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Paper presented at the European COST Action E15 Workshop, Helsinki, Finland, June 11–13, 2001

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INSTITUTET FÖR TRÄTEKNISK FORSKNING

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DETERMINATION OF THE MOST ECONOMICAL DRYING SCHEDULE AND AIR VELOCITY IN SOFTWOOD DRYING

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ABSTRACT

Simulation models for conventional softwood drying have been available and have also been used by kiln operators for many years. For instance models for Scots pine and Norway spruce, dried at temperatures below about 80°C, are in use in Sweden, Finland and Norway. These models predict drying rates as a function of climate (schedule) and air velocity. The models thus give a direct basis for calculation of instantaneous energy demand for moisture evaporation and ventilation. There is further a direct relationship between the air velocity in the space between the board layers in the kiln stack and the electrical power demand by the circulation fans. Finally, the smaller energy consumption associated with heat losses through kiln walls and the accumulated heat in timber etc. can be estimated with sufficient accuracy. Instantaneous energy costs can thus be calculated for each part of a drying schedule.

Capital costs associated with kiln investment and maintenance, personnel, insurance etc can be accounted for as an hourly cost, which is basically independent of whether timber is dried fast or slowly. A slow drying process thus accumulates more capital costs per m^3 timber. In this way it is possible to calculate the total instantaneous drying cost (€/m^3/h or €/m^3/MC-%) and the overall total cost (€ or €/m^3).

Some results obtained with a simulation model equipped with such a cost calculation are presented in the paper. A rapidly increasing drying cost is seen when the final MC is lowered. By minimising the instantaneous cost, an optimal drying schedule can be determined for a given fixed air velocity. Finally an optimal air velocity – constant or varying – can be found in the same way.

I. INTRODUCTION

For a long time the primary problem in softwood kiln drying was to find a drying schedule that would give a reasonably short drying time, without excessive quality losses such as checking. It was assumed that the solution to this problem automatically would produce a good kiln drying economy. Today, partly due to simulation models, this primary problem has essentially been solved, at least regarding checking for conventional low temperature (80°C) drying. It is now possible to predict in advance, with reasonable accuracy, the outcome of the drying process. There are also several different solutions available for each task, i.e. different temperature levels or more generally different drying schedules, using different air velocities, and different conditioning methods etc. The best alternative for performing a drying task should of course be decided on an economic basis. Such a calculation has to include all costs associated with the drying process, i.e. investment costs and other fixed costs, energy costs and timber quality losses.

There are several publications that analyse the cost associated with softwood drying. However, for the most part only statistical information regarding timber drying in general, at different sawmills, has been presented (Gjerdrum 2000, Esping 1990, 1996, Madaus 1998). Results regarding selection of fan speed for an essentially fixed drying schedule have been presented in (Riley and Haslett 1996). There seems to be very few previous studies that address the question how the drying schedule should be selected and what the corresponding optimal air velocity (constant or varying) would be. This lack of information is rather surprising.

A computer simulation model – called TORKSIM – has been used by kiln operators and persons responsible for the drying process for some three years. The model is described in (Salin 1999) and in another paper presented at this workshop (Salin 2001). This model has now been extended with a simple but fairly comprehensive cost calculation subroutine that gives both instantaneous and total drying costs. In the following the general structure of this cost calculation is described and results for a calculated example are presented.

2. COST CALCULATION STRUCTURE

In the model, costs are divided into certain fixed costs and energy costs. The fixed costs consist of several parts, the first of which is the investment cost for the kiln. The investment cost is transformed into a constant yearly instalment, based on appropriate pay back time and interest rate. This can further be expressed as a constant hourly cost. The other fixed costs, such as maintenance, personnel, material, insurance etc. are combined into two groups, in one group those expressed as a percentage of the investment cost and in the other group those expressed as €/year, depending on which is the easiest way to calculate each of these costs. These fixed costs are also transformed into an hourly constant cost. These hourly costs are assumed to be almost independent of the way in which the drying process is performed and they are thus labelled fixed. A slow drying process will thus accumulate more capital costs per cubic meter timber than a fast process.

