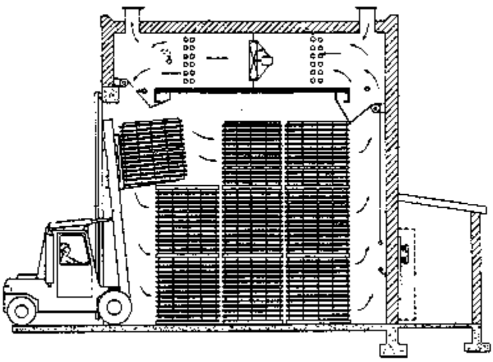
Optimized Wood Manufacturing with Main Focus on Wood Drying

by

Peter Carlsson



Doctoral thesis
Östersund and Stockholm 2000

Abstract

Optimization is performed on two applications from wood manufacturing, with the main focus on wood drying. As an introductory study of optimization, the design of a modern racing ski is investigated. The skating ski, which is partly built up by wood, is optimized against maximum stiffness with the restriction of a limited upper weight.

Wood drying is treated as an optimization problem. The total drying time is minimized, at the same time as restrictions on moisture content, stresses and deformations are considered. The outcome of the optimization is drying schedules which describe the environmental air dry temperature and relative humidity as a function of time. Design variables during optimization are the length of the individual time steps and the air dry temperature and relative humidity connected to each time step. Convex approximation methods are used for optimization (the so called MMA-method, Method of Moving Asymptotes). Necessary gradients are calculated with finite differences.

Optimization is performed with one- and two-dimensional (1D respectively 2D) moisture transport models. In optimization with 1D analysis, moisture content and stresses are calculated along a line in the middle of the board, and with 2D analysis the calculations are made in a numerical grid which covers the cross section of the board. In both cases, deformations are calculated as the global cup deformation. All structural calculations are made with a FEM-program (FEM = Finite Element Method) where the whole cross section is modelled with one single element. The moisture calculations are made with a FEM-program in the 1D-case, and with a FD-program (FD = Finite Difference) in the 2D-case. The transient solutions of the structural and moisture problems are obtained with a time stepping procedure. It is assumed that the moisture problem can be solved separately from the structural problem, i.e. that the stress and strain distribution during drying has no influence on the moisture transport.

The wood material is modelled as an orthotropic material with main directions in the radial, tangential, and longitudinal directions. Most material parameters vary with the main direction, the temperature and the moisture content. The total strain rate in the structural calculation is assumed to be the sum of the elastic strain rate, the moisture induced strain rate and the mechano-sorptive strain rate. It is possible to vary the dimensions of the board and the growth ring orientation (i.e. the pith position). In the two-dimensional model, it is also possible to simulate different distributions of sapwood and heartwood in the cross section.

Numerical examples are performed with both 1D and 2D analysis. In the last example with 2D analysis, optimization is performed as distributed computing with computers in a network.

The thesis shows that optimization methods work well for wood drying. Modern optimization routines offer powerful tools when constructing reliable drying schedules. The knowledge obtained in this work can be used to refine existing drying schedules, to develop schedules for new quality demands or to create schedules for drying kilns with improved performance.

Keywords: Optimization, wood drying, distributed computing, drying schedules, one-dimensional, two-dimensional, stresses, deformations, moisture content.

Thesis

This thesis deals with optimization of wood manufacturing. The main purpose with the work is to investigate if it is possible to treat wood drying as an optimization problem. The thesis comprises an introduction and six appended papers. Paper A also serves as an introduction to the optimization technique. The appended papers are:

Paper A
Optimization of a racing ski. 1995. Structural Optimization 10, pp 61-63,1995.
Peter Carlsson, Mats Tinnsten and Björn J.D. Esping.

Paper B
Optimization of the Wood-Drying Process. 1996. 5TH International IUFRO Drying Conference on Quality Wood Drying Through Process Modelling and Novel Technologies, Quebec Canada, Aug. 13-17, Proc. pp. 529-532.
Peter Carlsson, Björn J.D. Esping and Ola Dahlblom.

Paper C
Optimization of the Wood Drying Process. 1997. Structural Optimization 14, pp 232-241,1997.
Peter Carlsson and Björn J.D. Esping.

Paper D
Optimization, a Tool with which to Create an Effective Drying Schedule. 1998. Holzforschung, Vol 52, 1998, No. 5, pp 530-540.
Peter Carlsson, Björn J.D. Esping, Ola Dahlblom, Sigurdur Ormarsson and Ove Söderström.

Paper E
Optimized Wood Drying. 1999. 6th International IUFRO Drying Conference on “Wood Drying Research & Technology for Sustainable Forestry beyond 2000”, Stellenbosch, South Africa, Jan 25-28, Proc. pp 139-147. After a slight revision accepted for publication in Drying Technology Journal (publication is planned to vol.18, No 8, 2000).
Peter Carlsson and Jesper Arfvidsson.

Paper F
Distributed Optimization with a two-dimensional Drying Model of a Board, built up by Sapwood and Heartwood. 1999. Submitted to Holzforschung
Peter Carlsson.

Contents

1. Introduction **1**
1.1 Objective 2

2. Wood Drying, Wood Structure and Wood Physics **4**
2.1 Wood drying 4
2.2.1 Short history and overview *4*
2.2 Wood structure 6
2.2.1 General *6*
2.2.2 Wood structure and wood properties related to drying *7*
2.3 Moisture and moisture transport in wood 10
2.3.1 Moisture transport *10*
2.4 Strength, stresses and deformations during drying 11
2.4.1 Strength and its dependence of moisture content and temperature *12*
2.4.2 Stresses and deformations during drying *12*

3. Optimization **14**
3.1 Formulation of a general constrained optimization problem 14
3.1.1 Design variables *15*
3.1.2 Constraints *15*
3.1.3 Objective function *16*
3.2 The solution process 17
3.2.1 A general optimization algorithm *18*
3.2.2 Solving approximating subproblems *19*
3.2.3 Convergence and accuracy *21*
3.3 Practical example from optimization of a racing ski 21

4. Optimized Wood Drying **23**

5. Results from the Present Research **25**
5.1 One- and two-dimensional analysis during optimization 25
5.2 Optimization with one-dimensional analysis 25
5.2.1 FEM program for moisture transportation *25*
5.2.2 FEM program for structural problem *26*
5.2.3 Optimization *27*
5.3 Distributed optimization with two-dimensional analysis 29
5.3.1 Finite difference program for moisture transportation *29*
5.3.2 FEM program for structural problem *30*
5.3.3 Distributed optimization *30*
5.4 Applications 33

6. Discussion and Conclusions **35**

7. Future Development **37**

8. References **38**

9. Appended Papers **41**

1. Introduction

Optimization can be described as the act of obtaining the best result under given circumstances. The origin of optimization methods can be traced back to the days of Newton, Lagrange and Cauchy, but the great progress of practical methods started with the development of modern, high-speed computers. In its broadest sense, optimization can be applied to solve almost any engineering problem, see e.g. Arora 1989, Fletcher 1987, Rao 1996.

Typical applications for optimization in the wood-working industry are planning of transfer lines in plants, design of arches of glued laminated timber, design of chemical processes in paper mills etc. In this work optimization is performed on two applications from wood manufacturing. An introductory study of optimization is carried out on a modern racing ski. The skating ski, which is partly built up by wood, is optimized against maximum stiffness with the restriction of a limited upper weight. The main focus is, however, on wood drying. The drying process is a bottleneck in the production of a modern sawmill. Since it is both a time- and energy-consuming process, great benefits can be achieved if wood drying can be done more effective. Great values are also at stake. Badly performed drying might lead to quality degradation of first class timber. Incorrectnesses as checks, discoloration, uneven stress distribution etc. will lower the profit.

Modern kilns with increased temperatures and controlled, fan driven air streams have brought new possibilities to high quality drying; a brief overview over the field is given in Söderström 1996. It is therefore of great interest to develop optimized drying schedules. Traditionally drying schedules have been developed by trial and error in combination with experience from years of practical drying. The experimental way of developing drying schedules is both expensive and time consuming, but for many years, this has been the only way to improve drying schedules. Although the governing equations for moisture transport and stresses and deformations during drying have been known for a long time, analytical solutions considering the structure of wood have not been available. However, numerical methods in combination with fast computers make it possible to perform simulated wood drying. From a given drying schedule, it is possible to calculate the moisture distribution together with stresses and deformations at any moment of the drying process (the agreement with reality is of course dependent of the quality of the underlying analysis and material data).

Difficulties occur when the simulated drying result is not satisfying. The moisture content might be too low in some parts of the board after drying, and the stress levels too high during the initial steps of the drying process. How should the drying schedule be changed to correct these shortages without causing any new? Even a rather simple model of a drying schedule consists of several variables, and it is almost impossible to do the right adjustments manually, i.e. to do the proper variable corrections in the drying schedule.

Here mathematical optimization methods come to our help (the often seen term "programming" is synonymous with optimization. Originally programming was used to mean optimization in the sense of optimal planning). Compared with traditional analysis, optimization offers a backward calculation. If we talk in general terms, traditional analysis answers the question: "Is the design satisfactory?", while optimization answers the question: "What should the design look like if we want it to satisfy these demands?".

The differences between conventional design and optimized design can schematically be described as shown in Fig. 1. Traditional design depends on the designer's intuition, experience and skill. In optimum design, the designer's essential work is to identify the design variables, the objective function to minimize, and the constraints to satisfy (the process is of course simplified here, the designer's intuition and experience are still important for evaluation of the design proposed by the optimization process). The automatic optimization process works in an iterative way, and the process goes on until it converges, i.e. until the difference between two following designs is small enough. Modern optimization methods have no problems to handle hundreds of variables and thousands of constraints. This means that rather large models can be built up and processed on computers.

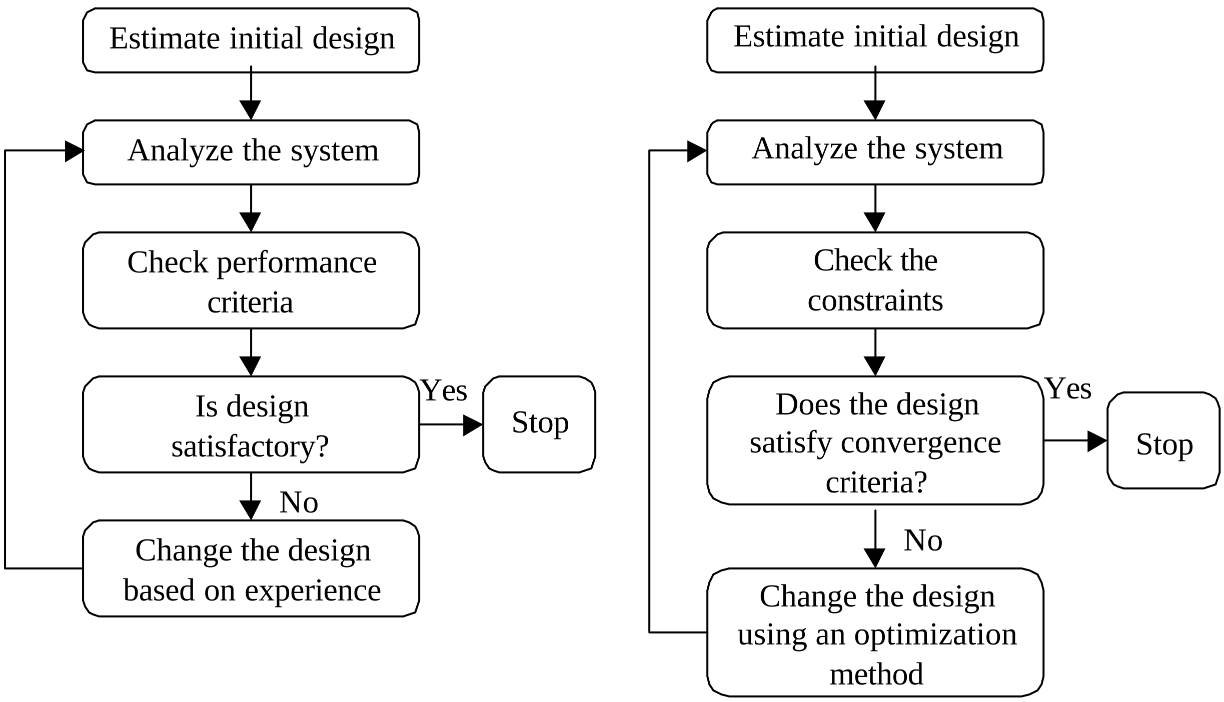


Fig. 1. Conventional design process versus optimum design process (adapted from Arora 1989).

What are the benefits of the optimization technique in wood drying? Since software for simulation of moisture transport and development of stresses and deformations during drying already exist, it might be a good idea to connect these programs with some effective optimization routine. And if optimization works well also for wood drying, we would then be able to answer the more qualified question: 'What should the drying schedule look like if we want to dry boards to this quality?' instead of solely answer the question: 'What is the drying result with this schedule?'. The answer of the former question is of course superior to the answer of the latter.

1.1 Objective

The main purpose with this work is to see if it is possible to treat the wood drying process as an optimization problem. The goal with the optimization is to determine the optimal environmental air dry temperature and relative humidity of the air in the drying chamber; i.e. air dry bulb temperature and relative humidity as a function of time. The intention is to produce a board with moisture content within a certain upper and lower level. The deformation and surface check intensity, i.e. relative check length, must also be under control. In this work, the stress levels during drying are used as a measure of the tendency for checks.

The optimization problem for wood drying is in loose terms formulated as follows (with some variations in different numerical examples):

Find a drying schedule that (the objective function)

- Minimizes the total drying time

such that (the constraints)

- Moisture content and deformations are within an upper and lower level after drying
- Stresses are below a certain level during the whole drying process

Upper and lower limits are also given to the air dry temperature and the relative humidity, and, in some cases, also to their rate of change per hour.

2. Wood Drying, Wood Structure and Wood Physics

2.1 Wood drying

Most timber, whether hardwood or softwood, is dried before it is used. There are many reasons for drying; it gives reduction in weight with a following lower energy consumption during shipping and increased mechanical properties as strength and hardness. Other advantages are improved paintability and increased resistance against wood-destroying fungi, blue stain etc. And if green wood is used before it is dried, it will slowly dry anyhow until it is in equilibrium with its environment. Besides problems with surface conditioning and deterioration etc., such unplanned drying also gives problems with deformations and checks.

Depending on later use, timber is dried to different levels of moisture content[1] (M). Boards in heated interior rooms must be dried to a moisture content of 10-12%, while 18-20% is satisfactory for timber in outdoor use.

