CHAPTER 3: SCHEDULE DEVELOPMENT FOR DRYING TIMBER IN SOLAR KILNS

3.1 INTRODUCTION

A drying schedule is a set of temperatures, relative humidities and corresponding equilibrium moisture contents of timber that change with either the actual average moisture content of the timber (a moisture-content based schedule) or the time from the start of drying (a time based schedule). The drying schedule is dependent on the timber species. A major challenge for researchers and industries in timber drying is to reduce the drying time and the loss of product due to drying degrade. Generally, longer drying times (low temperatures and high humidities in the early stages of drying, with a corresponding slow drying rate) for refractory hardwoods like eucalypts result in less product loss and vice versa. Vermass (1995) suggests that, in kiln drying green eucalypt timber of 25 mm thickness or more, the drying temperature should not exceed 45°C during the early stages and the relative humidity should be kept high, otherwise surface checks or internal checks (honeycombing) may develop. An optimised drying schedule (a strain-limited drying schedule) may trade off between these two opposing objectives (quality and productivity). The final aim is to achieve both faster drying and better product quality by applying an optimised schedule. The product quality here is indicated by the absence of any crack or split on the surface and the ends of the timber boards. The optimised schedule dries the timber in the fastest possible time, which is limited by a maximum strain level that is unlikely to cause the timber to crack.

Boral Timber has built solar kilns at their Herons Creek sawmill site in New South Wales for processing blackbutt timber boards. An effective drying schedule is necessary for use in these solar kilns to dry blackbutt timber boards for structural and other end-uses
as fast as possible while improving the product quality. These kilns include supplementary steam heating and water sprays, and these features give additional control of the air temperature and humidity, respectively, above the level of control normally present in a solar kiln, so achieving a preset drying schedule is usually possible.

### 3.2 THE ORIGINAL DRYING SCHEDULE

The solar kiln supplier (Australian Design Hardwoods Pty Ltd, NSW) has provided Boral Timber with a drying schedule for drying blackbutt boards of 38 mm thickness (nominal undressed dry), corresponding to a 43 mm green thick board and 35 mm thick dry dressed and finished board (after planing operations). The schedule is based on the moisture content of the timber. However, this schedule was followed by the kiln operator as a time-based one, after translating the moisture-content based schedule to a time-based schedule (Table 3.1).

**Table 3.1:** Original time-based schedule for drying 43 mm thick (green) blackbutt boards from the solar kiln supplier.

<table>
<thead>
<tr>
<th>Time (week)</th>
<th>Dry-bulb temperature (°C)</th>
<th>Wet-bulb temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Equilibrium moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>25</td>
<td>95</td>
<td>&lt; 21</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>24</td>
<td>87</td>
<td>18.0</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>33</td>
<td>85</td>
<td>17.1</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>32</td>
<td>80</td>
<td>15.2</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>30</td>
<td>70</td>
<td>12.5</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>29</td>
<td>65</td>
<td>11.3</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>28</td>
<td>60</td>
<td>10.5</td>
</tr>
<tr>
<td>8</td>
<td>35</td>
<td>27</td>
<td>55</td>
<td>9.5</td>
</tr>
<tr>
<td>9</td>
<td>35</td>
<td>26</td>
<td>50</td>
<td>8.8</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>29</td>
<td>45</td>
<td>7.8</td>
</tr>
<tr>
<td>11</td>
<td>40</td>
<td>25</td>
<td>30</td>
<td>5.7</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>29</td>
<td>30</td>
<td>5.3</td>
</tr>
<tr>
<td>13</td>
<td>45</td>
<td>29</td>
<td>30</td>
<td>5.3</td>
</tr>
<tr>
<td>14</td>
<td>45</td>
<td>29</td>
<td>30</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Each step (condition) of the schedule was applied for one week in the solar kiln. The total drying time was eight weeks for a moisture content change from green (above 60%) to about 25% for the first few batches. The same schedule dried timber in six weeks during the laboratory trial for a similar change in moisture contents. This original schedule required about twelve weeks to dry from moisture contents of 60% to 12% in a laboratory trial (a slight modification for the final drying stage was necessary) as described in a previous chapter (section 2.5.1). The supplied moisture-content based schedule is shown in Table 3.2.

### Table 3.2: Original moisture-content based schedule for drying 43 mm thick (green) blackbutt boards from the solar kiln supplier.

<table>
<thead>
<tr>
<th>Initial moisture content (%)</th>
<th>Dry-bulb temperature (°C)</th>
<th>Wet-bulb temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Equilibrium moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>25</td>
<td>24</td>
<td>85</td>
<td>18</td>
</tr>
<tr>
<td>60</td>
<td>25</td>
<td>23</td>
<td>80</td>
<td>16</td>
</tr>
<tr>
<td>45</td>
<td>30</td>
<td>27</td>
<td>75</td>
<td>13.5</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
<td>30</td>
<td>70</td>
<td>11.6</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
<td>29</td>
<td>65</td>
<td>10.7</td>
</tr>
<tr>
<td>25</td>
<td>35</td>
<td>28</td>
<td>55</td>
<td>8.5</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>29</td>
<td>45</td>
<td>7</td>
</tr>
<tr>
<td>15</td>
<td>45</td>
<td>29</td>
<td>30</td>
<td>5.5</td>
</tr>
<tr>
<td>Recondition</td>
<td>45</td>
<td>40</td>
<td>75</td>
<td>12.8</td>
</tr>
</tbody>
</table>

### 3.3 INDUSTRIAL OBSERVATIONS: ACCELERATED DRYING SCHEDULE AND CURRENT APPROACH

Later, two batches of timber were dried in the solar kiln using an accelerated schedule (Table 3.3) based on the original schedule. The drying time was seven weeks for a similar reduction in moisture content to the previous batches dried with the original schedule. According to the schedule, the moisture content (to 25%) should have been 12% after eight weeks, but in reality after seven weeks of drying time, the moisture content was
around 25%. The reason is that the drying conditions may have been changed each week, even though the timber did not reach the desired moisture content at the end of each week, implying that the translation from the moisture content based schedule to the time based schedule was not completely correct. However, the difference between the expected and actual drying times to a moisture content of 25% (eight weeks and seven weeks, respectively) was not large.

**Table 3.3:** Accelerated drying schedule for 43 mm thick (green) blackbutt boards.

<table>
<thead>
<tr>
<th>Time (weeks)</th>
<th>Dry-bulb temperature (°C)</th>
<th>Wet-bulb temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Equilibrium moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>28</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>27</td>
<td>80</td>
<td>15.5</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>36</td>
<td>75</td>
<td>13.5</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>35</td>
<td>70</td>
<td>12.1</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>33</td>
<td>60</td>
<td>10.1</td>
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<tr>
<td>6</td>
<td>40</td>
<td>31</td>
<td>50</td>
<td>8.5</td>
</tr>
<tr>
<td>7</td>
<td>45</td>
<td>31</td>
<td>35</td>
<td>6.1</td>
</tr>
<tr>
<td>8</td>
<td>45</td>
<td>29</td>
<td>30</td>
<td>5.5</td>
</tr>
</tbody>
</table>

It may require thirteen weeks or more to dry from green to 12% moisture content with such a schedule in solar kilns, considering the current operating procedure and the experience for the previous batch. Although there is an additional heating option in the solar kiln (namely, steam), the boiler is shut down during the night on every day, on the weekly closing days and on holidays. Since there were a large number of checks visible on the board surface and splits at the board ends during the early stage of drying compared with previous batches, this modified schedule was discontinued for later batches. However, at the end of drying there was no apparent difference between the final quality of the finished products dried with the slow and the accelerated schedules, due possibly to cracks in the boards closing up during drying. The boards of this batch (batch
1) of dry timber from the solar kiln using the accelerated schedule were thinner (unusual shrinkage) compared with the previous batches, although a similar procedure was followed from sawing to planing. However, the other batch (batch 2) dried using the accelerated schedule was standard grade (normally produced), and there was no such problem. Though there was no confirmation, there may have been a problem with the machine setting for the cutting-width at the saw-bench for that particular batch (batch 1) of timber boards, which resulted in boards that were thinner than the finally specified dimension. The cutting width at the saw-bench is fixed, according to the shrinkage percentage, in two different planes. These shrinkage percentages are usually 7% for the tangential direction and 4% for the radial direction, respectively, for blackbutt (Bootle, 1994). Green boards are sawn allowing for this shrinkage behaviour to achieve the final desired dimensions after drying, planing and finishing. If the machine setting drifts for some reason, and is not fixed and checked at regular intervals, boards will be cut with the wrong width and thickness, which can be a significant problem for later processing of the boards. As a result of the incorrectly setting the cutting width of the saw-bench, either there may be too little material available for adequate planing during further processing, or the finished board may be thicker than desired. This problem may have confounded the original assessment of the first batch of timber dried using the accelerated schedule.