It should be remembered that there are other investments and fixed costs than those directly related to the kiln. Stickering and destickering of kiln stacks are needed, as well as a boiler for heat generation etc. These costs should in principle be included and distributed among kilns in proportion to kiln size (capacity).

Of the variable costs, only the energy costs are considered in the model. These are directly related to how the drying process is performed. In the main part of the model, the instantaneous drying rate is determined as a function of drying schedule and air velocity for the timber dimension in question. This gives a basis for calculating the energy demand for heat of evaporation. If the ambient air conditions are known, then the total energy requirement associated with venting can be determined. Further, if the kiln wall area and heat transfer coefficients (heat insulation) are known, then the heat transmission losses can be estimated. This part is normally below 20% of the total energy consumption, so a relatively rough estimate is sufficient. Thus the total instantaneous energy requirement is rather easily obtained from the main drying simulation results.

It should be remembered that the electric power used by the air circulation fans will transform into heat. Thus a change in fan speed – air velocity – will not directly affect the total energy consumption, only the distribution of heat from heater coils and from electric power. However, as heat and electric power normally have different prices, a change in fan speed will affect the total cost. The circulation fan electric power consumption is proportional to (air velocity)^3 and the level can be estimated theoretically or from practical experience. In this way the total energy cost can be calculated from the drying schedule used and the air velocity between the board layers in the timber stack. This completes the cost calculation in the TORKSIM model.

The most important costs not included in the model are certainly the costs associated with timber degrade during drying. These are losses caused by checking, darkening, resin flow, deformations, uneven final moisture content etc. An exact determination of these costs is very difficult. Different customers will also evaluate such defects differently. It is thus easier to account for these costs in a more indirect way. In the cost calculation described above, the normal procedure is to accept only such drying schedules (and other conditions) that according to the stress calculation will not cause checking. In this way the cost associated with timber checking is indirectly accounted for. At least timber darkening and resin flow are rather directly coupled to the drying temperature level. The influence of these costs can be restricted if a maximal allowable temperature level is defined, when the optimal drying method is selected. This temperature level, which may vary as a function of the drying time, is certainly dependent on the type of timber product concerned.

Other costs connected to degrade are assumed to be constant (not necessarily zero) regardless of the way the drying process is performed. As the cost of degrade is partly ignored, the cost calculated by the computer model is not the complete total cost, but a cost value that can be used for *comparison* of different drying schedules, air velocities and other drying conditions.

3. AN INTRODUCTORY EXAMPLE

In the following, calculated results are presented for both an arbitrarily chosen case and for a cost optimisation development of the same case. The case concerns drying of 50 x 150 mm^2 Scots pine in a kiln built of concrete with a capacity of 70 m^3 for this timber dimension. Data for the kiln are selected based on the assumption that it is "normal" in every respect. The prices chosen for electric power and heat are 0,045 €/kWh and 0,028 €/kWh respectively. Only such drying schedules are accepted that does not induce checking. It is further assumed that the blow depth in the stack is short (effective distance from air stack entrance to exit). Thus quality losses due to uneven final MC can for this reason be neglected. Calculations are done with the TORKSIM model described above.

First the cost structure is demonstrated using an arbitrarily chosen drying schedule and a constant air velocity of 3 m/s in the space between the board layers. The drying schedule is based on a wet bulb temperature of 55°C and a gradually increasing dry bulb temperature. When the dry bulb temperature reaches 80°C the wet bulb depression is further slightly increased by lowering the wet bulb temperature. The calculated instantaneous cost is presented in Figure 1 as a function of drying time.

The capital costs, which are independent of the way the drying process is performed, represent a constant basic cost in Figure 1. The energy cost added to this basic level constitute the total drying cost. In the beginning of the drying cycle when the MC level is still high, water is easily evaporated from the timber and this high drying rate is seen as a high energy cost. Later the drying rate decreases and the energy cost *per hour* is correspondingly lower.