Green wood contains a lot of water. In the outer parts of the stem, in the sapwood, spruce and pine have an average moisture content of about 130%, and in the inner parts, in the heartwood, the average moisture content is about 35%. Wood drying is the art of getting rid of that surplus water under controlled forms

2.1.1 Short history and overview

The benefits of wood drying have been known for a very long time. As early as 735 BC warm gases from burning wood were used to dry timber, a method still in use for small kilns at the beginning of the 20th century, Esping 1992.

Air-drying was the dominating method for wood drying at the beginning of the 20th century. It seems to be a cheap way of drying, but the method has several drawbacks. The drying time might be up to a whole year, and if the weather is bad, great quantities of the timber might loose in value because of quality losses. Other drawbacks are high capital cost during drying and a minimum achieved moisture content of about 20%, a moisture content which is satisfactory only for outdoor use of the wood.

In order to reduce the drying time and reach lower moisture content, large drying kilns with heated, self-circulating air were developed at the beginning of the 20th century, Gyllenswärd 1985. Problems with varying drying conditions in different parts of the chamber lead to kilns with fan driven air streams at the beginning of the 1920's. Since waste products from the saw mill can be used as fuel for the heating, the improved drying quality and the up to 50 times faster turnover could be achieved with a rather low cost.

[1] Moisture content, M (in percent) is defined as:

$$M = \frac{\text{weight of water in wood}}{\text{weight of totally dry wood}} \cdot 100$$

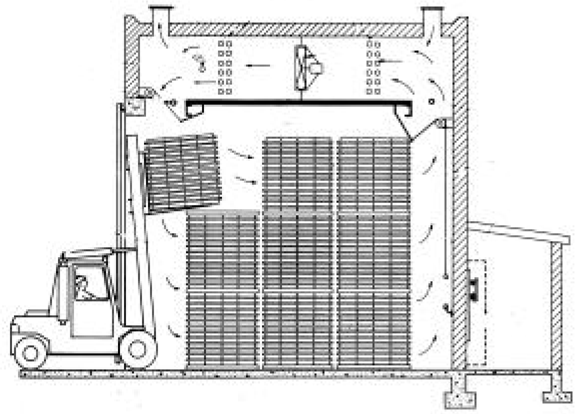


Fig. 2. Batch kiln (adapted from Simpson 1991).

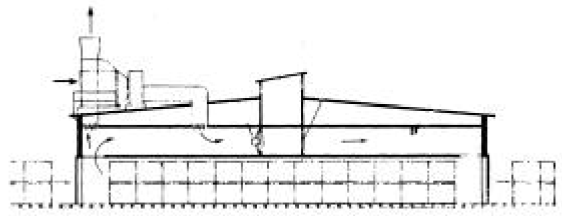


Fig. 3. Progressive kiln (adapted from Esping 1996).

The new kilns were soon divided into batch kilns and progressive kilns, see Fig. 2 and 3 above. The batch kiln is completely charged with timber in one operation and the timber remains stationary during the entire drying cycle. The progressive kiln is typically loaded with green wood in one end. During drying the timber moves slowly forward and after about one week the dry timber is removed from the other end. Generally the batch kiln gives better control over the drying process.

Somewhere about here we are in Sweden today. The basic functions remain the same also in modern dry kilns, even though they differ in working temperatures, heating system, building materials, air-circulation systems and equipment to control the drying conditions. It is still circulating air of controlled temperature and relative humidity that does the work during drying. Heat is carried by the air to the wood to bring about evaporation and the evaporated water vapour is removed by the same air.

This work deals only with conventional-temperature kilns, i.e. kilns that typically operate in a temperature range of 40 to 75 ^{o}C. This is the dominating way to dry timber in Sweden. High-temperature kilns which operate with temperatures over 100 ^{o}C are frequently used in Australia, New Zealand and USA, but are not commercially used in Sweden. High-temperature kilns have lower energy consumption than normal kilns during drying, and give much shorter drying times. The method has high demands on the building materials and among the disadvantages can be mentioned discoloration, loosening of knots and suspected degradation of mechanical strength. But for simpler purposes such as timber for building construction material, the method will probably be used also in Sweden in the future.

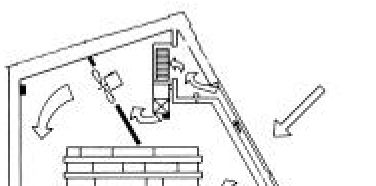


Fig. 4. Solar-kiln (adapted from Simpson 1991.

The raised energy prices in the mid-1970s lead to increased interest for solar dry kilns, see Fig. 4. They are cheap to run but since the maximum working temperature is about 55 ^{o}C, it is not a suitable method for large-scale drying (specially not in combination with Swedish summers). Solar drying is mainly used in warm, underdeveloped countries.

Vacuum drying was used for drying rifle butts as early as in the middle of the 19th century. Vacuum drying is much faster than conventional kiln drying but it is still a rather expensive way of drying. However, the method is motivated for thick, high-valued or hard species of hardwood, combined with danger for discoloration. Characteristic for the method is that the lowered boiling temperature of water in a partial of vacuum allows free water to be vaporised at temperatures below 100 ^oC.

In all the above mentioned drying methods, the wood is primary heated by convection. Microwave drying works in quite another way. Heat is developed inside the wood by the inter-molecular friction between the water molecules when they are exposed to microwaves. Drying is performed with low moisture content gradients which means low risks for checks. Microwave drying is rather expensive but high drying quality timber can be achieved for hardwood species like oak, beech and birch.

Among other, more unusual drying methods, immersing wood in heated organic liquids and press drying can be mentioned. In the first method the liquid is heated to a temperature over the boiling point of water, thus driving off the moisture. In press drying the wood is placed and pressed between two heated metal plates. The heat transfer from the plates is very effective and the wood can be dried without deformations. Press drying is also used for veneer drying.

2.2 Wood structure

2.2.1 General

If we define a tree as a plant with a length of at least 5 to 10 meters, there are totally about 12.000 species in the world. Of these trees about 500 are softwoods with their characteristic, needle-like leaves, while the rest are hardwoods with more normal leaves. Though the different species are often classified as softwood and hardwood, these terms are not directly associated with the hardness or softness of the wood. For example, the soft and fast growing Balsa tree is a hardwood. The softwoods are older as living organisms than the hardwoods, softwoods are about 200 – 300 million years old while the more complex hardwoods are about 100 million years old. For further information of wood and wood structure, see e.g. Kollman/Côte 1984, Haygreen and Bowyer 1994, and Rowell 1984.

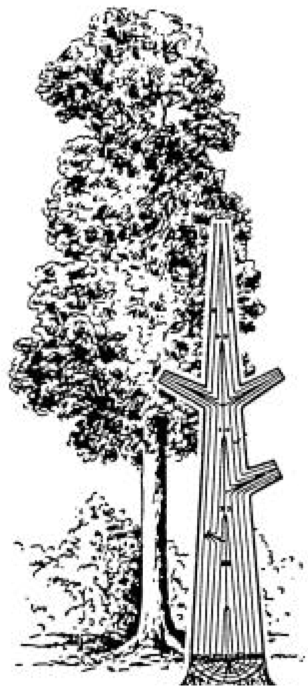


Fig. 5. Hardwood with intersection of stem (adapted from Esping 1992).

The big forests in the northern hemisphere, which has very few species, are mainly formed by softwoods. In Sweden and northern Scandinavia the dominating softwoods are Norway spruce *(Picea abies)* and Scots pine *(Pinus sylvestris)*. These two species are also the commercially most valuable, and the examples of wood properties given below refer mainly to these species.

2.2.2 Wood structure and wood properties related to drying

A living tree consists of root, stem and branches. Most of the wood material is located under the protective bark which covers the stem. The main directions in wood are termed radial (R), tangential (T) and longitudinal (L), see Figs. 6 and 8 (longitudinal direction is parallel to the stem). The radial and tangential directions are often called transversal directions since they have similar properties in many respects.

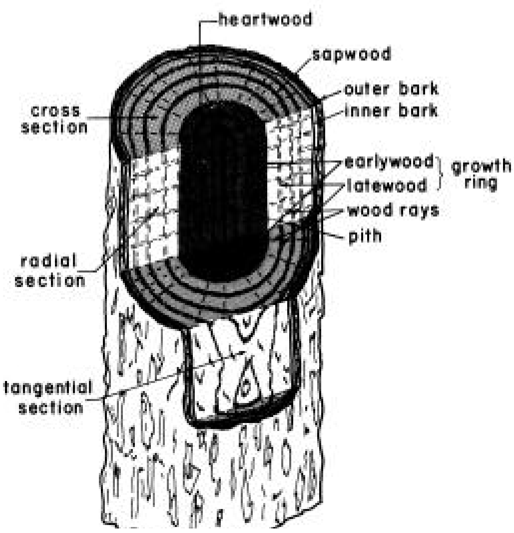


Fig. 6. Intersection of softwood (adapted from Bodig & Jayne 1982).

If we look at a cross section of the stem, several parts are visible for the naked eye, see Figs. 5 and 6. In the centre of the stem is the pith. It comes from the growing tip and it is built up by thin walled fibres. The wood close to the pith is called juvenil wood. It is built up by short, thin walled fibres with low strength. Both pith and juvenil wood crack easily during drying, and should therefore be avoided in boards.

The concentric growth rings are built up by earlywood and latewood, see Figs. 6 and 8. The brighter earlywood consists of thin walled fibres. It has a density which is only half or even a third of the density of latewood. The main function of the earlywood is to transport water from the root to the crown of the tree. The darker latewood has thick fibre walls and gives support to the stem. Latewood absorbs more water per volume because of its higher density. This causes latewood to shrink more than earlywood when it dries, a process which also gives a board its typical cup deformation after drying, see Figs. 7 and 9. Normal shrinkage values for spruce and pine are about 0.2% in L-direction, 4% in R-direction and 8% in T-direction (measured from green to totally dry conditions).

The orientation of growth rings to the face and edge of a board depends on how timber is cut from the log. The curvature of the growth rings varies in the cross section. Boards cut out from different parts of the log will therefore get different forms of deformation in the cross section after drying, see Fig. 7.

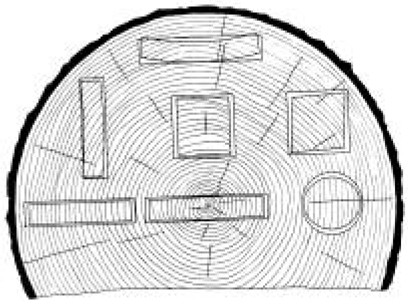


Fig. 7. Deformations (adapted from Simpson 1991).

When a tree grows, growth rings are laid to the tree as inverted, hollow cones, see Fig. 5. As seen in the same figure, a living branch normally starts at the pith. When a branch dies it will be an embedded knot in the stem which is slowly covered by growing wood. The fibres in a knot follow the main direction of the branch which means that wood with fibre directions almost perpendicular to each other will meet at a knot. Since the longitudinal shrinkage in the knot is much smaller the transversal shrinkage in the surrounding wood, there is a great risk for checks around a knot during drying, or even that the knot will drop out.

In a mature tree many species has a dark-coloured centre surrounded by a lighter coloured outer part, see Fig. 6. The dark inner part, the heartwood, is dead material and starts to develop when the tree is 20 to 40 years old. It is infiltrated with organic extractives as sugars, oils, fats, resins, aromatic and colouring materials and takes no active part in the water transport. The extractives in heartwood have a very small effect on the mechanical properties but make it more resistant to decay. The lighter outer part, the sapwood, has still living cells and many of them are active in the water transport. The sapwood is more permeable and dries faster than heartwood although its initial moisture content is higher in the living tree.

While the fibres transport water in vertical direction, the wood rays are responsible for the horizontal water transport in the stem, see Fig. 8. All wood have rays. In some hardwoods, like oak and beech, the rays are quite large and visible for the naked eye. In spruce and pine the rays are very narrow and hard to see even with a magnifying glass. The rays give some extra strength in radial direction which causes wood to shrink less radially than tangentially when it dries (the growth rings with varying density in earlywood and latewood have also an effect on this phenomenon). The great number of wood rays also explains the faster moisture transport in radial direction compared with tangential.

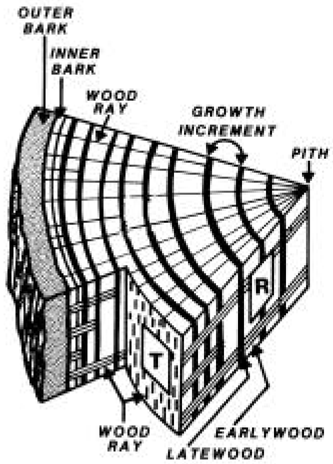


Fig. 8. Cross section of softwood with rays (adapted from Rowell 1984).

Between the fibres and other types of cells, different kinds of pits provide tiny passageways for the water flow. The pits perforate the cell walls and act like small valves. As long as there is free water in the fibres, the pits are open and the water moves easily between the cells. At lower moisture contents the pits will move to an aspirated position where they are “glued” to the surface of the pit border. This will strongly reduce the permeability of the wood.

Variations in structure as spiral grain or reaction wood affect the drying result. The fibres do not always follow the main direction of the stem. Spiral grain may cause twist during drying, see Fig. 9. Reaction wood occurs either as compression wood in softwoods or as tension wood in hardwoods. This special kind of wood is formed in a tree when it is brought out of its equilibrium position by an outside force. As an example, compression wood is formed on the lower side of a leaning softwood tree to meet the gravitational force. The stem (or the branch) develops eccentric growth rings, where the widest side of the eccentricity is composed of fibres with other properties and structure than normal wood. Among other differences, reaction wood has a much larger longitudinal shrinkage, and boards with sections of compression wood will get bow or crook deformation after drying, see Fig. 9. The corresponding phenomenon in hardwood is called tension wood. It occurs, for

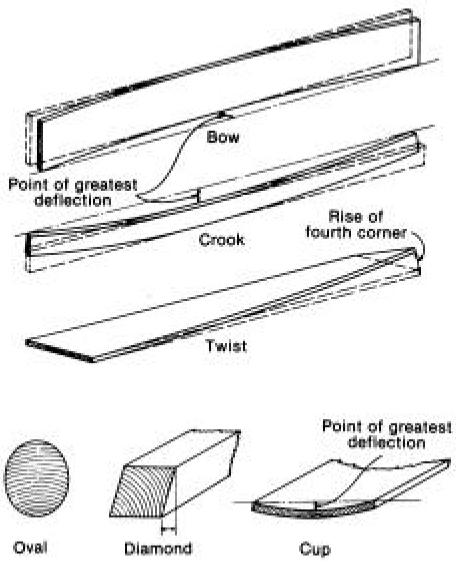


Fig. 9. Various deformation types (adapted from Simpson 1991).

example, on the upper side of leaning trees (the terms compression wood and tension wood are related to what kind of forces the wood tissue is formed to carry). The natural variability of a living tree makes it difficult to control the drying process in detail. Knots, density variations, disturbed growth rings and the above mentioned formation of reaction wood and spiral grain affect the drying result and thus the achieved drying quality.

