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Global modelling of kiln drying, taking local variations in the timber stack into consideration

Paper presented at the 7th International IUFRO Wood Drying Conference, Tsukuba, Japan, July 9–13, 2001

Trätek

INSTITUTET FÖR TRÄTEKNISK FORSKNING

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GLOBAL MODELLING OF KILN DRYING, TAKING LOCAL VARIATIONS IN THE TIMBER STACK INTO CONSIDERATION
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Sammanfattning

Simuleringsmodeller som förutspår torkningsförloppet för en ensam virkesbit i ett givet klimat, har funnits tillgängliga under många år. Sådana modeller för lågtemperaturtorkning av furu (Pinus silvestris) och gran (Picea abies), används av torkskötare vid många sågverk i Sverige, Finland och Norge. Den ensamma simulerade virkesbiten representerar i dessa fall medel-förloppet för hela torksatsen.

Många fenomen som uppträder i en verklig kammartork, kan emellertid inte direkt studeras med sådana en-bits modeller. Typiska problem av detta slag är, i blåsriktningen varierande klimat vilket ger ojämn torkning, inverkan av fläktreversering, inverkan av lufthastigheten på ojämnhet i fuktkvot etc. Enligt skandinavisk praxis, är ströpaketet uppbyggt av virkesbitar med sågfallande längd, så att varannan bit är jämndragen med ströpaketets ena ände, och varannan bit är jämn-dragen med paketets andra ände. Detta leder till en mittdel av ströpaketet där alla positioner är fyllda, och änddelar av ströpaketet där varannan position är tom. Dessa delar har olika geometri för luftflödet, vilket ger olika lufthastigheter och olika externa värme- och massöverföringspro-filer. Dessutom blir luftflödena genom mittdelen och änddelarna delvis sammanblandade vid passagen genom torksatsen. Det ofta betydande läckaget förbi virkespaketen blandas även delvis med det "aktiva" flödet. Dessa fenomen ger ett klimat som varierar både i blåsriktningen och tvärs denna riktning.

En global modell har utvecklats, som försöker förutspå lokala lufthastigheter och lokala över-föringskoefficienter, samt vidare det lokala klimatet utifrån växelverkan mellan luft och virke. Därefter beräknar modellen den samtidiga torkningen av upp till några hundra virkesbitar (eller positioner) i torksatsen. Denna artikel presenterar några överväganden rörande strukturen i en sådan global modell och några erhållna simuleringsresultat.

Global Modelling of Kiln Drying, Taking Local Variations in the Timber Stack into Consideration

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ABSTRACT

Simulation models that predict the drying behaviour of a single board in a given climate have been available for many years. In Sweden, Finland and Norway such models for low temperature drying of Scots pine and Norway spruce are used by kiln operators at many sawmills. The simulated single board represents in these cases the average behaviour of the whole timber load.

However, a lot of phenomena occurring in a real kiln, can not be directly studied with such single board models. Typical problems of that kind are changing climate in the airflow direction giving uneven drying, influence of air-flow reversal, influence of air velocity on MC unevenness, etc. In Scandinavian practice, kiln stacks are normally built from boards of random lengths so that every second board is located flush at one end of the stack, and the other boards flush at the other end. This produces a centre part of the stack where all locations are filled, and end parts of the stack where every second position is empty. These parts have different airflow geometries, thus giving different velocities and external heat and mass transfer profiles. Furthermore, the airflows through the centre and end parts are partially mixed during the passage of the timber load. Also the, often substantial, flow by-passing the stack is partially mixing with the "active" flow. These phenomena give a climate that varies both in the airflow direction and in the perpendicular direction.

A global model has been developed, that tries to predict local air velocities and local transfer coefficients and further local climate from the interaction between air and timber. Then the model calculates the simultaneous drying of up to a few hundred boards (or locations) in the stack. This paper presents some considerations regarding the structure of such a global model and some simulation results obtained.

INTRODUCTION

The Swedish Institute for Wood Technology Research (Trätek) has developed a computer based simulation model, called TORKSIM, for the batch kiln drying process. This model has been distributed to kiln operators and people responsible for the drying process, for some three years. The response has generally been very positive and many sawmills are using the model on a regular basis, as a tool for process analysis, schedule optimisation etc.