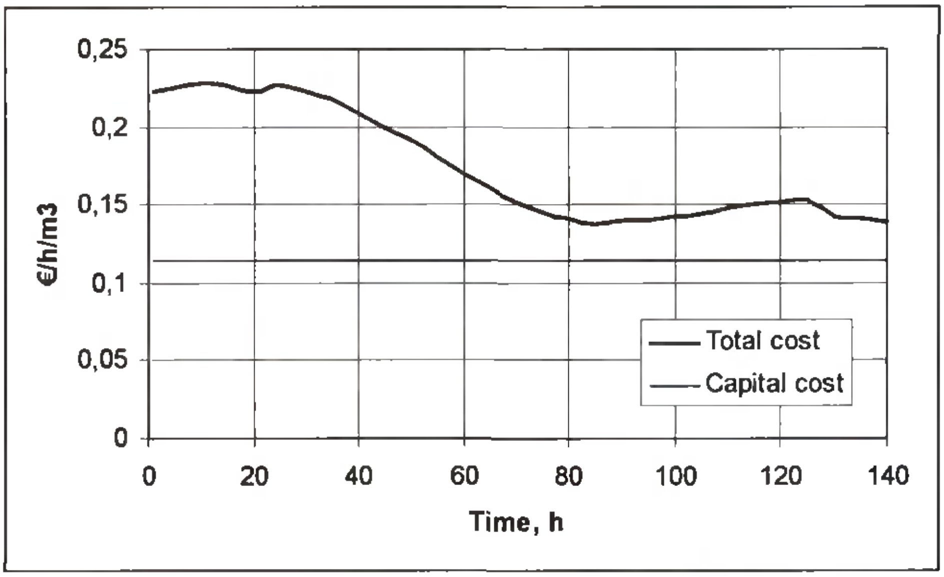

Figure 1. Instantaneous capital and total costs as a function of time.
Figur 1. Den momentana kapitalkostnaden och totalkostnaden som funktion av tiden.

However, if the same calculation is instead presented as a function of the average moisture content, then Figure 2 is obtained. Now the drying process proceeds from the right to the left in the figure.

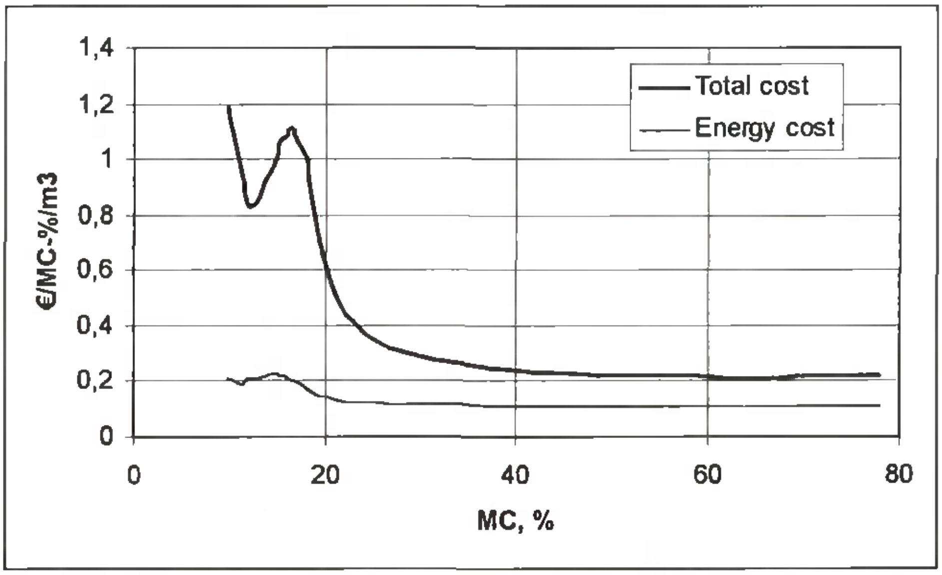

Figure 2. Instantaneous energy and total costs as a function of average moisture content.
Figur 2. Den momentana energikostnaden och totalkostnaden som funktion av medelfuktkvoten.