There were different trial-and-error modifications made to the original schedule. All those minor modifications did not reduce the drying time or change the product quality. Finally the solar kiln operator returned to using the original drying schedule provided by the supplier of the solar kiln. This work reported in this chapter is an attempt to apply a systematic technique to optimising and improving the original drying schedule.
3.4 OPTIMISED SCHEDULE DEVELOPMENT (LITERATURE REVIEW)

The task of schedule development has often been based on experience, essentially using trial and error approaches. However, this procedure can be very expensive due to the time required for testing. Many researchers have attempted to develop optimised schedules based on drying modelling and simulation approaches. The main features of some of these works are now presented.

Salin (1988) developed an optimised schedule for Scots pine (*Pinus sylvestris*) and spruce (*Picea abies*) for drying in batch and progressive kilns. He developed a one-dimensional computer simulation model for the sawn timber drying process using computer codes that gave a numerical solution of the moisture transport equations with convective heat and mass transfer boundary conditions. His drying model was based on the drying theory of Stanish *et al.* (1984, 1986), but after much simplification by neglecting temperature and pressure gradients inside the timber boards during drying. His argument was that both temperature and internal pressure fields relax very quickly compared with the moisture-content gradients if the drying temperature is well below the boiling point of water (since he used a maximum dry-bulb temperature of 80°C). Thus the system of differential equations was reduced to a single diffusion equation. The drying of boards was simulated by solving this simple Fickian diffusion equation with convective boundary conditions, assuming that the Chilton-Colburn analogy between heat and mass transfer is applicable. Moisture profiles in the wood were obtained as a function of time and drying conditions. The model was extended by calculating the internal one-dimensional stress profile, which developed from the shrinkage of wood below the fibre saturation point. The calculation of stresses and strains was made assuming particular
values of various wood mechanical properties, and pure elastic and viscoelastic components (no mechanosorptive effect was considered). He suggested that the model could be used to calculate the drying curve and energy consumption and to estimate the risk of check formation, which is an important timber quality factor. He reported simulation results for various dry and wet-bulb temperature differences, giving the drying rates and stresses as functions of time. For the progressive kiln, his simulation showed that the drying rate increased rapidly at the beginning of drying due to the rising dry and wet-bulb temperature difference as the board moved against the air flow, until the surface fibre saturation point was reached (until this point there was no stress). The minimum dry and wet-bulb temperatures were 54°C, with a maximum dry-bulb temperature of 64°C. The wet-bulb temperature was kept constant and the air velocity was 3 m s⁻¹. The stress started to develop when the drying rate was highest, and after that stage the drying rate dropped rapidly. The drying rate was highest after 25 hours, and the stress reached a maximum after 39 hours of the total drying time (120 hours). The timber stack was at the middle position of the progressive kiln after 60 hours and at the exit position of the kiln after 120 hours. The stress dropped sharply by about 50% just after 49 hours of drying. A peak in the stress curve indicated that the choice of air velocity and air conditions at the end of the dryer was restricted by a certain short period of the total drying time (10 hours). He suggested that the (one-stage) progressive kiln was not very suitable as far as stress development was concerned.

A drying schedule was also developed by Salin (1988) for a batch kiln. The wet-bulb temperature was kept constant at 44°C, but the dry-bulb temperature was adjusted according to the calculated stress at each moment, so that temperature was decreased
when the maximum stress rose above 80% of the tensile strength and increased if the stress was below that level. The maximum dry-bulb temperature was 64°C, and the air velocity was 6.5 m s⁻¹. A critical period was observed in the second day of drying (when the stress level reached its maximum value), where a low dry and wet-bulb difference of about 3°C was maintained, while the drying was started with a difference of 6°C. The total drying time was six days for a moisture content change from 74% to 10%. After this critical period, a rapid increase in the temperature was possible. The maximum dry-bulb temperature was recommended to be below 80°C for drying Scandinavian softwood. Generally, the drying time is significantly shorter for softwoods compared with hardwoods (Keey et al., 2000). The high temperature (dry-bulb temperature over 100°C) drying of softwood results in a very short drying time and is also current practice in timber industries in many parts of the world (Pang, 1994; Nijdam, 1998), so the reason for the lower temperatures used by Salin (1988) may have been to reach very high quality and appearance levels. The approach used by Salin (1988) is similar to the optimisation procedure used for developing drying schedules for hardwoods in the present research.

Doe et al. (1996) developed a PC based kiln control system called the Clever Kiln Controller (CKC). The CKC contains the full version 'Kilnsched' stress and moisture content model for hardwoods developed by Oliver (1991). In this system, acoustic emissions were also recorded using three sensors on sample boards in the kiln, and an 'acoustic emission threshold' was specified. A collapse threshold temperature (CTT) was determined (a method developed by Innes, 1996) and specified before the start of drying. This concept (CTT) is described in more detail in section 3.5 of this chapter. They incorporated a strain model that predicted a surface strain, which had an upper control
limit that was usually 50-75% of the estimated ultimate value; 0.02 m m\(^{-1}\) for Tasmanian hardwoods. The CKC continually 'looked ahead' to find a schedule using the historical kiln data (temperature, humidity, airspeed), and held the surface strain to the specified maximum value, so it effectively developed an optimised drying schedule on-line. The dry-bulb temperatures were as high as possible but were always kept below the collapse threshold temperature. Acoustic emission was used as a safety override. When any of the three acoustic emission sensors registered a level close to the specified value, then the CKC controlled the kiln based on acoustic emission as an indicator of product quality. When acoustic emission was below the safe level, then the CKC controlled the kiln based on the predicted surface strain as an indicator of product quality. Extensive industrial tests were necessary before commercialisation of this software. This control system has recently been commercialised on a limited scale, and a company has been formed called "Clever Kiln Control Company Limited". The University of Tasmania is a major shareholder of this company. This company is selling a few copies of the Kilnsched software (Pers. comm., 2001). Oliver (1997) expressed disappointment that the majority of innovations in timber drying through research and development have not widely been practiced and applied by the timber industries involved with hardwood processing. It is possible that this control system needs to be more user-friendly for kiln operators before being widely adopted by the industry.

Carlsson and Esping (1997) also formulated the drying process as an optimisation problem. The goal was to dry boards to a target moisture content, with acceptable deformation and intensity of surface checks, i.e. to find the optimal temperatures and humidities as a function of time to dry timber. They were concerned with drying boards
from the fibre saturation point, since their remark was that the drying above the fibre saturation point is pure water transport with no shrinkage. However, though the average moisture content may be above the fibre saturation point, the surface moisture content may be well below the fibre saturation point during the early stages of drying, so their clear statement that drying above the fibre saturation point (as an average moisture content) can be ignored in the optimisation of drying schedule is not always correct. Thus, the optimisation of drying schedules should include drying from the initial moisture content (which may be above the average fibre saturation point in terms of average moisture content). Reduction of drying time was their optimisation target. The constraints were that the moisture content must be below a certain level (i.e. target minimum moisture content for particular end-use and location), the deformation (cupping) at the end of the process should be minimal and checks are not acceptable at any time. The stress level was predicted as an indication of the tendency for checks. There were moisture transport and heat transfer models to find moisture content and temperature distributions, and a stress model was used to identify displacement and stress. The moisture transport was modelled as one-dimensional diffusion, and the driving force for moisture transport was assumed to be the difference in moisture concentration in the board. The stress model was a two-dimensional one developed by Dahlblom et al. (1994). The total strain was assumed to be the sum of elastic (instantaneous), shrinkage and mechanosorptive strain components. The viscoelastic effect was assumed to be significantly smaller and consequently was not considered. The transient solutions using a finite element method gave the moisture content, displacement, and stress distribution for each time step. However, the developed schedule was applicable only to the boards
they dried, and was not assessed for a timber stack in a kiln. The failure criterion needed improvement according to them, based on more experimental data on mechanical properties of timber. Thus the robustness and reliability of this model prediction for drying a stack of timber is uncertain.