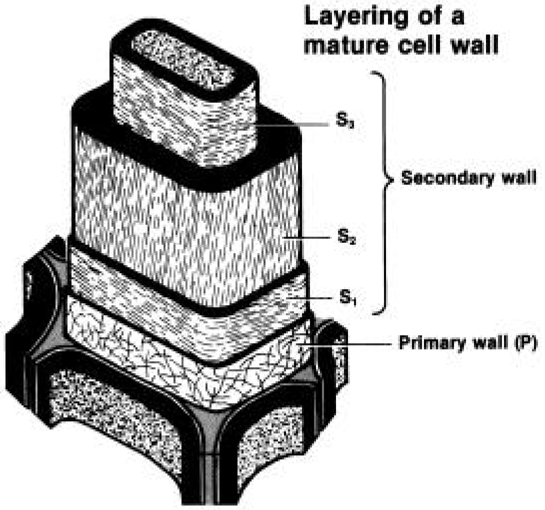


Fig 10. Fibre with cell walls (adapted from Haygreen and Bowyer 1994).

The whole tree is composed of different cells. The most common cell, the tracheid or fibre, is almost vertically oriented. About 90 – 95% of softwood is built up by these fibres. Between the fibres there is an intercellular layer which glues the fibres together The fibre has a cavity (lumen) in the middle and a cell wall which consists of several layers, see Fig. 10. The outer layer is called the primary wall. The inner layer, the so called secondary wall, is divided into three different layers termed S1, S2 and S3. The cellulose chains in the S1 and S3 layers are almost perpendicular to the fibre while the chains in the S2 layer are nearly parallel to the fibre. The S2 layer is thicker than the other layers, and most of the mechanical and hygroscopical properties come from that layer.

When water molecules diffuse into the S2 layer, its longitudinal cellulose chains are separated from each other and the wood expands in the transversal directions. The opposite occurs when water diffuses from the cell. Since S2 is the dominating layer, most of the hygroscopical movements are also in the transversal directions. An exception from this is the behaviour of compression wood. In such wood, the cellulose chains in the S2 layer have a slope of about 45^o from the longitudinal direction, and therefore the longitudinal shrinkage is of the same magnitude as the transversal. These big hygroscopical movements result not only in deformations, but also in checks in the areas where compression wood meets normal wood with less longitudinal shrinkage.

The vertically oriented fibres with lumen as water ducts, make moisture transport several times faster in longitudinal direction than transversal direction. But since the ends of a board have a small area compared with the faces and edges, the longitudinal moisture transport is of less importance during drying.

The organic constituents of wood are mainly the three polymers cellulose, hemicellulose and lignin. About 40 – 44% of the dry weight of normal softwood is cellulose, 20 – 32% hemicellulose and 18 – 25% lignin. Cellulose is the basic structural of the wood cell. It is a strong, long-chained linear molecule. Hemicellulose is believed to serve as matrix material for the cellulose chains. It is chemically more complex than cellulose and has a two-dimensional form. The third component, lignin, is a three-dimensional, highly branched structure. Lignin occurs between the cells as a glue to hold the cells together. Within the cell lignin is closely associated with cellulose and hemicellulose in the cell wall. Lignin gives rigidity to wood and is less hygroscopic than the other two components. A forth component is the extractives. The average content of extractives is about 3-6% in the stem of spruce and pine, but in the heart-wood the content might be much higher.

2.3 Moisture and Moisture transport in Wood

Water in green wood is found as free water in the cell cavities (lumen and other cavities) and as bound water in the cell walls. A more detailed information of moisture in wood is found in Skaar 1988, Siau 1995. There is also water in vapour form in the cell cavities, but it is normally negligible. When green wood dries, a lot of the free water in the cavities leaves the wood at the beginning of the drying process. It is not held as tightly to the wood as the bound water, and because of that it takes less energy to get rid of the water in the cell cavities than to evaporate the water from the cell walls. The point where the bound water starts to leave the wood is called the fibre-saturation point (M_f). It can be defined as the moisture content at which the cell cavities are empty of liquid water but the cell walls are still saturated with bound water, see Fig. 11. The moisture content of M_f is about 30% for spruce an pine.

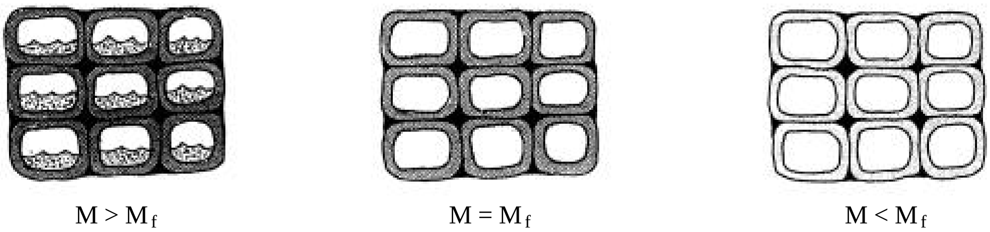


Fig. 11. Water in cell walls and lumen at different moisture content M (M_f = fibre saturation point, adapted from Saarman 1992).

During drying, most physical properties are not affected until the bound water starts to leave the fibres. When the bound water leaves the cell wall the fibre starts to shrink and the strength of the wood increases. Normally wood dries from the outside to the inside. Thus the outer parts of a board might be below M_f, while the inner parts still are over M_f.

2.3.1 Moisture transport

The moisture content in wood is continuously adjusted against changes in the environment. The point where the moisture content is in balance with the temperature and relative humidity of the environment is called the equilibrium moisture content (EMC). The relationship of EMC to relative humidity and temperature is shown in Fig. 12. There is a difference in EMC between adsorption and desorption of water. During adsorption, when water molecules diffuse into the wood, EMC is some percent lower compared to desorption. This phenomenon is called the hysteresis effect. Temperature affects EMC in that way that higher temperature gives a lower EMC at the same relative humidity.

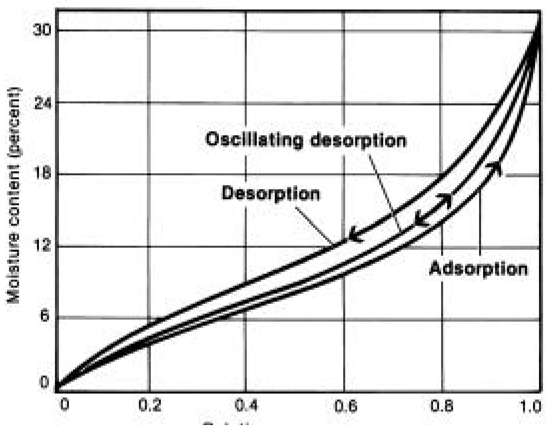


Fig. 12. Sorption isotherms of white spruce at 25 ^oC (adapted from Haygreen and Bowyer 1994).

At moisture contents over M_f water leaves the wood with about the same velocity in all directions. Below M_f the transport velocity varies with the main directions of the tree. Longitudinal diffusion is about 10 to 15 times faster than transversal diffusion. There are also some differences in transversal direction, the radial transport is because of the wood rays 1.5 – 2 times faster than the tangential transport. High internal temperature and high moisture content give a faster diffusion. The fast longitudinal water transport has normally a small effect on normal wood drying, but for knots it has a special importance. Since the knots have fibres almost perpendicular to the surrounding wood, they will dry much faster than the rest of the board.

The driving forces for water transport vary with different moisture content. At higher moisture levels capillary forces and pressure differences move the free water from the inner parts of the board to the surface. A lot of water is transported that way and the transport velocity is proportionately fast. At lower moisture levels, below M_f, the water transport is driven by differences in relative humidity for vapour transport and chemical potential for bound water transport (other potentials are suggested for bound water transport, see Skaar 1988). This diffusion dominated transport is slow. Generally wood with high density, i.e. wood with thick cell walls and small cavities, dry slower than species with low density. This is true both for drying above and below M_f. Heartwood has about the same effect on the drying velocity since the pits are often aspirated and a large portion of the cavities are infiltrated with extractives.

Temperature gradients during drying may also cause water transport in the wood, see Skaar 1988. While heating the wood at the beginning of the drying cycle (or during other temperature changes), the higher temperature at the outer part of the board transports the water in a direction opposite to the water transport caused by the moisture gradient. This water transport is normally negligible since the heat transport is much faster than the moisture transport, and the temperature induced transport is active only during a small fraction of the total drying cycle. At the beginning of the drying process, when the moisture content is over M_f and capillary transport is dominating, the temperature of the board surface is close to the wet bulb temperature. As drying advances, the surface temperature moves to the air dry temperature.

During drying the fibres on the surface of the board are usually in equilibrium with the surrounding air. If the air circulation is too slow, moisture on the surface of sapwood will not evaporate at the same rate as the water could be transported from the inner parts and drying will be slower than necessary. This is usually no problem during heartwood drying.

2.4 Strength, stresses and deformations during drying

In an idealised model, wood can be treated as an orthotropic material, see e.g. Bodig & Jayne 1982. This means that it has three symmetry planes perpendicular to each other. The modulus of shear and elasticity, moisture induced strain and mechano-sorptive strain[2] have all coefficients which vary with the symmetry directions in wood (i.e. radial, tangential and longitudinal directions).

[2] If a piece of wood under load is exposed to moisture content changes (as it is during drying), it will get a deformation which is much greater than the deformation under constant humidity conditions. That phenomenon is here called the mechano-sorptive effect, see e.g. Santaoja et al 1991, Salin 1992, Svensson 1997.

The density of a tree affects strongly the strength of the wood. High density means that internal forces can be distributed among more material. The density of the cell wall is the same for all species, i.e. about 1600 kg/m^3. Varying densities between different species reflect how big portion the cavities have in the wood.

2.4.1 Strength and its dependence of moisture content and temperature

Most mechanical properties increase at moisture levels below M_f (exceptions are toughness and pliability, Rowell 1984). Many of the properties increase exponentially as the moisture content decreases below M_f. The relationship can be expressed as

$$\frac{S_2}{S_1} = e^{-r(\frac{M_2 - M_1}{100})} \qquad (1)$$

where S_1 and S_2 are the magnitudes of a certain strength property at moisture contents M_1 and M_2 (moisture content in percent), and *r* is a coefficient that represents the percent increase in a certain strength property for a 1% decrease in wood moisture content M, Rowell 1984, Skaar 1988. The value of the coefficient *r* is about two for the modulus of elasticity and about six for compressive strength parallel to the fibres.

Temperature changes have about the same effect as moisture content changes. Most mechanical properties decrease when wood is heated and increase when it is cooled. Raised temperature in combination with high moisture content will make the wood more plastic. This has a great importance in kiln drying since drying at higher temperatures will reduce the risks for checks and level out the stresses. As long as the temperature does not exceed 100 ^oC, there is little permanent loss of strength in the wood.

2.4.2 Stresses and deformations during drying

Wood is not an ideally elastic material since mechanical properties of wood are affected by the length of time a load is imposed. If a piece of wood is loaded for a longer time, the deformation will not completely recover when it is unloaded. In Fig. 13 the beam has the deformation δ_2 when it is unloaded. After a while it has recovered to δ_1 but a residual deformation will remain even if it will disappear to some extent during the rest of the relaxation. Therefore wood is considered to be a viscoelastic material which means that it behaves both as an elastic material and a viscous (slow-flowing) liquid. The viscoelastic creep, together with the earlier mentioned mechano-sorptive creep, works together and level out unwanted stresses during drying. Among the two, the mechano-sorptive creep is dominating during drying, and without it, most timber would get damaged by cracks.

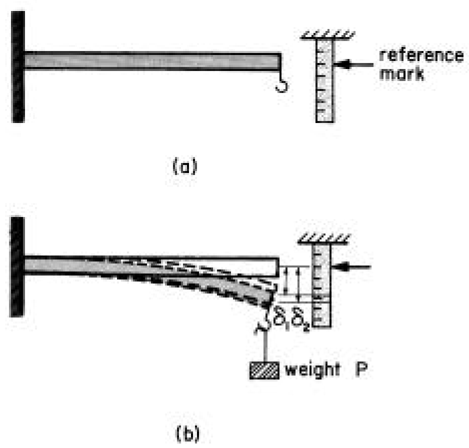


Fig 13. Unloaded beam (a) together with loaded and unloaded beam with residual deformation (b) (adapted from Bodig & Jayne 1982).

When a board dries, the outer parts will start to shrink before the inner parts of the board. Thus the shell of the board will get tension stresses at the beginning of the drying process, while the core will get compression stresses. There is a risk for surface checks at this early stage. As drying goes on, the water also leaves the core. The shrinkage of the core is, however, prevented since the shell has been permanently expanded due to creep caused by the tension stresses at the beginning of the drying cycle. The stresses will then be reversed, the core will get tension stresses and the shell compression stresses.

Hydrostatic stresses develop during the flow of capillary water. For certain species such stresses can result in an inward collapse of the cell wall (a more comprehensive explanation of the process is given in Siau 1995, chapter 4.5. See specially Fig 4.7 where the cell collapse is illustrated). The danger of collapse is greatest at the early drying stages when the cells are full of water. This is, however, not a problem for the Swedish species.

3. Optimization

To survive in the highly competitive world of today, it is not enough to develop only an acceptable design[3]. Often it is necessary to design the best solution. And furthermore, increased care about the environment raises questions as: Are we making the most effective use of our limited resources? Can we obtain a more economical design? Are we taking risks within acceptable limits? The mathematical optimization methods offer some of the needed tools to answer such questions.

During the past four decades, there has been a very fast growth of optimization models and techniques. Properly implemented into a software, the methods give powerful tools in combination with modern computers. Optimization is a general tool and it can be applied to solve almost any engineering problem, see e.g. Arora 1989, Fletcher 1987, Rao 1996. Below some typical applications from different engineering disciplines are given.