Each moisture %-unit removed requires approximately the same amount of energy (heat of evaporation) and thus the energy cost is almost constant when presented as a function of moisture content, as in Figure 2. The capital cost – and thus the total cost – will increase rapidly towards the end of the drying cycle. This is a result of the decreasing drying rate, which means that more capital costs are accumulated for each MC %-unit removed. The varying total cost seen in Figure 2 at the end of the drying process, is a result of the form of the drying schedule in this specific case, and is not necessarily a typical feature.

Figures 1 and 2 show rather clearly that the capital costs constitute a considerable part of the total drying cost. Thus a fast drying process will, generally speaking, be a better economic alternative than a slow process. For the same reason, removal of the last MC %-units will cost considerably more than removal of the first %-units.

4. COST OPTIMISATION – SOME EXAMPLES

The case presented above will now be analysed from a cost optimisation point of view, i.e. how should drying schedules and air velocities be selected in order to get a good drying economy. When simulating drying with different schedules and different air velocities, it becomes almost immediately clear that the temperature level has a strong influence on the total cost. A higher temperature gives a lower cost. This is due to a faster moisture migration, and faster mechano-sorptive creep with a lower risk of checking, which both enable shorter drying times. As the fixed costs (capital costs) are an essential part of the total costs, a shorter drying time will accumulate less costs, resulting in a lower total cost for higher temperature levels.

As both the equipment in the kiln and the timber product may put restrictions regarding the temperature level, a maximal allowable temperature has to be selected in each case. This upper limit may be time dependent, so that, for instance, thin boards are dried at a lower temperature in the beginning, in order to minimise knot problems. In this optimisation calculation we have selected two different levels for the upper temperature limit, i.e. a constant 80°C and a constant 60°C limit.

At first a constant air velocity is studied. This equals a case where there is no equipment available for continuous fan speed regulation. An optimal drying schedule is then determined by gradually modifying the detailed form of the schedule until a cost minimum is reached. This is mathematically a calculus of variations problem. In practise a solution can be found by minimising the cost of removing 1 kg of moisture during each short part of the schedule. Care should be taken not to use heat accumulated in the timber for instantaneous evaporation – heat that is better needed later on. By modifying the drying schedule in this way the optimal form can be found.

Figure 3 presents the results for the 80°C upper limit case, for three different fixed velocities – 3, 4 and 5 m/s. It turns out that the temperature should be quickly increased to the maximum level and then the wet bulb temperature should gradually be decreased, while the dry bulb temperature is kept at the upper limit. First it has to be pointed out that for this relatively high temperature, the wet bulb temperature curve is determined by the *cost*, not by the risk of checking. A faster increase in the wet bulb depression, and thus a faster drying, would have been possible from a stress level point of view, but that would not represent the most economical way.

It is further seen that the influence of the air velocity level on the shape of the wet bulb temperature curve is rather small. The optimal drying time to a given final MC is thus slightly shorter for the higher air velocities. The small irregularities seen in these curves depend on the method of calculation, rounding of errors and model inaccuracy, and are not reflecting actual cost differences.

The normal practise in Scandinavia, at least previously, has been to fix the wet bulb temperature and gradually increase the dry bulb temperature. According to this cost optimisation it would be better to fix the dry bulb temperature and let the wet bulb temperature gradually decrease.