The present work has used a similar approach to the previous works in terms of modelling and simulation of timber drying for developing the optimum combinations of dry and wet-bulb temperatures for use in an industrial kiln. Salin (1988) found it impossible to develop a satisfactory drying schedule for a progressive kiln when drying Scots pine (*Pinus sylvestris*). However, he developed a suitable optimised schedule for Scandinavian softwoods in a batch kiln. The high temperature drying schedules (currently practiced in many parts of the world) for softwood require a shorter drying time compared with Salin's (1988) optimised schedule.

The approach used by Doe *et al.* (1996) was logical, although determining the acoustic threshold level and the collapse threshold temperatures experimentally are expensive and time consuming processes in addition to finding the mechanical properties of timber. The use of acoustic sensors in the timber stack (strategically placed) for every batch may be too complex and inconvenient for ordinary kiln operators. That is why the development of optimised schedules based on the maximum strain level for indicating drying quality may have the greatest promise. Most of the previous work used this concept in some way, though a few others like Doe *et al.* (1996) used slightly modified approaches including some additional variables, e.g. acoustic properties of timber.

Carlsson and Esping (1997) used a similar approach of using the maximum strain as a constraint for developing an optimised drying schedule. However, their optimisation only
considered average moisture contents below the fibre saturation point, which is not always correct. Optimisation of drying schedules must be carried out from above the fibre saturation point in terms of the average moisture content, since the surface moisture content may fall below the fibre saturation point when the average moisture content is above it. In summary, all these previous approaches used a drying model for process simulation and a stress or similar model to predict drying quality. The real challenge is to implement these optimised schedules commercially in industrial kilns. The uncertainties and sensitivities of such schedules due to the variations in board thickness, drying properties and biological variability of timber species also need to be tested.

3.4.1 Current Approach: Model Predictive Control

Langrish et al. (1997) conducted research to develop optimised schedules for drying ironbark and other eucalypt timbers. They used a model predictive control (MPC) technique to find the best process conditions for each time step within a "prediction horizon", the time period over which the future process behaviour is calculated. The model predictive control technique has been described in detail by Patwardhan et al. (1990). A four-hour time step was chosen by Langrish et al. (1997) since the moisture transport dynamics is slow for the long timber drying processes involved in drying hardwood (about 137 hours in a conventional kiln for ironbark timber and 90 days in a solar kiln for green blackbutt timber). This model predictive control (as detailed by Langrish et al., 1997) technique has been used here to develop an optimised drying schedule. Model predictive control techniques were used to optimise the process conditions, namely the dry and wet-bulb temperatures as a function of moisture content,
to obtain the best possible drying schedule (that is, one that combines acceptable checks with a reasonably fast drying time).

There are at least two possible approaches for implementing model predictive control in timber drying. One is to minimise the overall drying time \( t_f \) using time-varying controller inputs \( u(t) \) (which represent the dry and wet-bulb temperatures) that maintain the timber within all process constraints at all times. This approach may be expressed mathematically as follows:

\[
\begin{align*}
\text{by adjusting } & \quad \text{minimise } t_f \\
\text{subject to } & \quad \frac{dX}{dt} f[X(t),T(t),u(t),p]=0 \\
& \quad \frac{dT}{dt} g[X(t),T(t),u(t),p]=0 \\
& \quad \varepsilon(t) < \varepsilon_{\text{max}} \\
& \quad X_S(t) \geq X_{S\text{min}} \\
& \quad \bar{X}(t_f) = \bar{X}_{\text{req}} \\
& \quad \max[X(t_f)] - \min[X(t_f)] \leq \Delta X_{\text{req}} \\
& \quad T_G \leq T_{G\text{max}} \\
& \quad X(t = 0) = X_o \\
& \quad T(t = 0) = T_o
\end{align*}
\]

(3.1)

In the above equation, the model parameter \( p \) represents the properties of the timber, and \( X(t) \) and \( T(t) \) are the profiles of the moisture content and temperature within the timber. This approach, which has been used by Carlsson and Esping (1997), is computationally very expensive, and a simpler approach is to minimise the average
moisture content (within all appropriate constraints) over successive time intervals, which are small relative to the overall drying time, in the following way:

\[
\text{minimise } X(t_{i+1})
\]

\[
\begin{align*}
\frac{dX}{dt} &= f[X(t), T(t), u_i, p] = 0 \\
\frac{dT}{dt} &= g[X(t), T(t), u_i, p] = 0 \\
\end{align*}
\]

subject to

\[
\begin{align*}
\varepsilon_i(t_{i+1}) &< \varepsilon_{\max} \\
X_S(t_{i+1}) &\geq X_{S_{\min}} \\
T_G &\leq T_{G_{\max}} \\
X(t = t_i) &= X_i \\
T(t = t_i) &= T_i \\
\end{align*}
\]

A combined drying and stress model (equations 2.2 to 2.12 in section 2.2.3) was used for the application of the model predictive control technique. This approach was implemented within the MATLAB programming environment using a moving time horizon of 4 hours, which is small compared with the overall drying time of over 137 hours (further details are given in Musch et al., 1998). The process behaviour was optimised subject to a number of constraints, the most important of which was an upper limit on the strain. Doe et al. (1994) suggested that a strain level of 0.02 m m^{-1} would lead to failure of the timber. In the optimisation of the drying schedule, therefore, this strain was used as a constraint, so the developed strain was less than 90% of the recommended upper value (90% of 0.02 m m^{-1} = 0.018 m m^{-1}). Also, the minimum surface moisture content was set to 7% to avoid excessive surface checking, while the maximum dry-bulb temperature was set to 80°C to avoid excessive collapse. Collapse is a
phenomenon known to occur at temperatures higher than a certain value and varies with
the species of timber (Campbell, 1980). The drying model predicted the drying rates for
the optimised schedule reasonably accurately (the maximum difference was 4% less than
the experimental value after 70 hours of drying). The initial drying rate with the
optimised schedule was significantly less (due to the use of a low dry-bulb temperature of
30°C for the optimised schedule) for ironbark timber than that for the conventional
schedule (initial dry-bulb temperature of 50°C). As a result, the surface moisture content
was initially greater with the optimised schedule (Langrish et al., 1997). The discrepancy
between the predicted and observed moisture contents in the initial stages of drying
(particularly for the optimised schedule) was felt to be due to slightly erroneous
prediction of surface moisture content. The drying time required to reach an average
moisture content of 15% from an initial moisture content of 60% using the optimised
schedule was 10% less (122 hours) than that for the conventional one (137 hours). The
timber quality was also improved significantly. The numbers of small and medium-sized
cracks, both internally and at the surface, were reduced to less than a quarter of those
observed with the conventional schedule, suggesting that the initial schedule was too
aggressive in the early stages and that the sudden changes in the conventional schedule
were seriously damaging the timber. The number of large cracks was also reduced in the
optimised schedule. The improvement in timber value using optimised schedules would
be substantial, since over 90% of the timber from the optimised schedule was suitable for
high-value products such as furniture (AUS$ 2,000 per m³), while less than half of the
timber dried using the conventional schedule was suitable for such use. The most
significant uncertainty in the application of this optimisation technique was the
mechanical properties of the timber, which were taken as those for another (related) species in the absence of data for this species. The extent of viscoelastic and mechanosorptive behaviour for ironbark timber was also not known during this study.

