. The creation of coloured compounds may occur within hours in beech and birch if the wood is exposed to elevated temperatures while having a high MC.

5.1 Industrial applications

Parallel to laboratory drying experiments, of which some have resulted in the appended publications promising test results have also been evaluated industrially on a full scale. While laboratory trials may be challenging with respect to the function of equipment, handling of samples etc., conditions during industrial trials are much more difficult to control. The scale of operation, drying batches of 25-300 m³ of wood, leads to variations caused by factors such as log storage, cutting pattern and wet timber storage even before the drying process has been initiated. During the actual drying process, factors such as location in the kiln, air flow variations, technical limitations of the kiln and disturbances in energy supply may increase the variation of the process. Since the timber in a full-scale batch typically represents a considerable economic value to the industrial partner, process development is based on a more moderate step by step approach than explorative laboratory trials.

5.1.1 White birch drying

Reducing the time for drying birch without causing dark or reddish discoloration to the timber has been a general objective for several of the industrial partners. Results in papers I, III and VI all indicate that time has a greater influence than temperature on the lightness of birch at high MC levels. In an attempt to utilise this effect, several kiln schedules were designed and tested in industrial convection-type chamber kilns. Kiln schedules were based on a high-low-high temperature design where the first high level was 10-15°C above the low level and the second high level corresponded more to conventional kiln schedules. The process started with an elevated temperature phase directly after the heating-up phase. This elevated temperature phase continued until the average MC of the kiln samples was below 55%. At that time the temperature was reduced to 33°C and kept at this level until an MC of 20-25% was reached when temperature was allowed to increase again gradually. The schedule and climate in this type of process can be seen in Figure 36. The high-low-high temperature approach was unsuccessful for conventional batch kilns. The principle depends on fast drying, which the
initial capillary drying phase requires a low RH. Although a high temperature in the first stage is beneficial for creating a low RH inside the kiln, it only succeeds for the outer packages of the kiln load. Wood in the middle packages, in the centre of the kiln load, still experiences high RH, as a result of the blowing depth. None of the kilns was capable of increasing the air velocity above 3 m/s which would have been helpful in reducing the effect of the blowing depth. In addition, when entering the low temperature stage it was obvious that the kilns were ill equipped regarding air shifting capacity. Not until the temperature was increased again did the climate reach the set values as can be seen in Figure 36. This appears to be a common problem in the industry, since many kilns are designed to operate between 40-70°C. Only a few kiln manufacturers in Europe design kilns with sufficient air shifting capacity for operation at low temperatures. The result of the two practical studies of full-scale kiln operation, was that the lightness of the outer edge packages was higher than that of the middle packages of the kiln load.

![Figure 36: Example of kiln schedule and climate trend in the industrial drying of 32 mm unedged birch from green to 8% MC using a high-low-high temperature schedule.](image_url)

The findings in paper VI laid the ground for more successful trials with low-high temperature schedules where the birch was initially dried at 37°C and 75% RH while keeping the low temperature but gradually reducing the RH until the MC of the wood reaches below 30%, while carefully monitoring that the moisture evacuation capacity was not exceeded. The temperature was then gradually increased to the limit of what the kiln’s fan motors could withstand, typically 70-80°C. This approach resulted in a colour similar to
that of the previously used low-high temperature schedules, where temperatures below 30°C were used but with a 30% shorter cycle time.

The general recommendation for drying birch without risk of notable darkening is either to keep the temperature below 30°C or to use moderate temperatures not exceeding 40°C in combination with a relative humidity below 75% during the initial drying from green to 25-30% MC. When the MC has reached a level below 15%, temperatures up to 80°C may be used.

5.1.2 White beech drying

The results in paper’s I and V gave a good insight into the problems causing grey stain on non-steamed white beech. For industries that dry beech a single step from green (70-80% MC) to a furniture dry level (7-9% MC) the same schedule as for birch has been successfully used. The moisture-removing capacity of a kiln has in some cases been improved by rebuilding the evacuation vents or installing additional dehumidifiers. For other industries which dry their timber in two stages the knowledge resulted in modifications to their shed drying, forced-air drying and pre-drying operations with a focus on avoiding a high RH.

General recommendation for drying of non-steamed beech and to avoid red and grey discoloration is to dry the wood at temperatures not exceeding 37°C and avoid relative humidity levels above 75% when drying from green to 30% MC. When the MC has reached a level below 15% temperatures up to 80°C may be used.

5.1.3 Simplified red beech drying

The production of pre-steamed red beech with its traditional pink-red tint typically involves a short steaming in a special steaming chamber or a longer steaming period in the kiln. This procedure increases the cost and requires an extra handling operation if external steaming chambers are used. Steam is also costly to generate since extensive pre-treatment of the water and high pressure boilers are required. Results in papers I and V showed that if beech is dried at high temperature and high RH the wood develops a colour similar to that of pre-steamed beech. Traditional kiln schedules for beech typically begins at 40-45°C (Pratt 1986, Trübswetter 2006), where the desired colour change develops but rather slowly. In order to secure an adequate colour modification and minimize the risk of mould growth, a wet temperature of 55°C was instead selected, Figure 37. The final drying temperature was determined by the limits of the kiln, in this case 80°C. Kiln drying at temperature higher than the conventional also resulted in an approximately 25% shorter processing time and reduced the risk of checking. This principle works best for sawmills which produce volumes sufficient to fill one chamber without long pre-storage of wet timber. Air drying during pre-storage may otherwise reduce the sensitivity to the desired colour modification, resulting in uneven colour in
different parts of the batch. This drying principle has successfully been practiced since 2005 industrially.

![Figure 37: Climate trend in the industrial drying of 28 mm beech from green to 8% MC.](image)

### 5.1.4 Oak drying

Compared to beech and birch, the drying of oak is a more challenging operation, mainly due to the significantly higher risk of checking, but discoloration may also be a problem. For oak heartwood there are in principle three common types of discoloration that the industry is facing; iron stain, yellow and brown discolouration. Iron stain can be reduced by ensuring that the wet wood does not come into direct contact with steel surfaces e.g. by protecting steel surfaces by paint and replacing wear and friction parts of steel with plastic. Iron stain on sawn timber is in many cases only a minor problem since the sawn surfaces are generally machined on the dry timber. Yellow stain is related mainly to poor air drying conditions and can be reduced by improved air drying, forced air drying or kiln drying using sufficiently high air speeds. Mould-infected stickers should not be re-used without sanitizing. The occurrence of brown discolouration can be limited but not avoided by initiating the drying process at low temperatures. If steam is available in the kiln, a short pre-steaming in direct connection to the drying may be beneficial for reducing the level of brown discoloration in the wood as well as for reducing end checking.

A general recommendation for drying oak to reduce the risk of brown discoloration is to use pre-drying at a temperature not exceeding 35°C or air
drying at 20°C when drying from green to 25% MC. Thick boards \( \geq 50 \text{ mm} \) may be dried at temperatures below 30°C since they require a high humidity climate in order to avoid checking. Yellow discoloration can be avoided by using sanitized dry stickers and air speeds that exceed 1 m/s in combination with relative humidity levels not exceeding 80%. This humidity level is unfortunately not suitable for thick board dimensions where chemical mould inhibitors may be required. When the average MC has reached a level below 15%, temperatures up to 90°C can be used without notable discoloration.
6 REFERENCES


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