The model is based on the one-dimensional diffusion equation and the wood temperature is determined from energy and mass balances. An important feature is that drying of only one board (or three, see below) is simulated. Properties of this board (initial MC, density etc.) are chosen according to the average values for the whole timber load. The drying schedule is thus also given as the average climate for the whole batch, i.e. in practice mean of air climate entering and leaving the timber load.

In Scandinavia there will in almost every board be both heartwood and sapwood in the same board. As heartwood and sapwood have different properties and quite different initial MC, this problem has to be solved in some way. In TORKSIM this matter is handled by a material property homogenisation procedure. Normally the simulation of the single average board is extended with two additional simulations, one for pure heartwood and one for pure sapwood. This makes a more reliable prediction possible of the risk of checking, based on stress calculations for each of these three cases.

The output from the model consists of MC profile and average MC, wood temperature, stress level (checking), slicing test gap, energy consumption and drying costs, all as a function of time. Details regarding the TORKSIM model are found in (Salin 1999, Salin 2001).

Although TORKSIM is a valuable tool that can solve many questions, there are, however, still many problems that are outside its area of application. Most of these problems are related to the fact that TORKSIM simulates only one board, which represents the whole load. This means that the individual drying behaviour of a board in a certain location in the stack, with the corresponding local climate, can not be studied. Also, the stack geometry cannot be handled in a more detailed way. The obvious solution regarding these restrictions is to develop a global model consisting of many TORKSIM models coupled in parallel, each of which simulates the drying behaviour of a single board in a specified location in the stack. This cluster is then extended with routines that determine the local climate for each of these boards from the air/timber interaction and the external heat and mass transfer coefficients for each board from aerodynamic considerations. Such a multiple board simulation model, called TORKSIM Global, is described in the following.

STACK GEOMETRY AND AIR FLOW

In Scandinavian practice, kiln stacks are normally built from boards of random length so that every second board is located flush at one end of the stack, and the other boards flush at the other end. Figure 1 illustrates this pattern, seen from above. Thus two different areas can be seen, a centre part of the stack where all locations are filled, and end parts of the stack where every second position is empty. It is quite clear that air velocity, external heat and mass transfer coefficients and thus drying behaviour are different in these two areas.

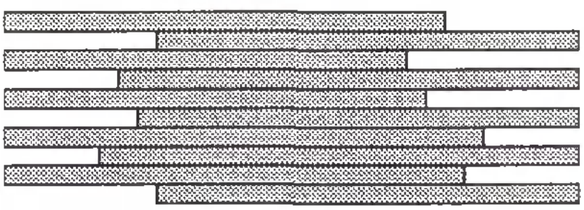

FIGURE 1. Layer of random length boards seen from above.
FIGUR 1. Ett strölager med sågfallande virkesbitar, sett från ovan.

In the model, the random pattern seen in Figure 1 is replaced by an assumed pattern where every board has the same length, equal to the average board length in the stack. In this way the centre and end parts of the stack are clearly defined and can be simulated separately. The first question is then how the air velocities in these parts differ for a given pressure drop across the whole stack.

The air velocity is higher in the centre part compared to the end part. In a theoretical investigation (Salin and Öhman 1998) the ratio 1,34 was found. Two full-scale measurements (Salin and Hájek 1999, Esping 1977) reported 1,3 and 1,21 respectively. Thus 1,3 could be an appropriate value.

Next external heat and mass transfer coefficients have to be chosen for each location. In the stack centre part a rather well defined flow channel is formed by board layers and stickers. Increased turbulence caused by entrance phenomena will increase the transfer coefficients for the first boards and the small gaps between boards will also influence coefficients further into the stack. The stack end part geometry produces highly turbulent flow and fairly constant transfer coefficients throughout this part of the stack. These features have been discussed in (Salin 1996b), but the numerical values given there (which are reproduced in Keey et al 2000 also) seem to overestimate the change in transfer coefficient for boards far from the entrance. Some new correlations have been developed from observed drying behaviour in a few full-scale tests. Figure 2 illustrates this for the calculated example reported below.