3.4.2 Solution Method

The solution procedure for the optimisation program using the model predictive control technique has been described by Brooke (1999). The optimisation problem represented by equation (3.2) was solved sequentially. The integration of the ordinary differential equations for moisture and energy transport was carried out using a stiff equation solver (Gear's method) in the Fortran programming environment. A sequential quadratic programming method was used for the solution of the optimisation problem. Figure 3.1 shows the general solution procedure for the model predictive control technique. The constraints need to be satisfied at each time step. The objective is to minimise the moisture content over each time step. The set points of dry and wet-bulb temperatures calculated for each time step (satisfying the constraints) become part of the optimised schedule. Model parameters such as diffusion coefficient and activation energy were previously fitted to the experimental data for a fixed schedule provided by the supplier of the solar kiln (Chapter 2). Stress model parameters were determined by experiments (Chapter 2). Then the optimisation routine was run to find the optimum set of conditions for each time step and finally the optimised drying schedule. The numerical solution of the diffusion model has been carefully tested and validated by Brooke (1999) and the appropriate solution parameters have been used here.
Figure 3.1: Block diagram illustrating the schedule development and calculation procedure for model predictive control (modified from Brooke, 1999).

3.5 OPTIMISATION OF THE DRYING SCHEDULE FOR BLACKBUTT TIMBER

A drying trial was undertaken in the laboratory using the original drying schedule. The objectives of this trial were to observe the drying behaviour of blackbutt timber in the laboratory kiln, establish a base case of final timber quality and drying time for later comparison with an optimised drying schedule and determine transport properties of
blackbutt timber for developing such optimised schedule. This trial was described in the
previous chapter (section 2.5).

Diffusion (diffusion coefficient and activation energy) and shrinkage (shrinkage
coefficient) parameters have been determined for blackbutt timber (Table 2.10). These
parameters have been used in a fixed drying schedule for predicting the maximum strain
as a function of time and moisture content. The original fixed drying schedule used here
is shown in Table 3.4. This drying schedule is similar to the schedule shown in Table 3.2.
During the drying trial, when the moisture content reached 15%, the drying was very
slow and there was negligible change in moisture content after that time. A modification
was made to the schedule in Table 3.2 after 15% moisture content to increase the drying
rate. The modified schedule is shown in Table 3.4. The relative humidities and the
equilibrium moisture contents were read from a standard hygrometric chart produced by
Walker et al. (1993).

Table 3.4: Original moisture-content based schedule for drying 43 mm thick (green)
blackbutt boards.

<table>
<thead>
<tr>
<th>Initial moisture content (%)</th>
<th>Dry-bulb temperature (°C)</th>
<th>Wet-bulb temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Equilibrium moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>25</td>
<td>24</td>
<td>85</td>
<td>18.0</td>
</tr>
<tr>
<td>60</td>
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<td>23</td>
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</tr>
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<td>45</td>
<td>30</td>
<td>27</td>
<td>75</td>
<td>14</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
<td>30</td>
<td>70</td>
<td>12.5</td>
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<tr>
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<td>55</td>
<td>9.5</td>
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<td>45</td>
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<td>26</td>
<td>15</td>
<td>2.0</td>
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<tr>
<td>10</td>
<td>55</td>
<td>25</td>
<td>12</td>
<td>1.5</td>
</tr>
<tr>
<td>Recondition</td>
<td>45</td>
<td>40</td>
<td>75</td>
<td>12.8</td>
</tr>
</tbody>
</table>
From previous assessment, and this drying trial, it was suggested that an apparent maximum strain level of 0.04 m m\(^{-1}\) did not cause the timber to crack (Figure 3.2). Here, and in subsequent parts of this thesis, maximum strain is used to mean the maximum absolute value of the instantaneous strain generated at any point through the thickness of the timber at a given point in time. This figure showed that the strain started to increase from an average moisture content of 60%, which is above the fibre saturation point (usually a moisture content of around 30%). At the higher average moisture contents, the drying model predicts that the moisture contents everywhere in the timber were above the fibre saturation point, so there is no initial predicted strain. The absence of initial strain also predicted by Salin (1988) due to the high moisture contents predicted by him everywhere in the timber at the start of drying. Strain should start to develop whenever the moisture content is reduced below the fibre saturation point, and the surface moisture content was predicted to be below or near the fibre saturation point even when the average moisture content was 60%. This caused the timber to show strain earlier than expected from just looking at the average moisture content. The strain started to increase and reached its maximum at around a moisture content of 35% and then started to decrease. The timber may not crack too severely if this maximum strain is used as a constraint because, in the test reported in section 2.5, the timber did not crack too severely (Table 3.7). In the optimisation of the drying schedule, therefore, the strain has initially been constrained to be less than the recommended upper value assessed from the original schedule (0.04 m m\(^{-1}\)). Also, the initial average moisture content was 70%, the initial surface moisture content was set to 20% and the maximum dry-bulb temperature
was set to 60°C (equal to the maximum value that can be achieved in a solar kiln). The following initial data have been used for optimisation:

a) Initial average moisture content of the board = 0.70 kg kg\(^{-1}\).
b) Initial surface moisture content = 0.20 kg kg\(^{-1}\).
c) Maximum strain = 0.04 m m\(^{-1}\).
d) Maximum dry-bulb temperature 60°C and minimum dry-bulb temperature 20°C.
e) Time step = 4 hours.
f) Board thickness = 43 mm.
g) Parameter values: activation energy = 3730 K; reference diffusion coefficient = 1.145 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}; shrinkage coefficient = 0.348.

Figure 3.2: Predicted maximum instantaneous strain as a function of average moisture content for the original (unoptimised) drying schedule.

An optimised schedule that was developed using a maximum strain of 0.04 m m\(^{-1}\) suggested higher dry-bulb temperatures in the early part of the drying regime compared with the original schedule (Figure 3.3). The behaviour suggested by this procedure has
almost certainly arisen because the optimisation process has tried to maximise the drying rate. The drying rate will be maximised when the diffusion coefficient is largest, which will occur at the highest temperature. Hence the optimisation procedure pushes the dry and wet-bulb temperatures to the highest value as quickly as is allowed by the strain constraint. The wet-bulb depression is adjusted to keep the maximum strain within the constraint, while the initial rate of temperature rise is also constrained to reflect the finite heating rate in a real kiln.

![Figure 3.3: First optimised schedule for the whole drying run.](image)

The use of this higher dry-bulb temperature (60°C) at the early stage of drying produced excessive degrade observed in an experimental trial in a laboratory kiln, i.e. numerous surface checks developed on the boards and end splits were present. The reason may be that the surface of the board was drying too fast while the centre of the board was still too wet, or that significant collapse occurred. This higher moisture content gradient would cause degrade. Also from industrial experience and literature (Vermass,
Innes (1996) introduced a concept called the "collapse threshold temperature" from the predictions of a single fibre model and the observations of drying trials. The single fibre model computed the stress and strain distributions within the fibre wall as a function of temperature, moisture content, and fibre wall strength properties and size in the early stages of drying. The fibre cell was modelled as a thick wall cylinder, since eucalyptus fibres are typically approximately round with a ratio of outside diameter to wall thickness of the order 5:1. The length to diameter ratio of fibre cells is typically of the order of 50:1. He found that if a timber board with a moisture content above the fibre saturation point is dried at temperatures above the collapse threshold temperature, then it will collapse. It was estimated that the collapse threshold temperature is below 40°C for ash type eucalyptus. He found that the collapse threshold temperatures was 24°C and 30°C for Tasmanian *Eucalyptus regnans* and Victorian *Eucalyptus regnans*, respectively, from both slice and board test methods. However, blackbutt (*Eucalyptus pilularis*) is not an ash-type eucalyptus. Innes (1996) also stated that the collapse threshold temperatures are different for the earlywood and latewood of a wood sample, but he did not report any test results. His trials were a little unclear, because several crashes of the control software (Clever Kiln Controller (CKC)) and repeated failure of the boilers affected the trial. However, he dried the load of timber from an initial moisture content of 120% to a moisture content of 40%. The load was later dried for one month to the minimum final moisture content that can be achieved in the air.
at Creswick, Melbourne. It is possible that those collapse threshold temperatures reported may be applicable for those samples tested, but may not be appropriate for other eucalyptus timber. One piece of evidence to support this argument is that the ambient temperatures in the air-drying yard at Boral Timber's Herons Creek site are frequently above 35°C during summer months, but there is no significant collapse found with the air-dried and finally kiln dried timber (mainly blackbutt, *Eucalyptus pilularis*) at this sawmill site. Thus it is reasonable to assume that the collapse threshold temperature may be higher for *Eucalyptus pilularis*.