- Design of aircraft and aerospace structures for minimum weight.
- Design of structures as buildings, bridges etc.
- Design of chemical reactors.
- Design of pumps, turbines, and heat transfer equipment of maximum efficiency.
- Shortest route taken by a salesperson visiting various cities during one tour.
- Planning of maintenance and replacement of equipment to reduce operating costs.
- Design of electrical networks.

3.1 Formulation of a general constrained optimization problem

Any problem in which certain parameters, or variables, must be chosen to satisfy constraints can be formulated as an optimization problem. A standard formulation of a constrained optimization problem can be stated as follows:

$$\text{Minimize} \quad f(\mathbf{x}) \tag{2}$$

$$\text{such that} \quad \mathbf{h}(\mathbf{x}) = \mathbf{0}$$
$$\mathbf{g}(\mathbf{x}) \leq \mathbf{0}$$

where $\mathbf{x}$ is a vector containing the design variables, $f(\mathbf{x})$ is the objective or cost function and $\mathbf{h}(\mathbf{x})$ and $\mathbf{g}(\mathbf{x})$ are vectors with equality and inequality constraints respectively (in the following boldface letters denote vectors). If the problem has no equality or inequality constraints, it is called an unconstrained optimization problem. A proper problem formulation is essential for the success of the optimization process, but once a problem is transcribed into the standard model they all look the same. This means that the same solution strategies can be applied to a great number of problems.

[3] Design should here be understood in its most general form. A design can be an electrical network, a mechanical construction, a chemical process etc.

3.1.1 Design variables

To improve or optimize a design there must be some freedom to change some parameters. These parameters are usually called design variables. Design variables can be cross-sectional dimensions, material properties, temperatures, etc. Once the variables are assigned numerical values, a possible design of the system is known. If the chosen values of the variables do not satisfy all constraints, the design is said to be infeasible. And consequently, with satisfied constraints the design is called feasible.

In many applications the design variables are allowed to take continuos values, often within a specified range of variation. In other cases, the design variables are only allowed to take discrete values. For example, if plate thickness is a design variable, the optimized thickness ought to be commercially available. Integer variables appear when the variables must have integer values. In a hydraulic system, for example, the number of pumps or valves must be an integer value. Optimization problems with discrete or integer variables is usually much more difficult to solve than similar problems with continuos variables. In some cases, however, the simple method of rounding to the closest value works well.

3.1.2 Constraints

The constraints of an optimization problem provide limits for the design variables. Constraints that represent limitations on the behaviour or performance of the system are called behaviour constraints. Simple constraints as upper or lower values of design variables are called side constraints. Let us as a simple example consider an optimization with four constraints. If the problem only has inequality constraints, they all have the form $g_i(\mathbf{x}) \leq 0$, $i = 1, 2, \ldots 4$. In a hypothetical design space with a two-dimensional design vector $\mathbf{x} = [x_1, x_2]$, the constraint surfaces that satisfy the equation $g_i(\mathbf{x}) = 0$ divide the design space in a feasible and unfeasible region, see Fig. 14.

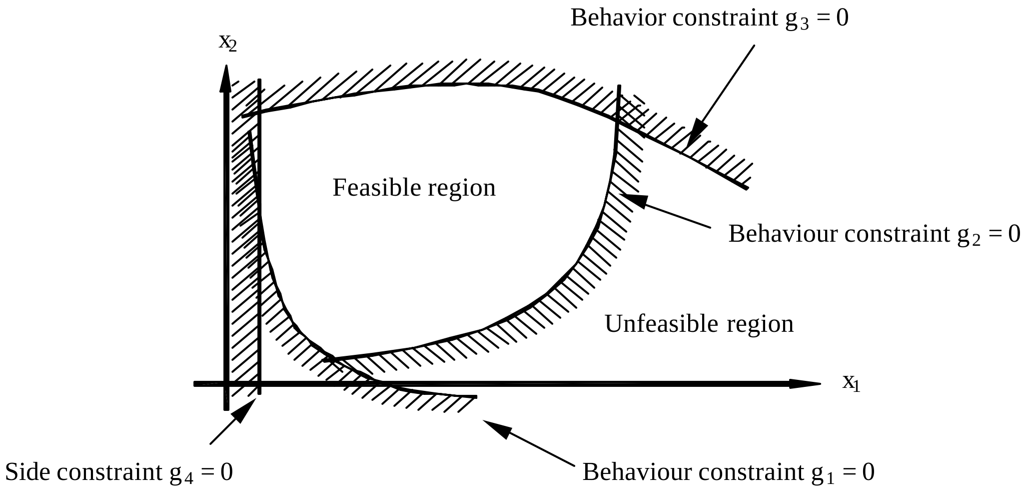


Fig. 14. Constraint surfaces with a two-dimensional design vector $\mathbf{x} = [x_1, x_2]$

A design point **x** that lies on a constraint is called a bound point and the corresponding constraint is called active. Design points that do not touch any constraints are called free points. If the design point lies within the feasible region it is either a free or a bound point.

Most optimum design points are at bound points, usually where two or more constraints meet each other.

3.1.3 Objective function

Among the feasible designs for a system, some are better than others. To compare the different designs, there must be some merit function $f(\mathbf{x})$ that can be improved and can be used as a measure of the effectiveness of the design. That function is usually called objective or cost function. Common examples of objective functions are minimized weight, maximized profit, minimized deflection, minimized time, etc.

If an objective function $f(\mathbf{x})$ is added to the hypothetical design space in Fig. 14, the graph of optimization problem might look like Fig. 15. In the figure the objective function is plotted for constant values f_1, f_2, f_3, where the objective function is descending as $f_1 > f_2 > f_3$. Optimum point is reached at $\mathbf{x} = \mathbf{x}^*$.

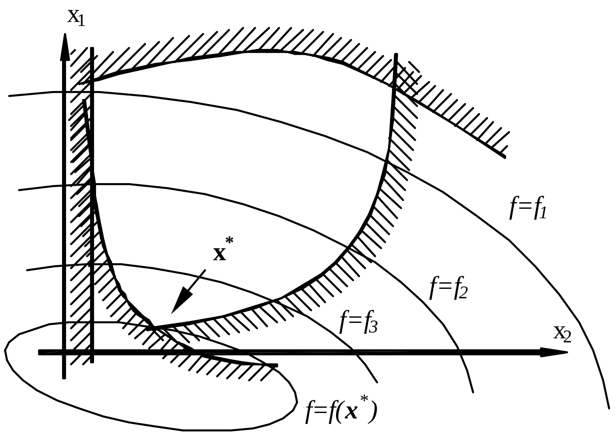


*Fig. 15. Contours of the objective function f(**x**) together with constraint surfaces.*

In the standard formulation of an optimization problem given above, the objective function will always be minimized. This can, however, be done with no loss of generality, since maximization of a function $f(\mathbf{x})$ can always be transformed into minimization of $-f(\mathbf{x})$, see Fig. 16.

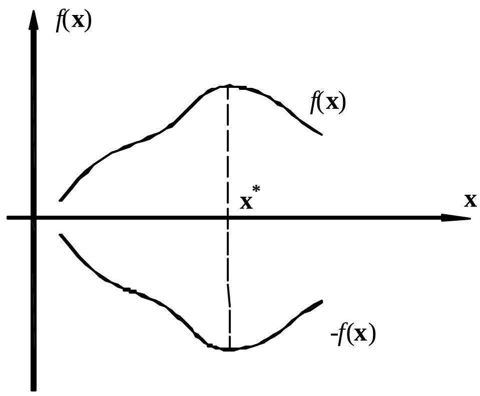


*Fig. 16. Point maximizing f(**x**) = point minimizing –f(**x**).*

In some cases multiple objective functions must be considered. In a structural design, for example, perhaps both the total weight and the stress in a certain point have to be minimized. A common way to treat such multiobjective problems is to construct a new, composite objective function as a linear combination of the different objective functions. If $f_1(\mathbf{x})$ and $f_2(\mathbf{x})$ denote two objective functions a new objective function can be constructed as

$$f(\mathbf{x}) = \alpha_1 f_1(\mathbf{x}) + \alpha_2 f_2(\mathbf{x}) \tag{3}$$

where α_1 and α_2 are constants which indicate the relative importance of the objective functions.

3.2 The solution process

If analytical expressions are known for objective function and constraints, classical methods of optimization can be used. The simple search of extrema of a single-variable function without constraints is well known, but for multivariable functions with non-linear constraints, the optimum points are harder to find. The method of Lagrange multipliers offers, however, a technique to solve such problems. Consider an optimization problem with only inequality constraints:

$$\begin{aligned} &\text{Minimize} && f(\mathbf{x}) \\ &\text{such that} && \mathbf{g}(\mathbf{x}) \le \mathbf{0} \end{aligned} \tag{4}$$

Introducing the Lagrangian function L and a vector $\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \ldots, \lambda_p)$ of Lagrange multipliers λ, it is possible to show that a stationary point of

$$L(\mathbf{x}, \boldsymbol{\lambda}) = f(\mathbf{x}) + \boldsymbol{\lambda} \cdot \mathbf{g}(\mathbf{x}) \tag{5}$$

is the solution of (4). The condition $\nabla L(\mathbf{x}, \boldsymbol{\lambda}) = \mathbf{0}$, completed with some other conditions, gives the Kuhn-Tucker conditions necessary for an optimization problem with only inequality constraints.

$$\nabla f(\mathbf{x}) + \boldsymbol{\lambda} \cdot \nabla \mathbf{g}(\mathbf{x}) = \mathbf{0} \tag{6}$$

$$\boldsymbol{\lambda} \cdot \mathbf{g}(\mathbf{x}) = \mathbf{0} \tag{7}$$

$$\mathbf{g}(\mathbf{x}) \le \mathbf{0}, \quad \boldsymbol{\lambda} \ge \mathbf{0} \tag{8}$$

If (6) is written as $\nabla f(\mathbf{x}) = -\boldsymbol{\lambda} \cdot \nabla \mathbf{g}(\mathbf{x})$, it is clear that the Kuhn-Tucker conditions say that optimum is reached when the gradient of the objective function is a linear combination of the active constraints gradients. In Fig. 17, a geometrical interpretation of the Kuhn-Tucker conditions is given.

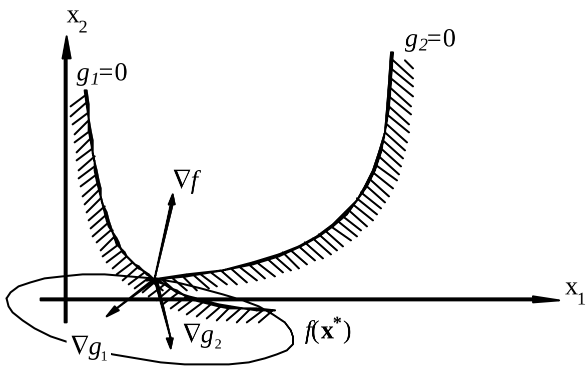


Fig. 17. A geometrical interpretation of the Kuhn-Tucker condition for two inequality constraints.

In a more general form, the Kuhn-Tucker conditions can be used to solve optimization problems with both inequality and equality constraints. But if there are too many variables or constraints, or if the functions are highly nonlinear, the analytical methods are usually of little use.

Another reason for failure of analytical methods is that objective and/or constraint functions in many practical applications only exist in implicit form. The values of the objective function and the constraint exist perhaps only as a solution from a FEM-program in the actual design point, which implies that some numerical method must be used to find a solution.

3.2.1 A general optimization algorithm

The common way to solve practical problems of varying complexity is to use numerical methods. The methods work in an iterative way; from an initial design improvements are made until optimality conditions are satisfied. There are several methods available today, but the methods for solving constrained, nonlinear optimization problems can all be classified into two broad categories: direct methods and indirect methods. In the direct methods the constraints are handled in an explicit manner, whereas in the indirect methods the constraints are "built in" in the objective function. The constrained problem can thereby be solved as a sequence of unconstrained problems. Although the optimization techniques may differ a lot, most of them can be described in the general algorithm given below.

STEP 1. Guess some initial design, $\mathbf{x}^{(0)}$, of the solution.
STEP 2. For k = 0, 1, ...
  If $\mathbf{x}^{(k)}$ is optimal, stop
  Determine an improved estimate of the solution $\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} + a_k \mathbf{d}^{(k)}$
STEP 3. Repeat from STEP 2

where $\mathbf{d}^{(k)}$ is the search direction (in a descent direction) and the scalar a_k is the step length in the search direction. In the following parts, only examples from the direct optimization methods will be given.

3.2.2 Solving approximated subproblems

Most methods for constrained optimization solve approximated subproblems $\tilde{P}$. The subproblems are created in STEP 2 in the general optimization algorithm above, and the approximations are obtained by linear Taylor series expansions for the objective and constraint functions (termed $\tilde{f}(\mathbf{x})$ and $\tilde{\mathbf{g}}(\mathbf{x})$). A first order Taylor expansion for problem (4) around the design point $\mathbf{x}^{(k)}$ gives the linearized subproblem (LS) $\tilde{P}^{(k)}$:

$$\tilde{P}^{(k)}: \qquad (9)$$
$$\text{Minimize} \quad \tilde{f}(\mathbf{x}) \equiv f(\mathbf{x}^{(k)}) + \nabla f(\mathbf{x}^{(k)}) \cdot (\mathbf{x} - \mathbf{x}^{(k)})$$
$$\text{such that} \quad \tilde{\mathbf{g}}(\mathbf{x}) \equiv \mathbf{g}(\mathbf{x}^{(k)}) + \nabla \mathbf{g}(\mathbf{x}^{(k)}) \cdot (\mathbf{x} - \mathbf{x}^{(k)}) \leq \mathbf{0}$$

As seen above, linearization requires knowledge of both function and gradient values at the design point $\mathbf{x}^{(k)}$. There are effective methods to solve optimization problems with linear objective function and constraints. Subproblems (9) can for example be solved with the standard Simplex method, and a way to solve the original optimization problem (4) is to solve iteratively as a sequence of linearized subproblems (SLP). In Fig. 18 two sequential linear approximations of the original problem are shown (the approximated subproblems are marked by dashed lines). In the first approximation, the solution of the subproblem moves from $\mathbf{x}^{(k)}$ to $\mathbf{x}^{(k+1)}$, and in the second approximation the solution moves to $\mathbf{x}^{(k+2)}$ which is a bit closer to the optimum solution of the original problem.