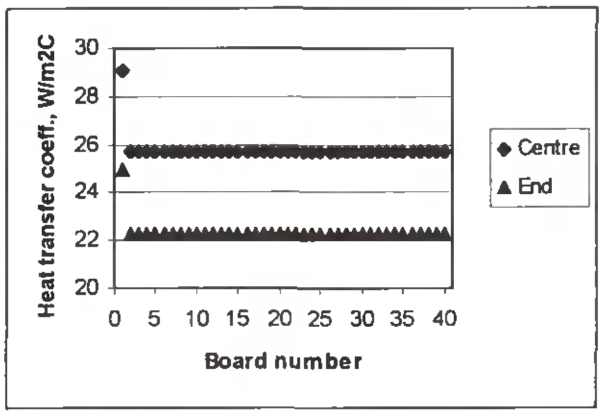

FIGURE 2. Heat transfer coefficients for the centre and end part of individual boards. Air velocity is 3 m/s between board layers in the centre part.
Figur 2. Värmeöverföringskoefficienter för mittdelen och änddelen av individuella virkesbitar. Lufthastigheten är 3 m/s mellan strölagren i mittdelen.

As is seen in Figure 2, only the first board on the pressure side has a clearly different heat transfer coefficient value according to this new correlation. The values for the second and third boards are so close to the "equilibrium" level, that the difference is not seen in this presentation. It should be remembered that the air velocity is lower in the stack end, and this is the reason for the lower values, despite high turbulence.

The external mass transfer coefficient is calculated from the heat transfer coefficient according to Lewis relation, but has to be corrected due to percolation and non-equilibrium phenomena. This correction procedure is described in more detail in (Salin 1996a).

In the discussion above we considered the flows through the stack centre part and its end parts, as separated flows. This is certainly not completely true. These flows will partly mix as they pass through the stack and this can be an important detail, especially for long blow depths (total effective distance from air entrance to exit). It is further well known that often considerable amounts of air will by-pass the timber stack through channels below and above the stack and through the gap between kiln wall and stack. This despite normal measures to restrict these "inactive" flows. It is important to consider this by-pass flow for two reasons. First, it will partly mix into the "active" flows as mentioned above, and change the climate development within the stack. Secondly, depending on where the temperature measurement point is located (on the suction side), the by-pass flow is either included or not included in the climate measured. This is important if, for instance, the drying schedule is defined as mean of air conditions entering and leaving the timber stack. These facts indicate clearly that it is important to include both the by-pass airflow and the flow mixing phenomena in the global model.

GLOBAL MODELLING

The general structure adopted for the TORKSIM Global model is as follows. Instead of simulating only one board representing the whole kiln load, all boards in one board layer across the kiln in the air flow direction are simulated in parallel. Each board is attributed properties (initial MC, heartwood content, density etc.) according to the average for the whole load. Each such board thus represents the average drying behaviour of all boards in that specific (vertical) position. Each board is in addition divided into two parts, one representing the situation in the centre part of the stack (see Figure 1) and the other representing the end part of the stack.

The simulation starts with the first board on the pressure (air entrance) side. The climate is then directly or indirectly known from the specified drying schedule. The air velocities for the centre/end parts of that board are fixed based on information regarding the kiln in question and the corresponding external heat and mass transfer coefficients are selected using appropriate correlations. Now drying of both parts of this first board can be calculated for the current time step. A TORKSIM-type model does this calculation.

The air (climate) "leaving" this first board can now be determined from energy and mass balances based on the now known interaction between this board and the drying air. This new climate is now "corrected" according to the airflow mixing phenomena. A small part of the by-pass flow is mixed into the flow passing through the stack end part and vice versa. The same applies to the stack centre/end part airflow pair. In this way the climate for both ends of the second board (in the airflow direction) is determined and now drying of this second board can be simulated, using the corresponding external heat and mass transfer coefficients. The change in by-pass air climate is obtained at the same time.

In this way the calculation proceeds through the whole kiln stack and finally the climates for the airflows (centre/end/bypass) leaving the stack on the suction side are obtained for the current time step. After that, the whole procedure is repeated for the next time step, starting again with the first board on the pressure side. It is rather common that the drying schedule is implemented as the mean of pressure and suction side dry/wet bulb temperatures. In such a case, the climate entering the stack is not known exactly in advance, but has to be guessed. The correctness of this guess is evaluated when the exit climate has been calculated. In principle, an iteration procedure should be used in this case. However, in practice the time step used in the calculation is very short compared to the rate of change in the drying schedule. Thus a deviation found for a certain time step, could be accounted for during the next time step, without any appreciable loss in accuracy.