A modified approach has been undertaken here to develop a practically applicable optimised drying schedule. Since the early of part of drying is most critical in terms of product quality, drying from green to this stage where the strain is maximum has been carried out using the original fixed drying schedule that was tested in the laboratory. It is possible that, after this critical stage, drying can be accelerated significantly using the optimisation procedure. This improved optimised schedule has been developed by retaining the original drying schedule for the early drying period and optimising the schedule for the later period. Once the strain reached its maximum, it was kept constant for faster drying as long as the dry-bulb temperature did not exceed the upper limit (specified value of 60°C). The dry-bulb temperature was limited because this is the maximum temperature that can be achieved and maintained in a greenhouse solar kiln (with a plastic cover). Thus the program was run in such a way that when the instantaneous strain reached its maximum level, then the optimisation routine started. The fixed schedule was retained up to the point when the instantaneous strain was a maximum. The newly developed optimised schedule has been assessed in a laboratory
drying trial (section 3.7). The improved optimised drying schedule and the original fixed drying schedule are shown in Figure 3.4. The predicted reduction of moisture contents for both schedules are shown in Figure 3.5. The predicted strain development during drying is shown for both schedules in Figure 3.6.

It is worth noting that the effect of the optimised schedules is to cut off some of the long "tail" of the original schedule, where increasing resistance to moisture movement as drying proceeds leads to reduced drying rates at low moisture contents. In the wider context of optimising drying schedules for other drying applications, for example microwave drying, it is very likely that the same overall considerations will apply. These considerations include the strain constraint in the initial stages of drying, which is likely to limit the intensity of microwave drying if cracks in the timber are to be avoided. The long "tail" in the moisture content curve (Figure 3.5) arises because of internal resistance to moisture movement, not internal resistance to heat transfer. The dominance of internal resistance to moisture transfer is consistent with the calculations of Pordage and Langrish (1999), which showed that heat transfer is externally controlled in hardwood timber drying, while mass transfer is internally controlled for most of the drying time. Since the application of microwaves overcomes any heat transfer limitations (which are not typically significant) rather than reducing internal moisture content gradients (except by causing internal checking, Engels, 2000), this suggests that microwaves may need to be applied with caution and may not be economically viable in timber drying.
**Figure 3.4:** The original and the improved optimised schedules, as a function of time.

**Figure 3.5:** Moisture contents as a function of time for the original and the improved optimised schedules.
The "improved optimised" schedule deliberately used the original schedule, and dried timber at low dry-bulb temperatures, in the early stages of drying, because this stage is the most critical period, when surface checks may be produced. After three weeks of drying, the dry-bulb temperature rises above 30°C. After six weeks, the dry-bulb temperature reaches 35°C, which is held for another week. Both schedules are the same until this stage (until seven weeks). The moisture contents after three weeks, six weeks and nine weeks of drying, were 0.48 kg kg\(^{-1}\), 0.33 kg kg\(^{-1}\) and 0.23 kg kg\(^{-1}\), respectively, for both the improved optimised and the original schedules, since the drying conditions until 0.23 kg kg\(^{-1}\) are the same. In the final stage of drying, after about nine weeks, the dry-bulb temperature reaches its maximum of 60°C for the new schedule. By comparison, the original schedule dried the timber boards with lower dry-bulb temperatures in the final stages. For the original schedule, the dry-bulb temperature was 40°C after ten weeks, and the highest temperature of 55°C was used for a very short period after about 12 weeks. The drying rate is faster after nine weeks for the improved optimised schedule.

**Figure 3.6:** Predicted strain as function of time for the original and the improved optimised schedules.
compared with the original schedule, since the dry-bulb temperature reaches its maximum for the improved optimised schedule after this time (Figure 3.4).

The predicted drying time for the original schedule is 85 days, whereas for the improved optimised schedule, it is 73 days. A similar drying rate is predicted for both schedules except that, below a moisture content of 0.22 kg kg\(^{-1}\), the drying rate is significantly faster for the improved optimised schedule compared with the original schedule (Figure 3.5). This improved optimised schedule is predicted to reduce the overall drying time by about 15% compared with the original fixed drying schedule for drying from green (70%) to a moisture content of 12%.

It was formulated in the simulation program that, once the strain reached its maximum, the difference between the dry and wet-bulb temperatures (the wet-bulb depression) was adjusted to keep the strain within this limit, so the maximum strain is considered as a constraint. While keeping the strain level constant, the second constraint is applied to the dry-bulb temperature, so the drying rate was increased as long as the dry-bulb temperature did not exceed the limiting value (a maximum dry-bulb temperature that can be achieved in a solar kiln). The strain was predicted to reach its maximum value on the 47\(^{th}\) day when the moisture content was 0.30 kg kg\(^{-1}\) and continued until the 67\(^{th}\) day when the moisture content was 0.17 kg kg\(^{-1}\). The strain later started to decrease (Figure 3.6) since the moisture content gradient after that point in time decreased rapidly, with the surface of the timber being close to the equilibrium moisture content and the centre moisture content decreasing. Below a moisture content of 0.22 kg kg\(^{-1}\), the optimisation routine maximised the drying rate within the constraints specified (particularly dry-bulb temperatures), also evident from the figures. The slightly harsher conditions (higher wet-
bulb depressions) make little difference to the strain because large moisture content gradients are not possible in the timber at these low average moisture contents. Hence, large stresses and strains were not predicted. That is why the current practice by Boral Timber (to dry predried boards, with less than 25% moisture content, in conventional kilns with harsher conditions (dry bulb temperature starting from 58°C with a 8°C depression)) is possible.

The predicted moisture content profile and corresponding strains from surface to half thickness of timber board are shown in Figures 3.7 and 3.8 for the improved optimised schedule.

**Figure 3.7:** Predicted moisture content profiles in a typical board for the improved optimised schedule at different times during drying.
Figure 3.8: Predicted strain profile in a typical board for improved optimised schedule at different times during drying.

The development of strains can be explained in terms of moisture content gradients for the timber board (43 mm) from the surface to the half-thickness (21.5 mm). The moisture content gradient is likely to be symmetrical about the half-thickness of the timber boards, since the boards are dried from both sides. The predicted strain and the changing moisture content profiles as a function of time are shown in Figures 3.7 and 3.8.

In the beginning of drying (time \( t = 4 \) hours), there is some condensation at the surface, and the surface moisture content increases above the initial value (Figure 3.7). The corresponding strain profile in Figure 3.8 shows that there is no strain at that time, since the moisture contents are above the fibre saturation point throughout the timber board.

After 8 days (\( t = 204 \) h) a small amount of strain \( (3 \times 10^{-8} \text{ mm/mm}) \) is predicted near the surface. After 25 days of drying (\( t = 604 \) h), the moisture content gradient is well developed from the surface (0.17 kg kg\(^{-1}\)) to the center (0.61 kg kg\(^{-1}\)). Thus the strain also started to develop much more (0.03 mm/mm) through the board, with tension strain up to
a depth of 2.7 mm and compression at greater depths. After 46 days \((t = 1124 \text{ h})\), the moisture content gradient is significant (surface to center is 0.12 to 0.4 kg kg\(^{-1}\)), and this causes a very large amount of tensile stress (on surface) and compression stress (towards the centre). After 66 days \((t = 1604 \text{ h})\), the moisture content gradient becomes shallower or milder than that for the early drying stages, resulting in lower strains. At the end of drying \((t = 1664 \text{ h})\), the moisture content becomes flattened, and the strains are also reduced.