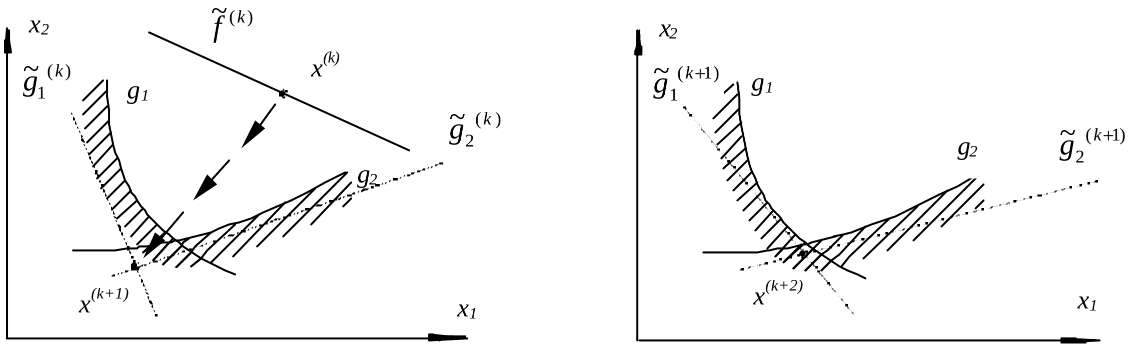


Fig. 18. Two linear, sequential approximations, showing the solutions of subproblem $\tilde{P}^{(k)}$ and $\tilde{P}^{(k+1)}$.

Since the Taylor expansion of the functions are only valid close to the design point, the changes in design may not become too large. Therefore, limits must be imposed on changes in design. These limits are usually called move limits, and are normally changed in each iteration. The move limits can be expressed as:

$$\underline{\mathbf{x}} \leq \mathbf{x} \leq \overline{\mathbf{x}} \qquad (10)$$

where $\underline{\mathbf{x}}$ denotes the lower accepted value of the design variables $\mathbf{x}$ and $\overline{\mathbf{x}}$ the upper accepted value. The method is simple to use and to implement in a software, but is has some serious drawbacks. The selection of move limits (10) is essential for the performance and convergence of the method, and since it is a trial and error process, the method is hard to automatize.

Another strategy for solving (9) is used in the Method of Moving Asymptotes, see Svanberg 1987 and 1991. In MMA, the approximating functions in the subproblems are obtained by a linearization in variables of the type $1/(x_j - l_j)$ and $1/(u_j - x_j)$ where l_j and u_j are parameters that satisfies $l_j < x_j < u_j$. (l_j and u_j are the lower and upper asymptotes to x_j) With the notations $f_0(\mathbf{x}) = f(\mathbf{x})$ and $f_i(\mathbf{x}) = g_i(\mathbf{x})$ the approximated MMA subproblem $\tilde{P}^{(k)}$ then looks as follows:

$\tilde{P}^{(k)}$: (11)

$$\text{Minimize} \quad \tilde{f}_0(\mathbf{x}) = \sum_{j=1}^{\substack{\text{number of}\\ \text{variables}}} \left(\frac{p_{oj}}{u_j - x_j} + \frac{q_{oj}}{x_j - l_j} \right) + r_0$$

$$\text{such that} \quad \tilde{f}_i(\mathbf{x}) = \sum_{j=1}^{\substack{\text{number of}\\ \text{variables}}} \left(\frac{p_{ij}}{u_j - x_j} + \frac{q_{ij}}{x_j - l_j} \right) + r_i \le 0, \; i = 1, \ldots \text{ number of constraints}$$

$$\underline{x_j} \le x_j \le \overline{x_j}$$

If $\frac{\partial f_i}{\partial x_j} > 0$ at $\mathbf{x}^{(k)}$ then $p_{ij} = (u_j - x_j^{(k)})^2 \cdot \frac{\partial f_i}{\partial x_j}$ and $q_{ij} = 0$.

If $\frac{\partial f_i}{\partial x_j} < 0$ at $\mathbf{x}^{(k)}$ then $q_{ij} = -(x_j^{(k)} - l_j)^2 \cdot \frac{\partial f_i}{\partial x_j}$ and $p_{ij} = 0$.

If $\frac{\partial f_i}{\partial x_j} = 0$ at $\mathbf{x}^{(k)}$ then $p_{ij} = 0$ and $q_{ij} = 0$.

$i = 0, \ldots$ number of constraints, $j = 1, \ldots$ number of variables

The parameters r_i are calculated as

$$r_i^{(k)} = f_i(\mathbf{x}^{(k)}) - \sum_{j=1}^{\substack{\text{number of}\\ \text{variables}}} \left(\frac{p_{ij}}{u_j - x_J^{(k)}} + \frac{q_{ij}}{x_l^{(k)} - l_j} \right), \; i = 0, \ldots \text{ number of constraints} \qquad (12)$$

which implies that $\tilde{f}_i^{(k)}(\mathbf{x}^{(k)}) = f_i(\mathbf{x}^{(k)})$. The values of the parameters l_j and u_j are normally changed between the iterations, and should therefore be denoted $l_j^{(k)}$ and $u_j^{(k)}$, just as p_{ij}, q_{ij} and r_i in fact should be denoted $p_{ij}^{(k)}$, $q_{ij}^{(k)}$ and $r_i^{(k)}$. More details on the MMA-method and MMA subproblem is given in Svanberg 1987, 1991 and Esping et al 1995.

If one let $l_j^{(k)} \to -\infty$ and $u_j^{(k)} \to \infty$ the MMA-approximation becomes (in the limit) equal to the linearized subproblem given in (9), while if one let $l_j^{(k)} \to 0$ and $u_j^{(k)} \to \infty$ the MMA-approximation becomes (in the limit) equal to linearization with the mixed variables x_j and $1/x_j$. The MMA-subproblem will always be convex and separable which means that dual methods can be applied. The MMA-method is usually stable and converges to a "sufficiently good" solution within 10-15 iterations. It has with great success been used in a variety of examples from structural, fluid flow, acoustic, and, in this application, wood drying optimization, see Esping 1995.

3.2.3 Convergence and accuracy

The iterative process in the general optimization algorithm goes on until it converges and all restrictions are satisfied. The accuracy of the obtained solution depends first of all on the accuracy of the analysis underlying the optimization. However, there is also a possibility that the optimization process has converged to a solution, which is a local minimum instead of a global minimum, see Fig. 19.

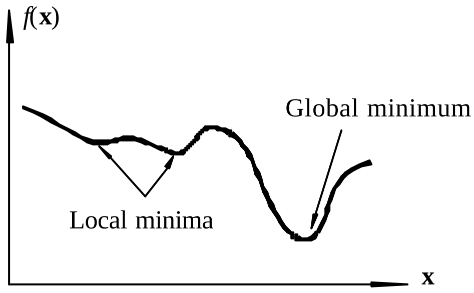


*Fig 19. Illustration of local and global minima for the objective function f(**x**).*

One way to test whether a local or a global minimum is reached, is to start a new optimization process with another initial design point.

3.3 Practical example from optimization of a racing ski

To exemplify the elements of optimization, references will be given to Carlsson et al 1995 (paper A) in the following. The object in paper A was to optimize a modern racing ski for skating. The core of the original ski was made of balsa-wood, covered with different layers of carbon fibre and reinforced plastic. An optimized ski should be developed by varying the outer dimensions of the ski together with the thickness of different layers with different angles of the fibre orientation.

The manufacturer believed that important properties of a good skating ski was high stiffness and low weight. The optimization problem for the ski was therefore formulated as:

$$\text{Minimize} \quad u(\mathbf{x}) \qquad (13)$$

$$\text{such that} \quad w(\mathbf{x}) \le \overline{w}$$

where w is the total weight of the ski, $\overline{w}$ is the maximum allowed weight and u is the deflection of the ski under the load F as seen in Fig. 20. The load F corresponds to the force from the skier during skating.

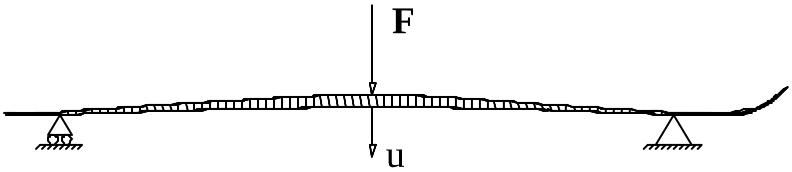


Fig 20. Deflection u under load F

The core of the racing ski was built up by small blocks in a finite element model as shown in Fig. 20. The different layers outside the core were collected in stacks, one stack for each side of the ski, see Fig. 5 in paper A. Thus natural design variables for the racing ski were the heights of the small blocks and the thickness of the different layers in the stacks. All variables were treated as continuos variables during the optimization, but to produce the ski, the thickness of the layers had to be adapted to materials commercially available.

The behaviour constraint of the racing ski was a constraint of the total weight of the ski. It was not allowed to be greater than the weight of the original ski. Side constraints were the demands that all dimensions must be greater than zero and that the height of the ski was limited to a certain value because of FIS[4] rules.

Objective function for the racing ski was the deflection under the load. It was not the only possible objective function, the total weight of the ski could also be a natural objective function. But instead of turning the problem to a multiobjective problem, the total weight was considered as a behaviour constraint in the optimization problem.

Optimization resulted in a much stiffer ski. With no change in weight, the stiffness of the ski was increased by approximately a factor of 10.

[4] Federation Internatonale de Ski

4. Optimized Wood Drying

The purpose of optimization is to determine the optimal environmental conditions for drying; i.e. air dry bulb temperature and relative humidity as functions of time. The goal is to produce a board with moisture content within a certain upper and lower level. The deformation and surface check intensity, i.e. relative check length, must also be under control. In this study, the stress levels during drying are used as a measure of the tendency for checks.

The optimization problem is formulated as follows (with some variations in different numerical examples):

Find a drying schedule that (the objective function)
- Minimizes the total drying time

such that (the constraints or restrictions)
- Moisture content and deformations are within an upper and lower level after drying
- Stresses are below a certain level during the whole drying process

Upper and lower limits are also given to the design variables, and, in some cases, also to their rate of change per hour. A mathematical formulation of the optimization problem is found in Carlsson and Esping 1997 (paper C).

A drying schedule can be optimized in many ways. Instead of minimizing the total drying time, the total energy consumption could be minimized etc. But no matter how the optimization problem is formulated, the drying process must still be controlled by some drying schedule. It is therefore natural to take the components which build up the drying schedule as design variables, see Fig. 21. In this study the length of each individual time step, together with the air dry bulb temperature and relative humidity connected to each time step, has been chosen as design variables (other state variables as wet bulb depression etc. could also be chosen).

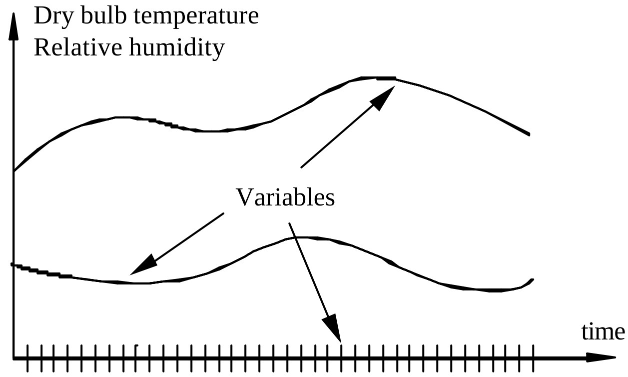


Fig 21. Drying schedule with design variables, i.e. time steps, dry bulb temperatures and relative humidity.

The design variables (denoted **x**) will change their values during the optimization process until the drying time is minimized (of course with all the constraints fulfilled). The iterative optimization process goes on until it has converged. In the presented numerical examples, the convergence criterion is that the relative difference between the total drying time of two iterations should be less than a given value.

The iterative optimization process starts from a given, initial drying schedule, see the schematic description of the optimization process in Fig. 22. In the outer loop, the optimization routine (the MMA routine) creates a modified drying schedule in each iteration.

To know how well the actual schedule performs its task, the optimization routine needs information of the current values of the total drying time, $f(\mathbf{x})$, and the constraints of moisture content etc, i.e. $g_i(\mathbf{x})$. And to know in which direction to change the variables, MMA also needs information of their gradients, i.e. derivatives with respect to the design variables. The gradients are calculated with numerical approximations which are built up with disturbed function values from the inner loop and undisturbed function values from the first moisture and structure calculation:

$$\nabla g_i = \left(\frac{\partial g_i}{\partial x_1}, \frac{\partial g_i}{\partial x_2}, \ldots, \frac{\partial g_i}{\partial x_n}\right)^T \qquad (14)$$

where

$$\frac{\partial g_i}{\partial x_j} \approx \frac{g_i(x_j + \Delta x_j) - g_i(x_j)}{\Delta x_j} \qquad (15)$$

Hopefully the optimization process converges to an optimized drying schedule. The problem formulation of the wood drying problem seems to work well. In most numerical examples, the process converges within 7-10 iterations.

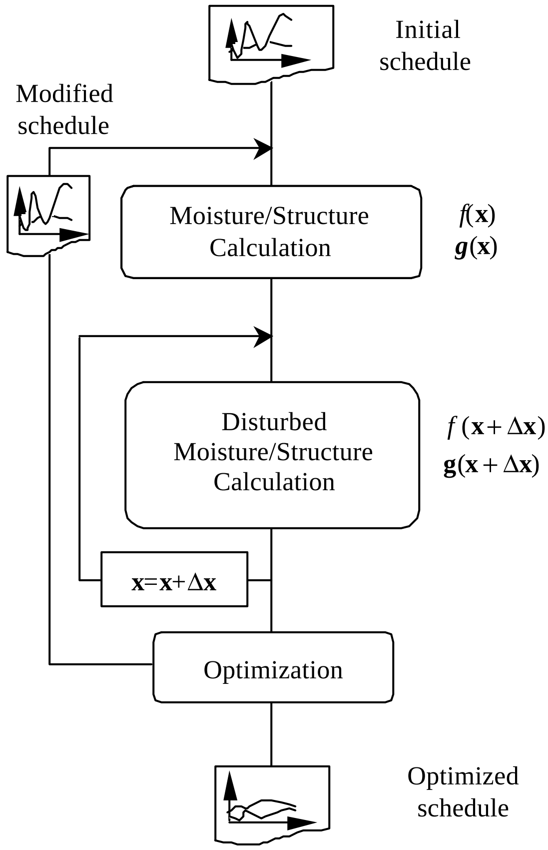


Fig. 22. Schematic description of the optimization process.