The airflow direction is normally reversed on a regular basis – in Scandinavia often about every 60 minutes. This is rather easily included in the global simulation, just by reversing the order in which the boards in the stack layer are simulated, i.e. always beginning from the pressure side.

As the above primary simulation was done using boards with average properties, the obtained local climates (and their time dependence) represent average (or most probable) climates in the stack for the case studied. If we are interested in how a specific board with different properties (high initial MC, low density etc.) dries in a given location in the stack, then we can use the corresponding climate calculated in the primary simulation. Such a secondary simulation could be done at the same time as the primary simulation, immediately after the local climate has been determined for the current time step. Alternatively this secondary simulation could be done separately if the calculated local climates are stored in a file.

As mentioned in the introduction, the single board simulation (TORKSIM) is preferably extended with two additional simulations, one for pure heartwood and one for pure sapwood. It is logical to use the same idea in the global simulation; i.e. a set of pure heartwood boards and a set of pure sapwood boards are studied in the secondary simulation. This gives a much better coverage of stress development and risk of checking for the whole kiln load.

A NUMERICAL EXAMPLE

A fairly typical case has been simulated in order to illustrate a few results that can be obtained by a global model of the type described above. The case concerns drying of 50 x 150 mm^2 Scots pine, in four stacks with 10 boards in each stack layer. There is thus a total of 40 boards in the air flow direction, corresponding to a blow depth of 6 meters. The stack length is 5,6 m, average board length 4,2 m and sticker thickness 25 mm. Air velocity in the gap between board layers is 3 m/s in the stack centre part and the flow direction is reversed every 60 minutes. The drying schedule, which is defined as the climate on the pressure side, has a constant dry bulb temperature and a decreasing wet bulb temperature as illustrated in Figure 3.

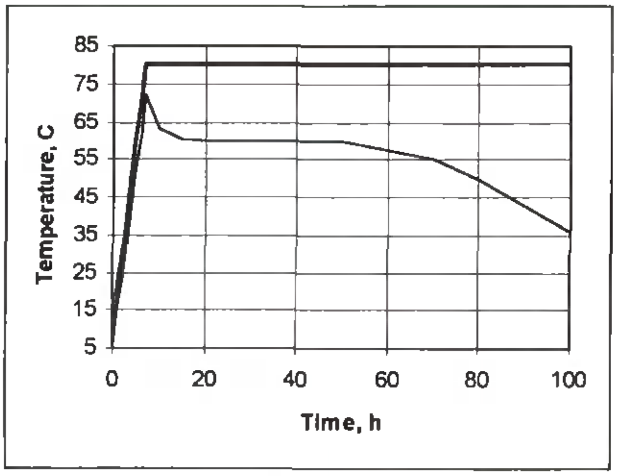

FIGURE 3. Dry and wet bulb temperature drying schedule for the numerical case studied.
FIGUR 3. Torkschema med torr och våt temperatur för det studerade numeriska exemplet.

First the calculated board MC as a function of location and time is presented in Figure 4 for the eentre part of the stack and in Figure 5 for the end part. It can be seen that the end part dries considerably faster than the centre part during the initial part of the drying cycle. It is also seen that there is a remarkable difference in MC level between boards close to the edge and boards farther into the timber load. According to a rule of thumb the blow depth (m) divided by the air velocity (m/s) should preferably be less than 2 for low temperature drying. In this case (ratio = 2) with a relatively high temperature, this rule seems too weak.

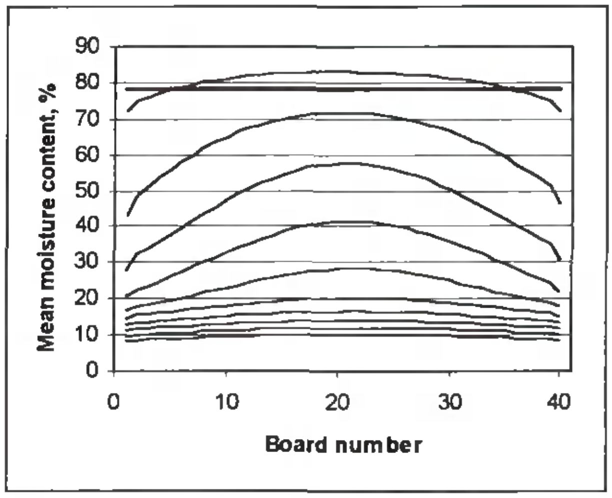

FIGURE 4. Board moisture profiles in the airflow direction in the stack centre part (10 h between curves).
FIGUR 4. Fuktkvotsprofiler i blåsriktningen i ströpaketens mittdel (10 h mellan kurvorna).