For the drying process, it is evident from this analysis that the strain is a constraint in the early and middle stages of drying due to moisture content gradients, whereas the dry-bulb temperature is a constraint in the final stages of drying, because the moisture content gradient is then very low.

The improved optimised schedule for drying blackbutt boards of 43 mm in thickness is shown as a "look-up" table after simplification in Table 3.5.

**Table 3.5:** Moisture-content based schedule (improved optimised) for drying 43 mm thick (green) blackbutt boards.

<table>
<thead>
<tr>
<th>Initial moisture content (%)</th>
<th>Dry-bulb temperature (^\circ\text{C})</th>
<th>Wet-bulb temperature (^\circ\text{C})</th>
<th>Relative humidity (%)</th>
<th>Equilibrium moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>25</td>
<td>24</td>
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<td>18.0</td>
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<td>60</td>
<td>37</td>
<td>24.5</td>
<td>4.0</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td>30</td>
<td>11</td>
<td>2.1</td>
</tr>
</tbody>
</table>
A simplified step-wise drying schedule can be implemented by extracting the values from the newly developed improved optimised schedule (Table 3.5). A step-wise drying schedule is conveniently applicable by kiln operators with simple kiln control systems. Table 3.5 suggests that once the actual average moisture contents fall below 35% (oven-dry basis), then the dry-bulb temperature can be increased to 35°C, with a 5 or 6°C wet bulb depression. The dry-bulb temperature may be increased to 53°C, with a wet-bulb depression of 16°C, for drying below the moisture content of 22%. A dry-bulb temperature of 60°C may be applied with a 30°C depression for drying below a moisture content of 18%. This may be a sudden change of drying conditions compared with the original schedule, but by this stage the timber may be able to tolerate such harsh conditions. For this final stage of drying, from moisture contents of 25% to 12%, the new schedule predicts that 16 days may be necessary for drying in solar kilns, if a constraint is put on the dry-bulb temperature (i.e. a maximum of 60°C).

**Figure 3.9:** Drying schedule below the fibre saturation point using a maximum dry-bulb temperature of 85°C.
However, in a conventional kiln, timber can be dried in five days by applying a dry-bulb temperature of 85°C and a depression of 30°C in the final stages of drying from a moisture content of 25% to 12%. Figure 3.9 shows the optimised drying schedule for drying below the fibre saturation point using a maximum dry bulb temperature of 85°C. If the maximum limit on the dry-bulb temperature is 85°C in the optimisation routine, the drying time from moisture contents of 25% to 12% is predicted to be 11 days for the optimised schedule (Figure 3.9).

It is possible that the intensity of surface and end checks may be significant in the products produced currently by using the standard schedule for conventional kilns because unlimited checks are acceptable for structural timber, which is currently produced by Boral Timbers Herons Creek site. The industrial performance of the original schedule was found to be poor for quality parameters, for example, surface checks and end splits when the drying performance was assessed. According to the guidebook published by the United States Department of Agriculture (USDA) Forest Service (Boone et al., 1992), drying quality has been evaluated based on a rating from 1 to 4. A rating of 1 indicates a need for a strong improvement. If end checks of deeper than 50 mm are found in more than 20 boards per package, the performance is rated as 1. If the number of such boards (per package) is less than 20, the performance is rated as 2 and for less than 10 boards the performance is rated as 3. If no end checks or splits are visible, the performance is 4. The rating scale for surface checks is that if no surface checks are visible, the performance rating is 4. If the surface checks are found in less than 4 boards per package, the performance is rated as 3, for 4 to 8 boards the performance is 2 and for more than 8 boards the performance is 1. The ratings for both surface checks and end
splits were 1 for the products from the conventional kiln. Though the amount of degrade due to surface and end checks may be acceptable at present, since the intended use of final product is for structural purposes. This product is not suitable for flooring, furniture or export grade products for which a stricter standard (for example, surface checks are not acceptable at all for appearance grade products) is followed. The products need to be free from surface checks for the flooring and furniture markets.

The current practice of using solar kilns by Boral Timber at the Herons Creek sawmill site is to use them as pre-dryers for moisture contents from green to about 25%. Then, this predried timber is dried in a conventional kiln to a final target moisture content of 10-12%. Since the same schedule is followed until around a moisture content of 25%, the new schedule may not accelerate the drying process unless the solar kiln is used for final drying. If the intended final use of product is for flooring or furniture timber, then it is suggested that it may be better to apply the new improved optimised schedule in solar kilns for complete drying to improve productivity and quality for such end-uses, compared with the use of conventional kilns.

3.6 SENSITIVITY ANALYSIS OF UNCERTAIN PARAMETERS IN OPTIMISED DRYING SCHEDULE

A sensitivity analysis is necessary for assessing the impacts of the variations in board thickness and uncertainties in other parameters (i.e. diffusion coefficient, shrinkage coefficient and mechanosorptive coefficient) on the maximum instantaneous strain as a function of time in both old (original) and new optimised schedules. The objective of this section is to identify and assess these uncertainties in the development of optimised schedules for drying blackbutt timber in a solar kiln. Some possible uncertainties include:
1. Board thickness in the common production range, due to imperfect cutting and preparation.

2. The mechanosorptive strain component.

3. Diffusion coefficient.

4. Other parameters (e.g. shrinkage coefficient).

For impermeable timber species like most eucalypts, the drying rate is approximately inversely proportional to timber thickness (Walker et al., 1993). Hildebrand (1989) reported an empirical approach, in which the drying time is proportional to (thickness)$^n$ where the exponential factor $n$ is equal to 1.5 for many species, as quoted by Keey et al. (2000). Thus thickness is an important consideration for the development of optimised drying schedules.

The maximum instantaneous strain as a function of time is a very important aspect that needs careful assessment, since this maximum instantaneous strain criterion has been used to develop optimised schedules to produce crack-free good quality timber after drying. The shrinkage coefficient has an effect on the development of the instantaneous strain, since the instantaneous strain is caused by shrinkage. The strain model has been described in Chapter 2. This shrinkage parameter is also tested in this sensitivity study.

It is also realised that the mechanosorptive strain is responsible for stress reversal or relaxation (decrease in strain for a constant stress level) in timber (Keey et al., 2000). For the optimised schedule developed here, the mechanosorptive strain component is assessed in the stress model. There is a large variability in the mechanosorptive strain coefficient for blackbutt across the grain, as shown in Chapter 2 (section 2.4.4). The mechanosorptive strain components relax and reduce the stresses and strains, so
neglecting them will lead to optimised drying schedules that overestimate (in general) the stress/strain on timber. An important limitation is that this statement cannot be made with absolute certainty because it is appreciated that, without considering mechano-sorptive strain components, important physical phenomenon such as stress reversal in timber during drying cannot be predicted. Hence the impact of the uncertainty in the mechano-sorptive component of strain will be assessed.

3.6.1 Procedure

Mechanosorptive Coefficient

The timber drying model (that includes a stress model with the mechano-sorptive effect, as described in Chapter 2, section 2.4) was simulated using Matlab and Fortran on a DEC AlphaStation 500/333 to obtain results for the assessment of the mechano-sorptive effect. This complete model was used to test the sensitivity of the development of total stress and instantaneous strain to the mechanosorptive coefficient. The value of the maximum mechanosorptive coefficient of $7.2\times10^{-8}$ (Pa$^{-1}$) has been determined from experiment, as discussed in Chapter 2 (section 2.4.4).