The disturbed moisture and structural calculations in the inner loop in Fig. 22 are suitable for parallel computing since they are independent of each other. The optimization program used in the last numerical example allows as many computers as wanted to be connected, and the total time of computation will decrease considerably with several computers in a network. The above description is valid for distributed optimization of *one* board with several connected computers. It is however also possible to use the program to optimize a drying schedule for *several* boards at the same time. These boards can be given different material data, such as distribution of heartwood/sapwood, orientation in trunk, initial moisture content, etc. During optimization of several boards, all disturbed and undisturbed calculations of one individual board is performed on one and the same computer. This means that optimization of a drying schedule for three different boards takes three connected computers and so on.

5. Results from the Present Research

The optimization problem for wood drying, as described in section 4, has been implemented with the MMA optimization method and various programs for solution of the moisture transportation and structural problems. Optimization has been carried out for both one-dimensional and two-dimensional analysis. To reduce the time of calculation in the two-dimensional case, optimization has also been performed with distributed computing, i.e. with computers in a network. The objective function, i.e. minimization of the total drying time, has been the same in all calculations, but various formulations of the constraints have been tested.

5.1 One- and two-dimensional analysis during optimization

Optimization with two-dimensional analysis will give more realistic results compared with optimization with one-dimensional analysis. A disadvantage is that the complexity of the calculations increases a lot with two-dimensional analysis. In optimization with one-dimensional analysis, moisture and stresses are only given at a line in the middle of the board. With two-dimensional analysis stresses and moisture are given in a numerical grid that covers the whole cross section of the board, and since several constraints are connected to each cell, the number of moisture and stress constraints increase considerably in the two-dimensional case. The number of deformation constraints will, however, be the same in both cases since it is measured as the global cup deformation, see Fig. 25. The optimization routine does of course not know whether analysis is performed with one- or two-dimensional analysis. The only difference for the optimization routine is the number of constraints when solving the optimization problem. In all numerical examples the length of the individual time step, together with the air dry bulb temperature and relative humidity was chosen as design variables. The MMA optimization routine was used in all calculations.

5.2 Optimization with one-dimensional analysis

Two basic analysis programs have been developed by Dr. Ola Dahlblom, Division of Structural Mechanics, Lund University. These programs use the Finite Element Method to solve both the moisture transportation and the structural problems (an introduction to the FEM-method is given in Ottosen and Peterson 1992, Zienkiewicz 1994). Within this time-dependent solution, it is possible to determine the moisture, displacement, and stress distribution for each time step. The programs are briefly described below.

5.2.1 FEM program for moisture transportation

The moisture program is a one-dimensional program which solves the time-dependent moisture problem with 9 linear elements, orientated in the middle of the board as shown in Fig 23. Moisture is calculated for the eight numbered points in the same figure (the points on the upper and lower surface of the board have a moisture content corresponding to the surrounding air). Differences between sapwood and heartwood are not considered.

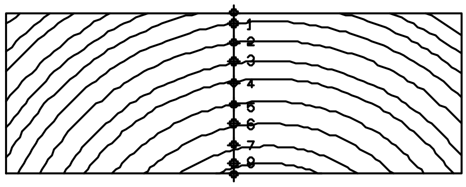


Fig 23. FEM elements for moisture transportation and numbering of moisture points.

The diffusion coefficient D_w is given a simple linear temperature dependence by Taylor expansion of the Arrhenius equation

$$D_w = D_0 e^{\frac{-E_s}{RT}} \qquad (16)$$

(see Skaar 1988). Temperature changes will otherwise have no effect on the total drying time. The driving force for the moisture transportation is the differences in moisture content in the board.

5.2.2 *FEM program for structural problem*

The structural program is a two-dimensional program, Dahlblom and Ormarsson 1994. It gives the displacements and stresses from one single element with linear and cubic polynom as approximating functions for the vertical and horizontal sides of the board, see Fig 24.

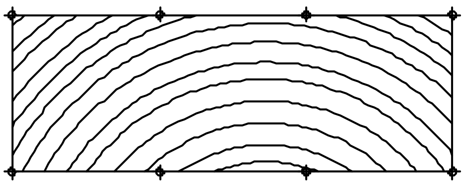


Fig 24. FEM model for structural calculation.

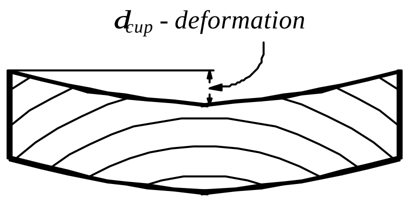


Fig. 25. Illustration of the global deformation, the so called cup deformation.

It is possible to vary the dimensions of the board and the growth ring orientation (i.e. the pith location). The wood material is modelled as an orthotropic material with head directions in the radial, tangential, and longitudinal directions. Material parameters vary with the head directions. The influence of temperature and moisture content on material parameters is also considered. The total strain rate $\dot{\varepsilon}$ is assumed to be the sum of the elastic strain rate $\dot{\varepsilon}_e$, moisture strain rate $\dot{\varepsilon}_w$ and mechano-sorptive strain rate $\dot{\varepsilon}_{ws}$ (usual creep is neglected), i.e.

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_w + \dot{\varepsilon}_{ws} \qquad (17)$$

The stress is expressed as $\dot{\sigma} = E\dot{\varepsilon} - \dot{\sigma}_0$ where E is the Hooke matrix and $\dot{\sigma}_0$ is a pseudo-stress vector which describes the effect of moisture change and is given as $\dot{\sigma}_0 = E(\dot{\varepsilon}_w + \dot{\varepsilon}_{sw})$. The structural problem is solved as a plane problem and stresses are calculated at eight points in the middle of the board which coincide with the moisture points, see Fig. 23. Deformation is calculated as the global cup deformation, see Fig. 25.

5.2.3 Optimization

Both the analysis programs, as well as the optimization routine (the MMA-routine), are written in FORTRAN and put together in one single program, see Carlsson et al 1996 and 1998 (paper B and D). The cross section of the studied board is given in Fig. 26. Material parameters for moisture transportation and strength are based on Scots pine (*Pinus silvestris*). Current optimization is carried out with 48 time steps, and drying starts from a moisture content corresponding to the fibre-saturation point, i.e. u=30%.

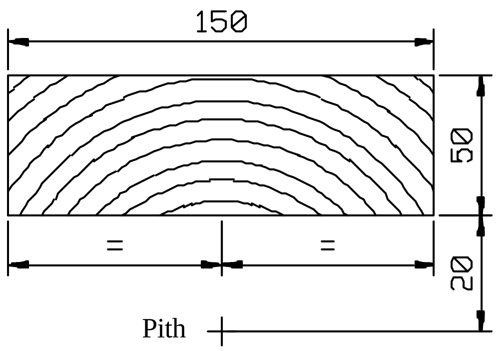


Fig. 26. Cross section of studied board with pith location.

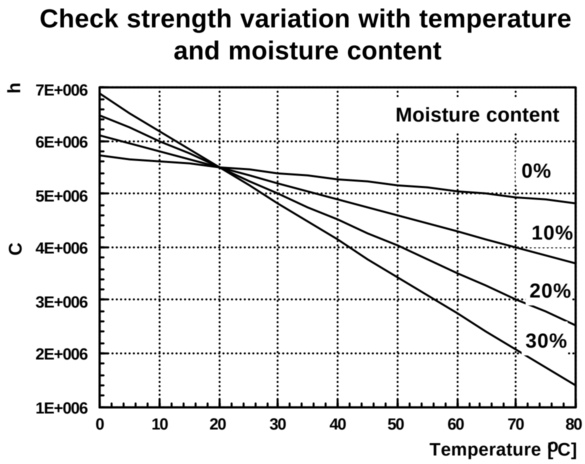


Fig. 27. Assumed check strength variation with temperature and moisture content.

The optimization problem with one-dimensional analysis *(P^{1D})* is formulated as follows:

(P^{1D}):
minimize t_K
such that

$$10\% \leq w_i(t_K, x) \leq 12\%$$

$$s_{i,k} \leq s_{upper}$$

$$d_{cup} \leq 2.0 \text{ mm}$$

$$-1.5 \leq \frac{dT}{dt} \leq 1.5$$

$$-1.5 \leq \frac{d(W.B.D.)}{dt} \leq 1.5$$

where:

K	is the number of time steps, i.e. 48	$s_{i,k}$	is the tangential stress in point i at time step k
k	is the number of time step k, k=1-48	s_{upper}	is the maximum allowed tangential stress according to Fig. 27
i	is the number of calculation point i, i=1-8	d_{cup}	is the global cup deformation at the end time t_K
t_K	is the total drying time $\left(t_K = \sum_{k=1}^{48} \Delta t_k\right)$	T	is the dry bulb temperature of air
Δt_k	is the individual time step k	*W.B.D.*	is the wet bulb depression
$w_i(t_K,x)$	is the moisture content in point i at the end time t_K	t	is the time
x	is the set of design variables		

The moisture content restriction has both an upper and a lower limit, and the time-consuming heating of the wood stacks are imitated by limited maximum values of the dry bulb temperatures at the beginning of the drying process. All derivatives are calculated with finite differences. Maximum values for tangential stress are collected from Fig. 27 (the graph is similar to the graph over the relationship between bending strength, moisture content, and temperature in Dinwoodie 1981). Initial dry bulb temperature is locked. Wet bulb and air dry temperature are given limits as well as maximum changes of wet and dry bulb temperatures between each iteration. The optimization problem has totally 593 restrictions, and the number of design variables is 3*48=144. The initial drying schedule is given in Fig.28.

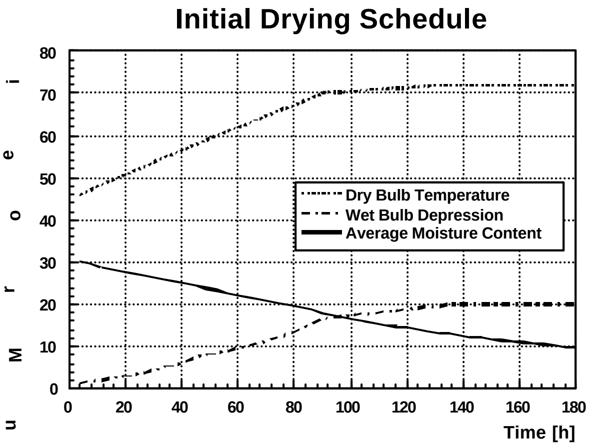


Fig. 28. Initial drying schedule

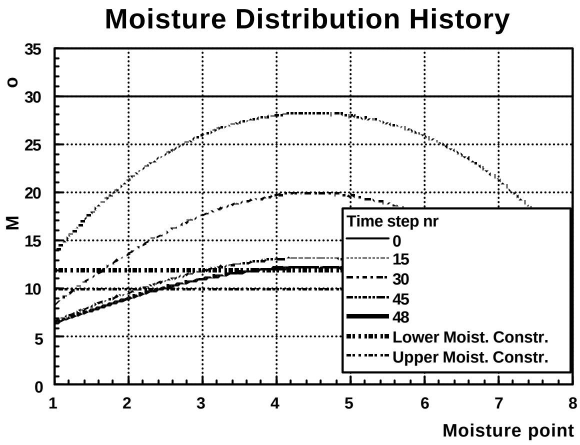


Fig. 29. Moisture-distribution history from initial drying schedule.

Moisture content history of the initial schedule is shown in Fig. 29. The average moisture content for the dried board is probably between the moisture content restrictions, but the moisture content in the outer and inner parts of the board is outside the allowed limits. After 13 iterations in the optimization routine, the drying schedule has the shape shown in Fig. 30.

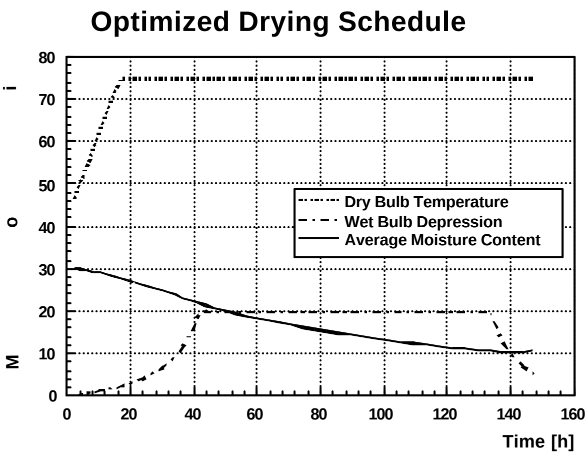


Fig 30. Optimized drying schedule

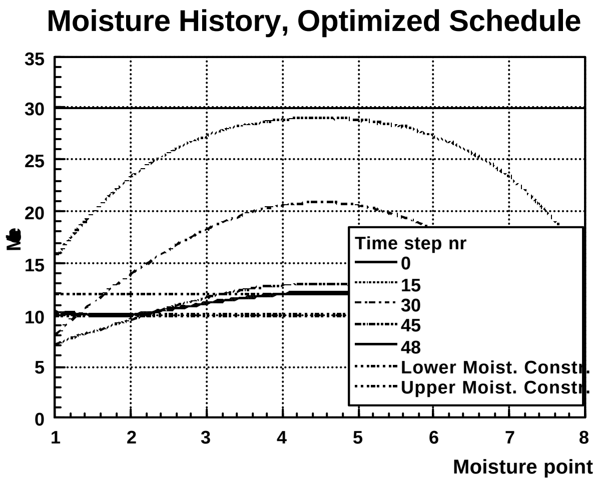


Fig. 31. Moisture-distribution history from optimized drying schedule.

The optimized drying schedule has the steepest slope of the dry bulb temperature that its derivative restriction allows. The moisture-restriction history for the optimized schedule is given in Fig. 31. Due to critical stresses at the beginning of the drying, the wet bulb depression raises slowly at first. After about 40 h it has reached the maximum allowed value, but toward the end of the process it decreases fast in order to satisfy the lower moisture restriction. A study of the stresses at the end of the process shows that they are far from critical.

The optimization routine has found that the most effective way to dry a board, with the given restrictions, is:

- careful drying at the beginning, to avoid checks
- hard drying in the middle of the process (small risk for checks)
- drying with low wet bulb depression at the very last hours of drying in order to fulfil the moisture restriction (i.e. conditioning treatment).

It is clear the moisture content distribution, after the last time step, is just inside the upper and lower restriction. The cup restriction is not active during any part of the optimization. The stress restrictions vary from point to point (and time to time) during drying, but the optimization routine manages to keep it below the stipulated maximum stress during the whole drying process

5.3 Distributed optimization with two-dimensional analysis

The program for the structural analysis is basically the same as for the one-dimensional case. The major difference is that stresses and strains now are calculated over the whole cross section. The program for moisture transport is the so called JAM-W program, developed by Dr. Jesper Arfvisson, Department of Building Physics, Lund University.