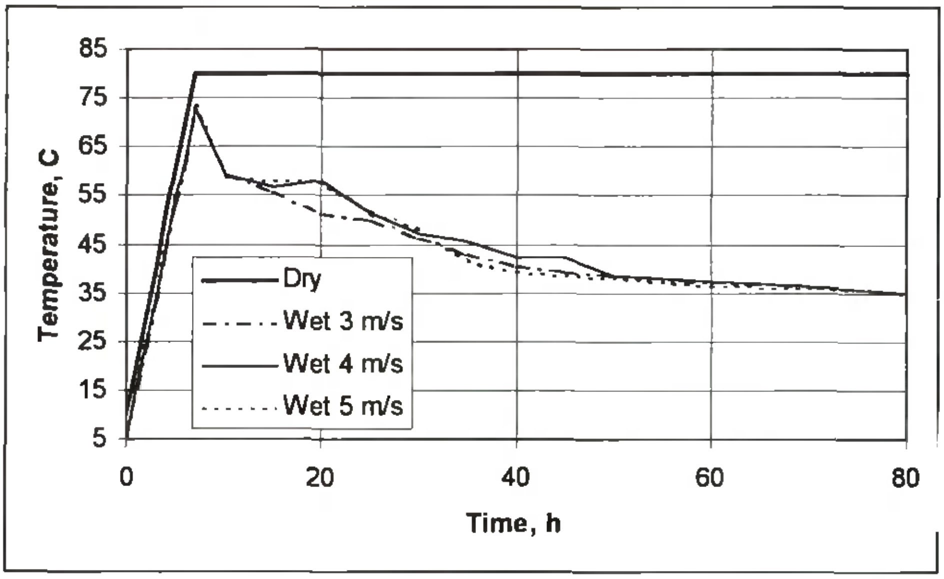

Figure 3. Optimal drying schedules for different air velocities. Maximal temperature 80°C.
Figur 3. Optimala torkscheman vid olika lufthastigheter. Maximal temperatur 80°C.

Figure 4 presents the corresponding instantaneous total cost as a function of average moisture content. The cost is expressed as € per m^3 and %-unit MC removed. It is seen that the cost

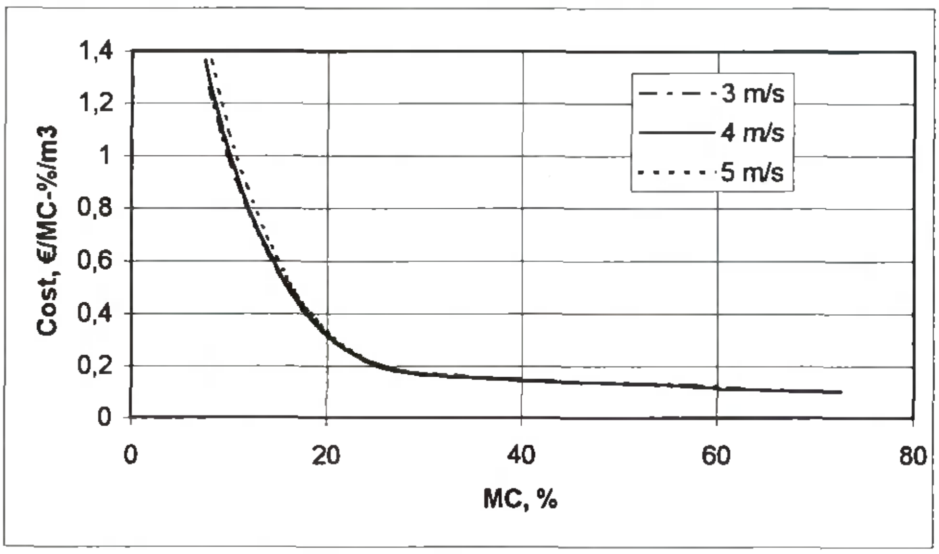

Figure 4. Instantaneous total cost for different air velocities. Maximal temperature 80°C.
Figur 4. Momentan totalkostnad vid olika lufthastigheter. Maximal temperatur 80°C.

remains almost constant at a relatively low level until the equilibrium moisture content is approximately reached. Then the cost increases rapidly, which reflects that the drying rate decreases and that the longer time needed for each MC %-unit removed accumulates more fixed costs.
It is also seen that the influence of the air velocity is very small, at least in the range 3...5 m/s in this case. It has to be pointed out that each air velocity in Figure 4 corresponds to a slightly different drying schedule and a slightly different drying time. In Figure 4, the area below the curve and between the initial and final MC gives the total cost in €/m^3 for drying to that final MC.