Board Thickness, Diffusion Coefficient and Shrinkage Coefficient

The effects of variations in board thickness, shrinkage coefficient and diffusion coefficient on optimised schedules have also been assessed. The thicknesses simulated for timber boards were 43 mm, 54 mm and 30 mm (green) in the drying model. These correspond to 38 mm, 50 mm and 27 mm nominal thicknesses or 35 mm, 45 mm and 25 mm final finished board thicknesses (after planing and sanding operations), respectively. These dimensions are within the common industrial production range. The drying experiments conducted here showed that 8% shrinkage occurred in the thickness direction.
(for green 46 mm thick board) of flat-sawn blackbutt board and 8.6% shrinkage occurred in the width direction of the board (green 270 mm) after drying. There was no change in the longitudinal direction (green 591 mm). The implication of this finding is that, for producing 38 mm thick (nominal) board (before planing and sanding), the green cutting should be 42 mm, whereas these boards were actually cut at the sawmill to 46 mm, 10% higher than necessary for every board. However, the boards were cut with a large margin since cupping developed during drying. 2 mm cupping means that the board should be cut 2 mm thicker than would otherwise be necessary.

Diffusion coefficients used for this assessment were the cross-grain reference diffusion coefficient for blackbutt determined by fitting to experimental drying data \((1.145 \times 10^{-5} \, \text{m}^2 \, \text{s}^{-1}\) in Table 2.10), and a value that was 10% less. The range of values for the reference diffusion coefficients found later (Table 3.6) shows a smaller amount of variation. The shrinkage coefficient value was 0.35 m m^{-1}/kg kg^{-1} (from fitting, as a base case value), and the other value in this sensitivity analysis was 10% less. It was assumed that the variation in these properties is 10% of the mean values, since there were no other experimental values found in the literature for comparison with this species. The experiments to measure physical and mechanical properties (described in Chapter 2) indicated that the coefficient of variation for the modulus of elasticity was around 9%, but the sample size here was small. Keey et al. (2000) indicated that the coefficient of variation for many timber properties is ± 30%, so the actual variation may be larger than measured here.
3.6.2 Results and Discussion

The effect of board thickness on drying rate within the production range of a sawmill using an optimised schedule is shown in Figure 3.10 and on the development of maximum strain in Figure 3.11.

**Figure 3.10:** Effect of different board thickness on drying time.

**Figure 3.11:** Effect of different board thickness on maximum strain.
This assessment showed that the board thickness has a significant influence on the drying time, as expected from the work of Hildebrand (1989) and Walker et al. (1993). The drying time from an initial moisture content of 70% to a final moisture content of 12% was 112 days, 74 days and 39 days for 54 mm, 43 mm and 30 mm thick green blackbutt boards, respectively, found from the simulation using the optimised schedule (Figure 3.10). This means that the drying times were 65% and 33% lower for 30 mm and 43 mm thick boards, respectively, compared with the drying rate of 54 mm boards. The drying time (in hours) is nearly proportional to the square of the thickness (in mm) of timber, as predicted by Walker et al. (1993) and Keey et al. (2000). The analytical solution of the diffusion equation for constant diffusion coefficient (McCabe and Smith, 1976) also predicts that the drying time should be proportional to the square of the thickness. The finding that the drying time is not exactly proportional to the square of the thickness here is due to the diffusion coefficient being dependent on temperature, with both the temperature and hence the diffusion coefficient being non-constant in this case. If the thickness is doubled, the drying time is predicted to increase by over three times (30 days for 25 mm and 100 days for 50 mm). The optimised schedule for drying 43 mm boards developed here may still be suitable for drying 54 mm boards because the maximum strain exceeds the limiting maximum strain of 0.0398 by only 0.5% (Figure 3.11) for 54 mm boards. Since this predicted strain increase is very small in magnitude, this may not cause surface checks to develop in the boards. The dry-bulb and wet-bulb temperatures as a function of moisture contents for 43 and 54 mm thicknesses are similar, when optimised schedules were produced for 43 and 54 mm boards (Figure 3.12). The drying schedule is only slightly milder for a 54 mm board compared with a 43 mm board.
For example, the maximum dry and wet-bulb temperatures were 60°C and 39°C, when the moisture contents were 23.7% for 54 mm board and 22% for 43 mm board. Similarly, the maximum wet-bulb depression of 30°C was applied below moisture contents of 18.3% for 54 mm boards and 17.7% for 43 mm boards.

![Figure 3.12](image-url)

**Figure 3.12:** The dry-bulb and wet-bulb temperatures as a function of moisture contents for 43 mm and 54 mm boards.

There is a variation in thickness due to the drift of the saw-bench setting over time during the sawing of logs into green boards due to the use of old equipment and also either unintended changes or irregular monitoring. The typical thickness for producing 43 mm boards ranges from 42 to 46 mm. The effect of variations of this thickness on drying time has been assessed (Figure 3.13) for this smaller range.
Figure 3.13: Effect of variation in board thickness due to saw-bench setting for the production of 43 mm boards.

An assessment, using an optimised schedule to dry such boards, showed that the drying time may be 10% longer in case of 46 mm boards and 4% shorter for 42 mm boards compared with exactly produced 43 mm boards (Figure 3.13). It is probably not necessary to alter or change the drying schedule for such variations in thickness because the maximum strain for 46 mm boards did not exceed the limiting maximum strain, which is a quality parameter, by any significant amount (less than 0.1%).

The effect of the mechanosorptive coefficient on the maximum instantaneous strain development as a function of moisture content for 43 mm thick boards in both original and new optimised schedules is shown in Figure 3.14. The mechanosorptive coefficient only affects the strain model, not the drying model, and so has no effect on the drying rate. The mechanosorptive coefficient (m) of $7.2 \times 10^{-8} \, (\text{Pa}^{-1})$ used here is the maximum value found in section 2.4.4.
Figure 3.14: Effect of mechanosorptive coefficients on maximum instantaneous strain using original and new optimised schedule for 43 mm boards.

There is a significant effect of mechanosorptive coefficients on the development of maximum instantaneous strain. Figure 3.14 shows that the mechanosorptive strain has a stress relaxation effect, as expected, because the mechanosorptive strain increases with increasing stress and so tend to decrease the instantaneous strain that tends to crack the timber. Thus the maximum instantaneous strain is higher without including the mechanosorptive effect (or using a zero value of the mechanosorptive coefficient) compared with the maximum strain developed including the mechanosorptive effect (or using a non-zero mechanosorptive coefficient) for any given schedule (e.g. original or optimised). From this assessment, the maximum instantaneous strain was 62% lower with the mechanosorptive effect compared with the situation ignoring the mechanosorptive effect for the optimised schedule. The maximum strain was 73% lower for the original schedule with the mechanosorptive effect included (Figure 3.14). The optimised schedule developed here has neglected the mechanosorptive effect. The neglect of this effect
means that stress relaxation due to the mechanosorptive effect is not simulated, so the predicted strains from omitting the effect (as here) are greater than those if the effect were included in the optimisation. Hence the current procedure is conservative in the sense that it will predict strains that are higher than those in reality. Figure 3.14 also suggests that the strains throughout both the original and the optimised drying schedules (as a function of moisture content and hence of time) are predicted to be more constant with respect to time when accounting for mechanosorptive strains than without taking these strains into account. Including the mechanosorptive effect, as in reality, means that the strains imposed on the timber during drying will be both lower and more slowly changing with time. The maximum strains, taking the likely maximum amount of mechanosorptive strain into account, are also of the same order as the failure strains measured in Chapter 2 (section 2.3.3) of 0.0145 m m⁻¹, suggesting (on the basis of including the mechanosorptive effect) that both the original and improved optimised schedules are unlikely to cause severe cracking. The stress strain reversal can be demonstrated for improved optimised schedule with the mechanosorptive effect by plotting the predicted instantaneous strains through the board from surface to the half-thickness (21.5 mm), as shown in Figure 3.15. In the beginning of drying (when time t = 4 hours), there is no strain, since the moisture contents are above the fibre saturation point throughout the timber board. In Figure 3.15, negative strain is regarded as a tensile strain and positive strain is regarded as a compressive strain. After 8 days (t = 204 h), a small amount of tension (-0.0004 mm/mm) is predicted near the surface. After 25 days of drying (t = 604 h), the moisture content gradient is well developed from the surface (0.17 kg kg⁻¹) to the center (0.61 kg kg⁻¹). Thus the strain also started to develop more (0.0019 mm/mm)
through the board, with tensile strain up to 2.7 mm depth and compression at greater depths. After 46 days (t = 1124 h), the moisture content gradient is significant (surface to center is 0.12 to 0.4 kg kg⁻¹), and this causes a small amount of compressive stress on the surface (up to 0.2 mm depth), then a maximum tensile strain of 0.0066 mm/mm, and again compressive stress below a depth of 5.9 mm (a maximum compressive strain of 0.01 mm/mm). Thus this demonstrates how stress reversal from compression to tension to compression is predicted. After 66 days (t = 1604 h), the moisture content gradient becomes shallower or milder than that for the early drying stages, resulting in lower strains. At the end of drying (t = 1664 h), the moisture content becomes flattened, and the stresses are also reduced, being compressive on the surface and tensile towards to the centre from a depth of 5.9 mm.
Figure 3.15: Strain profile in a typical board for the improved optimised schedule at different times during drying with the mechanosorptive effect.