The disturbed calculations in the inner loop in Fig. 22, section 4, are suitable for parallel computing since they are independent of each other. The two-dimensional version of the optimization program allows as many computers as wanted to be connected, and the total time of computation will decrease considerably with several computers in a network.

5.3.1 Finite difference program for moisture transportation

The moisture balance equation is solved numerically with the two-dimensional moisture calculation program JAM-W. The program considers the orthotropic nature of wood, and the different moisture flow coefficients in radial and tangential directions for both heartwood and sapwood, see Fig 32. These coefficients depend strongly on the moisture content. In JAM-W four different Kirchhoff potentials Y for the moisture flow are used to take care of the non-linear anisotropic moisture flow in wood. A more detailed description of the moisture program is given in Arfvidsson 1998, Carlsson and Arfvidsson 1999 (paper E). In this two-dimensional isothermal model, hysteresis and moisture flow due to temperature gradients in the wood are not considered. The temperature level may change with time.

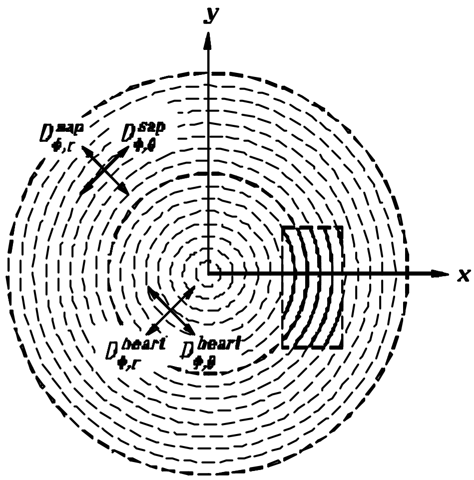


Fig. 32. A log in a two-dimensional cross-section. There are different moisture flow coefficients in radial and tangential directions both in heartwood and in sapwood.

The moisture equation is solved numerically by an explicit forward difference method. An arbitrarily chosen rectangular piece of wood, the board in Fig. 32, is divided into a rectangular mesh of cells, the so called numerical grid, there calculations are performed.

5.3.2 FEM program for structural problem

As mentioned above, the structural program is basically the same as for the one-dimensional case. Adapted for two-dimensional analysis, stresses are calculated in the same numerical grid which is used for the moisture content calculations, see Fig. 35.

5.3.3 Distributed optimization

The control program, responsible for message and file transfer between the connected computer etc., is written in Java. The control program also starts the analysis programs on the connected computers The structural program and the optimization routine (the MMA-routine) are written in FORTRAN and the moisture program is written in Pascal. Communication between the analysis programs and between the optimization routine and the analysis programs are handled by ascii-files, see Carlsson 1999 (paper F) for a more detailed description. Material parameters are based on Scots pine (*Pinus silvestris*). The location and dimensions of the studied board together with the approximate sapwood and heartwood distribution are shown in Figure 33 (heartwood shaded).

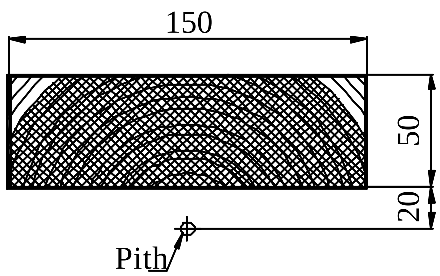


Fig. 33. Dimensions and pith location together with approximate sapwood and heartwood distribution of the studied board (heartwood shaded).

The drying process is modelled with 20 time steps, and the derivatives are calculated with finite differences. For the moisture and structural calculations a numerical grid with 10 columns and 8 rows covers the cross section of the board, see Fig. 35. Restrictions are connected to each cell in the numerical grid. The deformation restriction is, as in the one-dimensional example, the global cup deformation.

The optimization problem with two-dimensional analysis *(P^{2D})* is formulated as follows:

(P^{2D}):
minimize t_K
such that

$$12\% \le u_i(t_K, x) \le 14\% \quad i = 1,2,\ldots 80$$

$$s_x(t_k, x) \le 10 \text{ MPa} \quad i = 1,2,\ldots 80,\ k = 1,2,\ldots 20$$

$$-2 \text{ mm} \le d_{cup}(t_K, x) \le 2 \text{ mm}$$

$$\text{where } x \in (W_k, T_k, \Delta t_k) \quad k = 1,2,\ldots 20$$

where:

K is the total number of time steps, i.e. 20

k is the number of time step k, k=1-20

i is the number of cell i, i=1-80

t_K is the total drying time $\left(= \sum_{k=1}^{20} \Delta t_k\right)$

$u_i(t_K, x)$ is the moisture content in cell i the end time t_K.

$s_x(t_k, x)$ is the x-component (horizontal component) of the stress in cell i at time step k

$d_{cup}(t_K, x)$ is the global cup deformation at time t_K

x is the set of design variables W_k, T_k, Dt_k

W_k is the air relative humidity at time step Dt_k

T_k is the air temperature at time step Dt_k

Dt_k is the length of the time step at iteration k

Initial air dry temperature is locked to 45 ^{o}C. Maximum and minimum air dry temperature, relative humidity and length of each time step are given certain limits. To obtain a stable performance of the optimization, the maximum change of the relative humidity is maximized. The optimization problem has totally 1762 restrictions, and the number of design variables is 3*20=60. Optimization is performed with two connected computers and starts with the initial drying schedule, showed in Fig. 34.

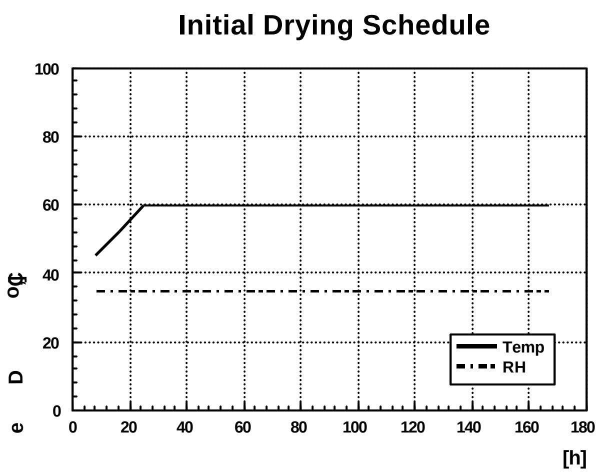


Fig. 34. Initial drying schedule.

The initial moisture content, together with heartwood and sapwood distribution in the numerical grid is shown in Fig 35 (heartwood shaded).

30.0	30.0	30.0	27.0	27.0	27.0	27.0	30.0	30.0	30.0
30.0	30.0	27.0	27.0	27.0	27.0	27.0	27.0	30.0	30.0
30.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	30.0
27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0

Fig 35. Distribution of heartwood and sapwood in the cross section of the board together with initial moisture content.

The initial drying schedule gives a maximum stress s_x=24.8 MPa during drying and a deformation d_{cup}=1.0 mm after drying. The moisture content after drying with the initial drying schedule is shown in Fig. 36.

6.9	7.3	7.4	8.4	8.9	8.9	8.4	7.4	7.3	6.9
7.4	8.6	12.2	12.3	12.7	12.7	12.3	12.2	8.6	7.4
8.0	12.5	13.3	13.3	13.3	13.3	13.3	13.3	12.5	8.0
9.6	12.9	13.6	13.8	13.7	13.7	13.8	13.6	12.9	9.6
9.9	12.9	13.6	13.8	13.8	13.8	13.8	13.6	12.9	9.9
9.6	12.3	13.1	13.4	13.4	13.4	13.4	13.1	12.3	9.6
8.7	10.7	12.1	12.7	12.8	12.8	12.7	12.1	10.7	8.7
7.5	8.2	8.6	8.9	9.1	9.1	8.9	8.6	8.2	7.5

Fig 36. Moisture content after drying with the Initial Drying Schedule.

The average moisture content is 11.0%. The cup deformation is below the allowed value, the stress restriction is violated and the moisture content in the outer parts of the board is far too low. After 27 iterations the optimization routine proposes the drying schedule shown in Fig. 37.

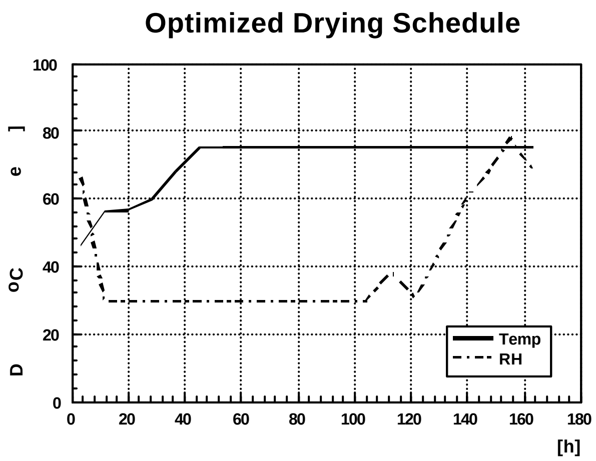


Fig. 37. Optimized drying schedule after iteration no. 27.

The optimized drying schedule gives a maximum stress s_x=10.2 MPa during drying and a deformation d_{cup}=1.1 mm after drying. The moisture content after drying with the optimized schedule is shown in Fig 38 (the initial moisture content is still as shown in Fig 35).

12.7	12.8	13.2	13.8	13.6	13.6	13.8	13.2	12.8	12.7
12.1	12.1	13.7	13.9	13.9	13.9	13.9	13.7	12.1	12.1
12.0	13.2	13.7	13.9	14.0	14.0	13.9	13.7	13.2	12.0
12.0	13.1	13.9	14.1	14.1	14.1	14.1	13.9	13.1	12.0
12.1	13.1	13.8	14.1	14.1	14.1	14.1	13.8	13.1	12.1
12.0	13.0	13.7	14.0	14.1	14.1	14.0	13.7	13.0	12.0
12.6	13.0	13.6	14.0	14.0	14.0	14.0	13.6	13.0	12.6
13.3	13.3	13.5	13.6	13.6	13.6	13.6	13.5	13.3	13.3

Fig 38. Moisture content after drying with Optimized Drying Schedule.

The average moisture content is now 13.4%, with a range from 12.0% to 14.1%. The stress restriction is close to its upper limit, and the deformation restriction, d_{cup}, is still a bit from its maximum allowed value. The optimization routine has managed to keep the moisture content within the lower and very close to the upper limit. The total drying time is about the same, but the great difference that the optimized schedule fulfils the restrictions in a much better way.

The example shows that the optimization technique works well also for a two-dimensional drying model with an increased number of restrictions. The conclusion for optimization with two-dimensional analysis is the same as for the one-dimensional: If a minimized drying time is wanted, dry as hard as possible, but dry with raised relative humidity at the beginning and at the end of the drying cycle: At the beginning to avoid high stresses and at the end to keep the moisture content within the restrictions. The great advantage with the two-dimensional analysis is that it is possible to simulate the moisture and stress distribution and deformation over the whole cross section. This is also important at the boundary between sapwood and heartwood, where high stresses may occur because of discontinuities in moisture content.

Compared with the simulation program TORKSIM[5] the moisture program (JAM-W) gives, with this set of material data, a slower drying. Material data exist only for an air dry temperature of 60 ^{o}C, which means that the internal moisture transport always takes place at that temperature. The transport velocity at the boundary against the surrounding air is, however, affected by the temperature, and that is why the temperature curve raises to its maximum, i.e. 75 ^{o}C.

To keep the upper and lower values of the moisture restrictions the optimization routine raises the relative humidity strongly at the end of the drying process and decreases it at the very last time step. This is necessary because of the faster moisture transportation in sapwood compared to heartwood and the faster drying in the corners compared to the middle parts of the board. This phenomenon is not found with the one-dimensional analysis. Complementary calculations showed that this decrease in relative humidity in the very last time step does not occur when the range between the lower and upper moisture restriction is raised to 3%. With such moisture restrictions, the curve of the relative humidity raises also in the very last time step.

5.4 Applications

Optimization opens new, promising fields in the art of wood drying. Several applications can be found for the technique. Reliable material parameters, together with accurate programs for the moisture transport and the structural problem make it possible to develop drying schedules for a great variety of industrial needs.

[5] Developed at the Swedish Institute for Wood Technology and Research.

- Existing schedules can be refined by optimization methods. A given schedule, tested and industrially used, can serve as input to the optimization program. Depending on what kind of improvements the user wants, the schedule can be refined in different ways. It can either be optimized for shorter drying time with retained restrictions, or optimized with changed restrictions such as other final moisture distribution, other final deformations etc. (of course with the total drying minimized).

- When developing schedules to meet new quality needs, it is possible to give the wanted quality as restrictions to the optimization program. With a rough drying schedule as input, the optimization routine calculates a drying schedule that fulfils all restrictions with a minimum of drying time.

- The same course of action, as described in the paragraph above, can be used when developing drying schedules for spices not very much used today. The only condition is that reliable material parameters for strength, moisture transportation etc. are available. This technique also makes it possible to start the expensive development of new drying schedules if the material parameters are not so well known. Different outcome from different values of the parameters can be easily tested that way.

- When constructing new dry kilns, improved performance characteristics can be taken care of in a better way. It is possible to use restrictions, which concern both the dry kiln and the wood material, as input to the optimization routine. The kiln restrictions might concern qualities as allowed air dry bulb temperature increase (or decrease) per hour, maximum wet bulb depression, maximum air dry bulb temperature etc., while restrictions on the wood material concern quantities as strength parameters, moisture transport coefficients etc.

- A dry kiln is normally loaded with a mixture of different boards. The boards may have different dimensions, and various outtake from the log gives various distribution of sapwood and heartwood in the board. Boards sawn from different trees, or even from different parts of the same tree, have different initial moisture content and material parameters. To develop a drying schedule for representative mixture of boards, the distributed optimization technique with many computers in a network offers a powerful tool, see Esping 1993 and Carlsson 1999 (paper F). An optimized schedule for a given distribution of different boards can be achieved, a schedule which is the best compromise for the wanted outcome.

6. Discussion and Conclusions

First of all, it must be clarified that the result of the optimization can not better than the quality of the used analysis programs and input of material data. The drying schedules are optimized according to the behaviour of the analysis programs, which may differ from the real drying process.

The main purpose with this work was to see if it was possible to treat wood drying as an optimization problem. Minimization of the total drying time was set as the objective function, and the wanted quality of the board as the constraints to the drying process. As quality parameters, the moisture content and cup deformation after drying were used, together with stresses during the whole drying process. With regard to the physical limits of the dry kiln, side constraints concerning maximum and minimum temperature, relative humidity, temperature increase per hour etc. were also given.