Next the results for 60°C maximal temperature are studied. Figure 5 shows the optimal cost schedules for three different fixed air velocities, 2, 3 and 4 m/s.

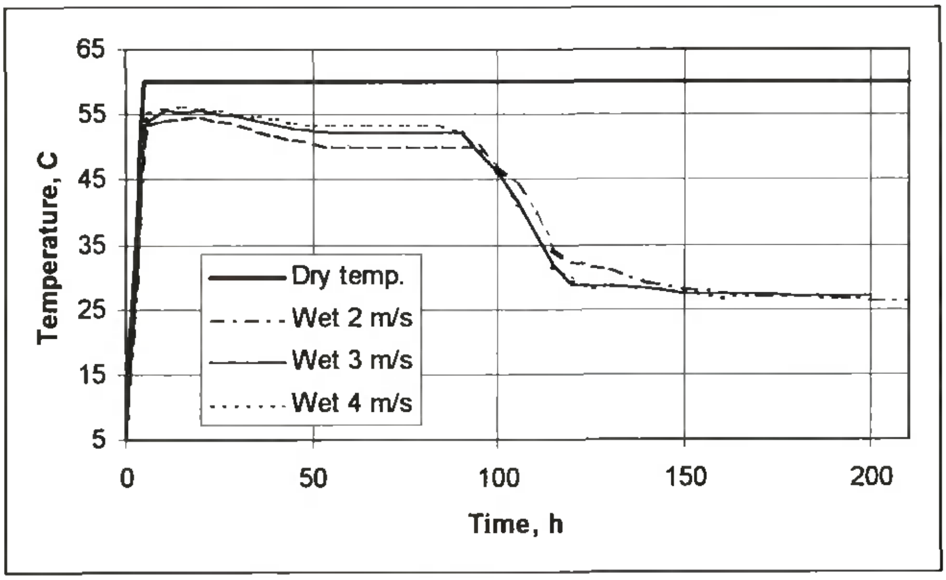

Figure 5. Optimal drying schedules for different air velocities. Maximal temperature 60°C.
Figur 5. Optimala torkscheman vid olika lufthastigheter. Maximal temperatur 60°C.

Again the best result is obtained by quickly heating to the maximal temperature and then gradually increasing the wet bulb depression. Now, for this lower temperature level, the beginning of the schedule is determined by the restrictions caused by the stress development. Without the cost associated with checking, a faster drying would have been optimal. After 110-120 h the form of the schedule is determined by the cost only. In this case there are some differences between the schedules depending on the air velocity, but a higher velocity would still give a slightly shorter drying time.

Figure 6 presents the corresponding instantaneous total cost as a function of moisture content. An intermediate rise in cost is seen at an MC just below 20%, and this is due to the restrictions caused by the risk of checking. The shape of the curves is otherwise similar to those seen for 80°C in Figure 4, but the cost level is now considerably higher, which shows that an increase in temperature decreases the cost. Figure 6 again points out that the air velocity has a minor influence on the total cost, provided that the corresponding drying schedules are individually optimised in each case.

These results so far, represented a situation where the possibility to continuously regulate the fan speed is not available. Next the question of optimal fan speed, i.e. optimal air velocity, is studied. The insignificant influence of air velocity, seen in Figures 4 and 6, indicates that a varying velocity will only give a marginal additional economic benefit. It is, however, interesting to investigate the general principle for how such a fan speed regulation system should be operated.