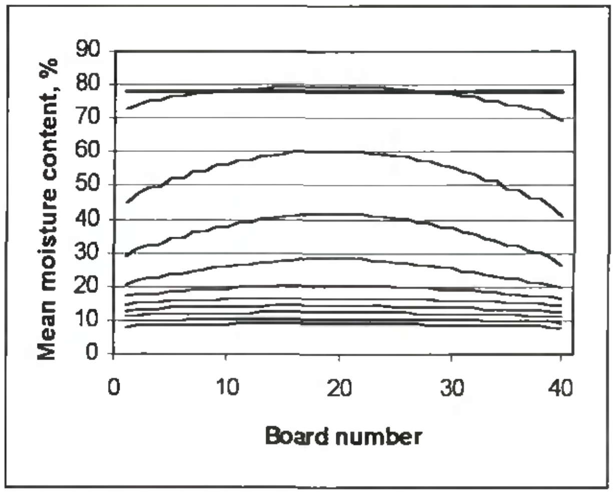

FIGURE 5. Board moisture profiles in the airflow direction in the stack end parts (10 h between curves).
FIGUR 5. Fuktkvotsprofiler i blåsriktningen i ströpaketens änddelar (10 h mellan kurvorna).

The standard deviation for the moisture content of individual boards in the timber load can of course be found from the results of the simulation. This is presented in Figure 6 for the centre and end parts of the stack and for the whole timber load.
It should be noted that this standard deviation is the variation caused by the *position* of the board, i.e. equal boards in different positions. To obtain the standard deviation found in practice, both the variation caused by different board properties (initial MC, heartwood content, density etc.) and by different EMC (Esping 1992) has to be superimposed on the result seen in Figure 6.

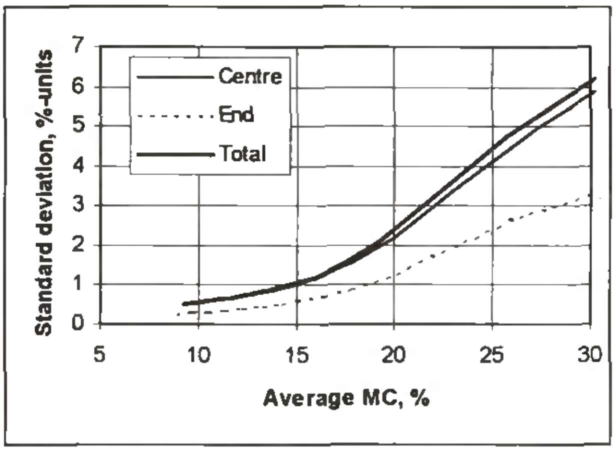

FIGURE 6. Board MC standard deviation as a function of average MC.
FIGUR 6. Standardavvikelsen för virkesbitarnas fuktkvot, som funktion av medelfuktkvoten.

Figure 6 shows that the MC variation is lower in the end part of the stack compared to the centre part. The blow depth and air velocity ratio, mentioned above, is about 1,3 for the end part, which explains this result. It seems that the variation in the centre part of the stack dominates in the calculation for the whole load.

It is of some interest to study the temperature transients in the stack in connection with fan reversal. Figure 7 presents air temperature in the stack centre part as a function of location and time during one reversal cycle. The curve starting in the upper right corner of Figure 7 gives the dry bulb temperature at 48 h drying time (see Figure 3) a moment before reversal. The air enters at 80°C, according to the schedule, and exits the stack at about 71°C. At that moment boards with high board numbers are warmer than boards with low numbers. The curves starting at the upper left corner represent air temperature profiles for every 10 minutes during one 60 minutes period between fan reversals. The most rapidly dropping curve presents the situation immediately after fan reversal, when the "cold" boards on the left side cool the air quickly. But on the right side the still "hot" boards will reheat the air so that it exits the stack at a rather high temperature. Gradually the temperature profiles change shape and the last (thick line) curve just before the next fan reversal is close to a mirror image of the corresponding curve one hour earlier.