As the work advanced, it became clear that optimization was not only a way to find drying schedules for minimized drying time. It is also a powerful tool to create schedules that fulfil different restrictions of moisture content, deformations, stresses etc.

Optimization was performed with one- and two-dimensional programs for the moisture and structural analysis. The optimization process worked well in both cases; the process was stable and it has been possible to reach the wanted goals even from very rough initial drying schedules.

Optimization with one-dimensional analysis has the advantage of giving a relatively short time of calculation. It is however not possible to consider the effects of a given distribution of heartwood and sapwood in the cross section with one-dimensional analysis. To get more reliable drying schedules from the optimization process, the uneven moisture and stress distribution at the boundary between sapwood and heartwood must be considered. Another important matter to consider are the different moisture transport velocities in sapwood and heartwood. A way to combine both kinds of analysis would be to create a 'one-dimensional optimized' schedule first, and then use that schedule as input to a continued optimization with the slower, but more accurate, two-dimensional analysis.

An imperfection with the two-dimensional analysis is that the moisture program (JAM-W) only has material data for a drying temperature of 60 ^{o}C. Data exist for different levels of relative humidity, but the internal moisture transport will always take place at the constant temperature of 60 ^{o}C. The structural program considers, however, variations in the temperature during drying. A consequence of that imperfection might be that it is not possible to get the optimal curve for the temperature variation during drying, a curve which in its turn could lead to a modified curve for the relative humidity.

In the FEM-model (the same model is used in all calculations) the cross section of the board is built up by one single element. The structural calculations could be refined with a cross section that is built up with smaller triangular or rectangular elements. The calculations would of course be more time consuming, but the result would be more accurate. Another way to refine the precision of the structural calculations is to increase the number of time steps in the FEM-program. The improved resolution would give more reliable results, but during development of the optimization process, it has been necessary to work with relatively small models to save computational time (the total computational time will increase more than proportional to the number of time steps (NTS), since the number of design variables to disturb during optimization is three times NTS, and the calculation time for the structural program also is proportional to NTS. The computational time of the moisture program is, however, not dependent of NTS since it always works with a constant time increment).

A completion to the stress constraints should be to add some check constraints. Alternatively the strains, either principal strains or strains expressed along and across the annual rings, might be used. Strain criteria are common in advanced fibre-composite applications.

The distributed optimization is a cheap way to decrease the total computational time. Instead of working with one expensive but fast work station, several cheap and simple computers, connected to Internet, can be used in the calculations. The distributed optimization also opens possibilities to optimize drying schedules for a simulated mixture of boards in a drying kiln. Such calculations would be very time consuming on a single computer, but with many computers in a network, the calculations can be performed in reasonable time.

7. Future Developments

The moisture transportation calculations always start at the fibre saturation point. With more material data for the moisture program, it would be possible to start the drying from a point above the fibre saturation point. The drying schedules would also be improved if the air dry temperature affected the internal moisture transport in the wood.

Another detail that requires refinements is the check restriction. Check constraints are represented by stress constraints in this study. A possible future extension could be to consider the tangential stress component s_t instead, where the allowed upper level of the stress varies with temperature and moisture content in the actual part of the board. Altematively might principal strains or strains expressed along and across the fibre direction be used. Strain criteria are common in advanced fibre-composite applications. Hopefully a better failure criterion will be developed to complete the stress criterion. Statistical distribution of material properties, in combination with constraints on the probability for failure, is another possible future extension.

In optimization carried out in these examples, only one board at a time is seasoned. This is of course far from rational, industrial drying. It is however possible to extend the optimization process to include several boards at the same time. These boards can be given different material data, such as distribution of heartwood and sapwood, orientation in trunk, initial moisture content, etc. The technique of distributed optimization with several computers in a network, see Carlsson 1999 (paper F), will make even such a time-consuming calculation reasonable (in the distributed optimization, each computer calculates one board).

Drying schedules are usually adapted for flatsawn boards or possibly for quartersawn boards. Experiments with new sawing pattern give products with new demands on drying schedules. The products may have other geometries and orientation of the annual rings (e.g. vertical annual rings). With some adjustments, the optimization program could also be used to develop drying schedules for these new wood products.

If two-dimensional analysis gives more reliable drying schedules than one-dimensional, one could expect that three-dimensional analysis would give an even better outcome. Such models exist, both for structural analysis and moisture transport, see e.g. Ormarsson 1999, Turner and Perré 1999, but the benefits of such models must be weighed against strongly increased calculation time in the analysis and optimization.

8. References

Arvidsson, J., 1998. Moisture transport in porous media, modelling based on Kirchhoff potentials. Doctoral thesis, Department of Building physics, Lund Institute of Technology. Lund 1998, report TVBH-1010.

Arora, J.S., 1989. Optimum Design. McGraw-Hill, International Editions, Mechanical Engineering Series.

Bodig, J and Jayne, B. A. 1982. Mechanics of wood and wood composites, Van Nostrand Reinhold Company, New York.

Carlsson, P., Tinnsten, M. and Esping, B.J.D., 1995. Optimization of a racing ski. Structural Optimization 10, pp 61-63, 1995.

Carlsson, P, Esping, B.J.D., and Dahlblom, O. 1996. Optimization of the Wood-Drying Process, presented at the 5TH International IUFRO Drying Conference, "Quality Wood Drying Through Process Modelling and Novel Technologies", Aug. 13-17, Proc. pp. 529-532.

Carlsson, P, and Esping, B.J.D. 1997. Optimization of the Wood Drying Process. Structural Optimization, 14, pp 232-241.

Carlsson, P., Esping , B.J.D., Dahlblom, O., Ormarsson, O. and Söderström, O, 1998. Optimization, a Tool with which to Create an Effective Drying Schedule. Holzforschung, Vol 52, 1998, No. 5, pp 530-540.

Carlsson, P. Arfvidsson, J., 1999. Optimized Wood Drying. 6th International IUFRO Drying Conference on "Wood Drying Research & Technology for Sustainable Forestry beyond 2000", Stellenbosch, South Africa, Jan 25-28, Proc. pp 139-147. After a slight revision accepted for publication in Drying Technology Journal (publication is planned to vol.18, No 8, 2000).

Carlsson, P., 1999. Distributed Optimization with a two-dimensional Drying Model of a Board, built up by Sapwood and Heartwood. Submitted to Holzforschung

Dahlblom, O, Ormarsson, S, 1994. Two-dimensional simulation of wood deformation during drying, Division of Structural Mechanics, Lund, Institute of Technology, Report TVSM-7086.

Dinwoodie, J M. 1981. Timber, its nature and behaviour, Van Nostrand Reinhold Company, New York.

Esping, B, 1992. Trätorkning 1a, Grunder i torkning (only in Swedish). Trätek

Esping, B, 1996. Trätorkning 1b, Praktisk torkning (only in Swedish). Trätek

Esping, B.J.D., Clarin, P, Romell, O. 1993. OCTOPUS - A Tool for Distributed Optimization of Multi-Disciplinary Objectives, International Series of Numerical Mathematics, Vol. 110, pp. 1165-1194, Birkhäuser Verlag, Basel.

Esping, B.J.D., Carlsson, P., Arfvidsson, J., Ormarsson, S. and Dahlblom, O., 1995. Optimization of the wood drying process. Report 1995:1, Mid Sweden University, Östersund, Sweden.

Esping, B.J.D., 1995. Design Optimization as an engineering tool. Structural Optimization 10, pp 137-152.

Fletcher, R., 1987. Practical Methods of Optimization. John Wiley & Sons, New York, Chichester, Brisbane, Toronto, Singapore.

Gyllenswärd, C.G., 1985. En kort historik över virkestorkar och virkestorkning (only in Swedish). Tidningen Sågverken, No. 5, 1985.

Haygreen, J.G., Bowyer, J.L., 1994. Forest Products and Wood Science, An Introduction. Second edition. Iowa State University Press/Ames

Kollman, F.F.P., Côté, W.A., 1984. Principles of Wood Science and Technology, Volume I: Solid Wood. Springer-Verlag, Berlin, Heidelberg, New York, Tokyo.

Ormarsson, S., 1999. Numerical Analysis of Moisture-Related Distortions in Sawn Timber. Doctoral Thesis, 1999:04, Chalmers University of Technology, Göteborg 1999.

Ottosen, N, and Peterson, H. 1992. Introduction to the Finite Element Method, Prentice Hall International (UK) Ltd.

Rao, S.S., 1996. Engineering Optimization, Theory and Practice, Third edition. John Wiley & Sons, Inc. Professional, Reference and Trade Group, New York, Chichester, Brisbane, Toronto, Singapore.

Rowell, R., editor, 1984. The Chemistry of Solid Wood. Advances in Chemistry Series. American Chemical Society, Washington D.C.

Saarman, E., 1992. Träkunskap (only in Swedish). Sveriges Skogsindustriförbund, Markaryd.

Salin, J-G. 1992. Numerical prediction of checking during timber drying and a new mechano-sorptive creep model. Holz als Roh- und Werkstoff, 50, pp. 195-200.

Santaoja, K, Leino, T, Ranta-Manus, A, Hanhijärvi. 1991. Mechano-sorptive structural analysis of wood by the ABAQUS finite element program, Technical Research Centre of Finland, Research notes 1276, Espoo.

Siau, J.F., 1995. Wood: Influence of Moisture on Physical Properties. Department of Wood Science and Forest Products. Virginia Polytechnic Institute and State University.

Simpson, W.T., editor, 1991. Dry Kiln Operator's Manual. United States Department of Agricultures, Forest Products Laboratory, Madison Wisconsin. Agriculture Handbook No. 188.

Skaar, C. 1988. Wood-Water Relations, Springer-Verlag, Berlin Heidelberg New York.

Svanberg, K. 1987. MMA - Method of Moving Asymptotes - A New Method for Structural Optimization, Int. Journal for Numerical Methods in Engineering, Vol. 24, pp. 359-373.

Svanberg, K. 1991. MMA With Some Extensions, presented at the NATO Advanced Study Institute Conference Optimization of Large Structural Systems, Berechtsgarden, September 23-October 4.

Svensson, S. 1997. Internal Stresses in Wood Caused by Climate Variations. Doctoral thesis, Department of Structural Engineering, Lund Institute of Technology. Lund 1997, report TVBK-1013.

Söderström, O. 1996. The Development of Quality Wood Drying from Skellefteå 1987 to Quebec 1996 and an Example of its Effect on a National Research Program, Keynote Address at the 5TH International IUFRO Drying Conference, ”Quality Wood Drying Through Process Modelling and Novel Technologies”, Aug. 13-17, Proc. pp. 3-8.

Turner, I.W., Perré P. 1999. A 3D version of TransPore: A Comprehensive Heat and Mass Transfer Computational Model for Simulating the Drying of Wood, 6th International IUFRO Drying Conference on “Wood Drying Research & Technology for Sustainable Forestry beyond 2000”, Stellenbosch, South Africa, Jan 25-28, Proc. pp 213-222.

Zienkiewicz, O.C. and Taylor, R.L, 1994. The Finite Element Method, Volume I and II. McGraw-Hill Book Company

9. Appended Papers

Paper A *Optimization of a racing ski.* 1995. Structural Optimization 10, pp 61-63,1995.
By: *Peter Carlsson, Mats Tinnsten and Björn J.D. Esping.*

Summary: This paper shows how a very tradition-bound construction can be improved by the use of modern technology. A racing ski is optimized against minimum deflection with prescribed maximum weight. The paper also serves as a brief introduction to the optimization technique.

Paper B *Optimization of the Wood-Drying Process.* 1996. 5TH International IUFRO Drying Conference on 'Quality Wood Drying Through Process Modelling and Novel Technologies', Quebec Canada, Aug. 13-17, Proc. pp. 529-532.
By: *Peter Carlsson, Björn J.D. Esping and Ola Dahlblom.*

Summary: The first results of optimization of the wood drying process with one-dimensional analysis are presented. Total drying time is minimized with constraints of moisture content and cup deformation after drying and stresses during the whole drying process. The initial drying schedule is based on a Malmqvist drying schedule.

Paper C *Optimization of the Wood Drying Process.* 1997. Structural Optimization 14, pp 232-241,1997.
By: *Peter Carlsson and Björn J.D. Esping.*

Summary: The paper demonstrates how the wood drying process can be treated as an optimization problem. A detailed introduction to the problem formulation is given: Minimization of drying time serves as objective function while wanted moisture content, deformations and stresses are treated as constraints. Alternative formulations of objective function and constraints are also discussed. Numerical results of optimization with one-dimensional analysis from a very rough initial schedule are presented. Additional constraints on maximized temperature and relative humidity change rate are also considered.

Paper D *Optimization, a Tool with which to Create an Effective Drying Schedule.* 1998. Holzforschung, Vol 52, 1998, No. 5, pp 530-540.
By: *Peter Carlsson, Björn J.D. Esping, Ola Dahlblom, Sigurdur Ormarsson and Ove Söderström.*

Summary: The theoretical foundations are laid to the one-dimensional analysis used in the optimization process. The FEM-programs for the moisture transport and the structural calculations are described more thoroughly. A numerical example is presented where the problem formulation is same as in paper C, with the addition that the upper stress constraints are dependent on the actual temperature and moisture content.

Paper E *Optimized Wood Drying.* 1999. 6^{th} International IUFRO Drying Conference on "Wood Drying Research & Technology for Sustainable Forestry beyond 2000", Stellenbosch, South Africa, Jan 25-28, Proc. pp 139-147. After a slight revision accepted for publication in Drying Technology Journal (publication is planned to vol.18, No 8, 2000).

By: *Peter Carlsson and Jesper Arfvidsson.*

Summary: The first results of optimization with two-dimensional analysis are presented. Moisture content, deformations and stresses are calculated in a numerical grid which covers the cross section of the board. The two-dimensional moisture transport program (JAM-W) is described more in detail. A numerical example is presented with a reduced optimization problem formulation. Only the moisture constrains (the moisture content after drying) are considered. The simulated board is built up by heartwood only.

Paper F *Distributed Optimization with a two-dimensional Drying Model of a Board, built up by Sapwood and Heartwood.* 1999. Submitted to Holzforschung

By: *Peter Carlsson.*

Summary: Distributed optimization is performed with full two-dimensional analysis and computers in a network. The simulated board has a cross section built up by a mixture of sapwood and heartwood. In the presented numerical example, total drying time is minimized with constraints on moisture content and cup deformation after drying, and stresses during the whole drying cycle.