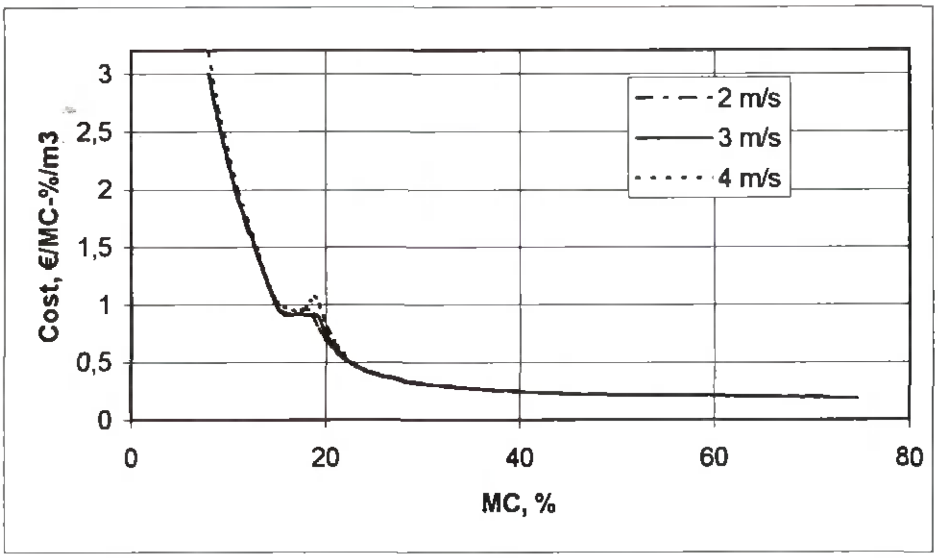

Figure 6. Instantaneous total cost for different air velocities. Maximal temperature 60°C.
Figur 6. Momentan totalkostnad vid olika lufthastigheter. Maximal temperatur 60°C.

In the previous calculations the air velocity was fixed throughout the drying cycle, and the shape of the drying schedule was optimised. Now the schedule is divided into short parts and within each part the air velocity is kept constant and the schedule is optimised. By selecting different values for the velocity within each part, the optimal combination velocity/schedule is

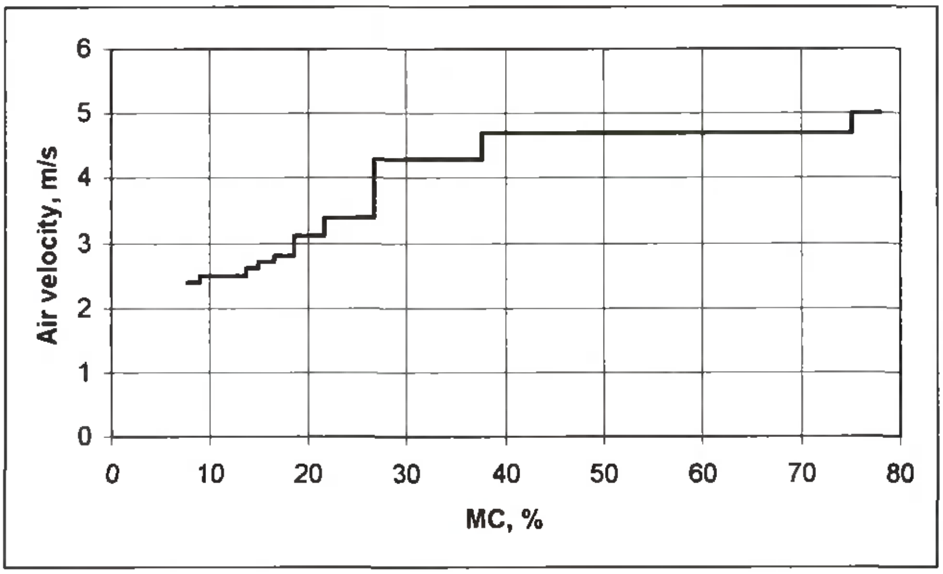

Figure 7. Optimal cost air velocity. Maximal temperature 80°C.
Figur 7. Kostnadsoptimal lufthastighet. Maximal temperatur 80°C.

eventually found. This procedure produces a step curve for the air velocity variation, which is a sufficient result for the very marginal benefit.

The result for the 80°C case is found in Figure 7. In the beginning a rather high velocity (4,5...5 m/s) is optimal, but starting from a point slightly above EMC, the velocity should gradually be decreased. For very low MC levels the optimal velocity is only half the level in the beginning.

Finally the corresponding result for 60°C is presented in Figure 8.