It is however obvious that a steady state is not completely reached during the time period between fan reversals, at least not during this part of the drying schedule. As is seen in the lower left corner of Figure 7, the air is still slightly reheated just before fan reversal. This means that the boards close to the stack edge on the suction side are always warmer than the air at that location (during this part of the drying schedule), which is a rather remarkable feature.

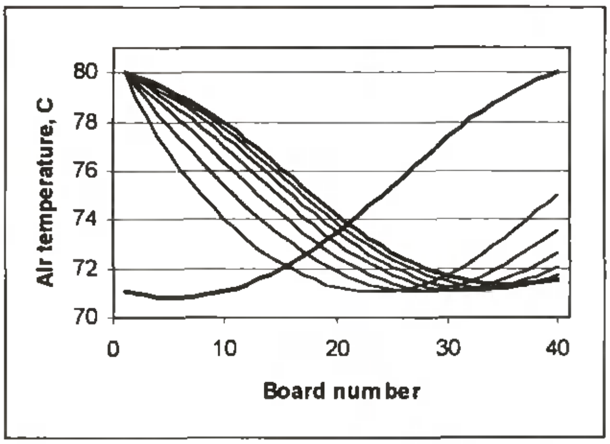

FIGURE 7. Air temperature profiles in the stack centre part during one fan reversal cycle.
FIGUR 7. Lufttemperaturprofiler i ströpaketens mittdel under en fläktreverseringscykel.

It can further be concluded, that a kiln regulation system based on "Temperature Drop Across the Load" would be very difficult to realise, as a steady state is never reached in this specific example. It should also be noted that the air entering the stack had constant dry and wet bulb temperatures during the time period studied (see Figure 3). For a non-constant climate, the changes would have been superimposed on the curves in Figure 7, making the situation much more complicated.

In this numerical example, the drying schedule has above been defined as dry and wet bulb temperatures on the pressure side of the timber load. This corresponds to schedule A in Figure 8. It is, however, perhaps a more

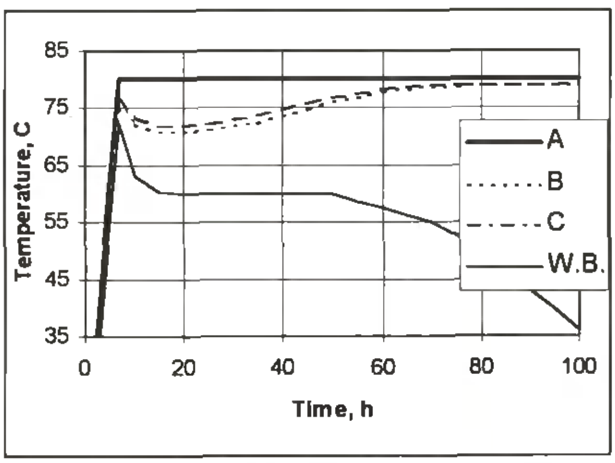

FIGURE 8. Different modes of drying schedule presentation.
FIGUR 8. Olika sätt att presentera ett torkschema.

common practice to express the schedule as the mean of pressure and suction side temperatures. It is in that case important to define the position of the suction side measurement point. Sometimes the thermometers are fixed to the end of a beam that is turned in front of the stack after loading. Then perhaps only the air leaving the centre part of the stack affects the measurement, which corresponds to schedule B in Figure 8. Another possibility is that all flows (centre/end/bypass) are measured together after mixing. This corresponds to schedule C in Figure 8. Schedule A differs for obvious reasons from B and C, but B and C may also differ, especially for high by-pass flows.

CONCLUSIONS

This paper describes a multiple-board simulation model and some aspects regarding the structure of such a model. The numerical example presented shows that several important and interesting features – that can't be handled by single-board models – can now be simulated and analysed. A multiple-board model is more complicated to use and requires more computer time, but it is our intention to distribute it to kiln operators and people responsible for the drying process in Swedish sawmills, as a compliment to the single-board model. One important benefit for the sawmill is the use of this tool for educational purposes (Salin 2001).

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