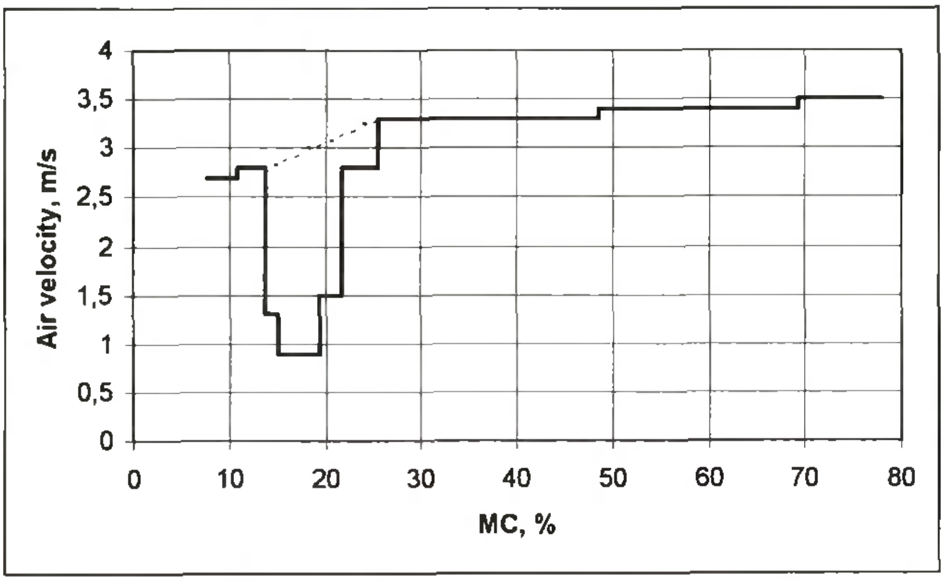

Figure 8. Optimal cost air velocity. Maximal temperature 60°C.
Figur 8. Kostnadsoptimal lufthastighet. Maximal temperatur 60°C.

The result seen in Figure 8 is rather surprising. In this case the schedule and the velocity is determined by the risk of checking restriction down to about 15% moisture content. During this period there is a rather well defined maximal allowable drying rate and a corresponding energy demand. It is then better to supply this energy in the form of cheaper heat, instead of electric power, which means low velocities and high wet bulb depressions. From a practical standpoint, however, such an air velocity regulation procedure is not recommended. A better procedure is indicated by the dotted line in Figure 8. In that case the end of the curve is rather similar to the 80°C case in Figure 7.

Table 1. Total drying costs in € per m^3 for the calculated cases.

Temperature	Air velocity	15% final MC	8% final MC
60°C	2 m/s	21,5 €/m^3	34,5 €/m^3
	3 m/s	21,4 €/m^3	34,5 €/m^3
	4 m/s	22,1 €/m^3	35,6 €/m^3
	variable	21,1 €/m^3	34,0 €/m^3
80°C	3 m/s	13,2 €/m^3	19,2 €/m^3
	4 m/s	13,2 €/m^3	19,3 €/m^3
	5 m/s	13,4 €/m^3	20,0 €/m^3
	variable	13,1 €/m^3	19,1 €/m^3

The calculated cases are summarised in Table 1, expressed as total cost per cubic meter for two different final moisture content levels. It is clearly seen that both the temperature level and the final moisture content target influence the cost very much. The air velocity, on the contrary, has a rather small influence. As stated earlier, these costs do not contain all costs, but can be used for comparison of the different situations.

5. CONCLUSIONS

From the cases calculated it can be seen that of the costs associated with the timber drying process, the capital costs represent a considerable part of the total costs. Fast drying is thus in general favourable, but especially for relatively low temperatures the risk of checking may restrict the drying rate. Optimisation calculations show that the temperature has a dominating influence on the total cost. Thus the highest possible temperature that can be accepted based on kiln equipment and timber quality considerations should be used. For constant air velocity (fan speed), the selected velocity level has a minor influence on the total cost, if the corresponding drying schedule is properly chosen. A very marginal additional benefit is obtained if the air velocity is continuously regulated during the drying cycle.

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