The effect of the diffusion coefficient on the drying rate is shown in Figure 3.16 and on the development of the maximum strain in Figure 3.17.

Figure 3.16: Effect of diffusion coefficient on drying time for 43 mm boards.
Figure 3.17: Effect of diffusion coefficient on strain for 43 mm boards.

The reference diffusion coefficient was a sensitive parameter for the two values used in this sensitivity study in terms of the drying time, but not so much on the maximum strain level. The drying rate was slightly higher and the drying time is 8% shorter (Figure 3.16) for a 10% higher reference diffusion coefficient (e.g. the original value for blackbutt). Changing the reference diffusion coefficient by 10% has changed the drying time by 8%, so the drying time is virtually inversely proportional to the diffusion coefficient. This result is expected according to the theory outlined in Chapter 2, because the higher value of the diffusion coefficient means that the moisture can migrate more quickly within the boards due to any given moisture content difference compared with the boards having a lower diffusion coefficient. Specifically, the finding that the drying time is virtually inversely proportional to the diffusion coefficient (which is directly proportional to the reference diffusion coefficient) is consistent with the analytical solution of the diffusion equations for constant diffusion coefficient (McCabe and Smith,
1976). This analytical solution shows the above inverse proportionality. The finding that the inverse proportionality is not exactly true here is due to the diffusion coefficient being non-constant and, specifically, temperature dependent. There is little effect of the diffusion coefficient on the maximum strain level (Figure 3.17). The maximum strain as a function of moisture content was slightly lower for a higher diffusion coefficient until the strain reached its maximum at about a moisture content of 30%. The strain was same for both diffusion coefficients below this moisture content. The significance of this is that, due to a lower diffusion coefficient, a larger moisture content gradient is predicted to develop in the board (the difference in moisture content between the centre and the surface of the board). A lower diffusion coefficient not only impedes the flow of moisture from timber, but it also causes the development of larger moisture content gradients, and hence strains particularly in the early part of drying regime. The moisture content gradient becomes less steep in the later stages of drying. The strains were virtually the same for the two different diffusion coefficients in the final period of drying (Figure 3.17).

The effect of the shrinkage coefficient on the maximum instantaneous strain development as a function of moisture content is shown in Figure 3.18. This coefficient, like the mechanosorptive coefficient, also only affects the strain model, not the drying model, so the drying rates are not affected.
Figure 3.18: Effect of the shrinkage coefficient on the maximum instantaneous strain for 43 mm thick boards.

The shrinkage coefficient has a significant effect on the maximum strain development (Figure 3.18). The maximum strain was 10% lower for a 10% reduction in the shrinkage coefficient from the original value (0.348 for blackbutt determined from experimental data and discussed in Chapter 2). This means that developing a drying schedule using a higher shrinkage coefficient will be more conservative and slower than using a lower shrinkage coefficient, because a higher shrinkage coefficient will result in higher strains for the same drying conditions. Hence harsher drying conditions, resulting in faster drying, will be suggested by the optimisation procedure if the shrinkage coefficient is lower. In other words, the optimised schedule developed here using a higher shrinkage coefficient (0.348) would be more conservative than any schedule using a lower shrinkage coefficient than 0.348. All these assessments have been carried out using the improved optimised schedule, except the assessment of mechanosorptive coefficient which used both the original schedule and the improved optimised schedule. The
distinction between "initial optimised schedule" and "improved optimised schedule" will be clarified in the next section of this chapter.

An assessment has been carried out to establish the need for the determination of all the mechanical property data. The modulus of elasticity value of 678 MPa (reported by Alexiou et al. (1989) for blackbutt) has been used to produce an optimised schedule. This optimised schedule was not significantly different compared with the improved optimised schedule produced here using the measured modulus of elasticity of 404 MPa. It appears that the determination of the diffusion and shrinkage coefficients is essential, because there is no data in the literature for blackbutt for these properties. The shrinkage coefficient for blackbutt (0.348 m m⁻¹/kg kg⁻¹) is very different to that for ironbark (0.15 m m⁻¹/kg kg⁻¹). Also, the diffusion coefficient for blackbutt (1.145×10⁻⁵ m² s⁻¹) differs significantly from that for ironbark (4.66×10⁻⁵ m² s⁻¹). The sensitivity analysis in this section has shown that these parameters have a significant effect on the strains predicted during drying. Hence estimating the parameters (which do not exist in the literature for blackbutt) from those for ironbark would almost certainly affect the optimised schedule significantly, so these parameters (diffusion and shrinkage coefficients) need to be measured. However, it may not be so important to measure parameters such as the modulus of elasticity so carefully, which have less effect on the optimised schedules, and literature values for similar species may be used.

3.7 RESULTS AND DISCUSSION: DRYING TESTS

The results of the second (using the initial optimised schedule), the third and the fourth (using an improved optimised schedule) drying tests are presented here in section 3.7.1. The results of the first drying test (using the original schedule) were discussed in
Chapter 2 in relation to fitting transport properties. The transport properties (diffusion coefficient and activation energies) were also obtained from fitting to the data in these drying tests. In section 3.7.2, the timber qualities before and after drying for the original, the initial optimised and the improved optimised schedules have been compared.

3.7.1 Drying Tests

The second and third drying tests were conducted in a laboratory kiln for a stack of blackbutt timber using the initial optimised schedule and the improved optimised schedule, according to the experimental procedures described in section 2.5.1. These drying schedules, including the original one, are shown in Figure 3.19. In this figure, $T_g$ and $T_w$ are the dry and wet-bulb temperatures and number 1 is for the original, 2 is for the initial optimised and 3 is for the improved optimised schedules, respectively.

The initial optimised schedule was developed in the same way as described in this chapter, but without the consideration that the fibre saturation point is dependent on temperature. The maximum instantaneous strain for the original schedule was predicted to be $0.047 \text{ m m}^{-1}$ for this case. When the fibre saturation point was considered to be temperature dependent for the original schedule, this predicted maximum instantaneous strain was $0.039 \text{ m m}^{-1}$ for the simulation. Thus the former assumption (fibre saturation point not temperature dependant) produced a harsher drying schedule compared with the later optimisation procedure.
The improved optimised schedule was developed considering that the fibre saturation point is dependent on the temperature, because the assumption of using a constant fibre saturation point (i.e. independent of temperature) is not appropriate according to the literature (Skaar, 1988). The fourth drying test was a repeated experimental trial of the improved optimised schedule.

![Graph](image)

**Figure 3.19:** Original, initial optimised and improved optimised schedules for drying 43 mm (green) blackbutt timber.

The data from the second, third and fourth drying tests were used to fit the diffusion parameters to the diffusion model described in section 2.2.3. A least-squares method was used to fit the parameters to the moisture content and temperature data for the complete drying run by adjusting the values of the activation energy ($D_E$) and reference diffusion coefficient ($D_r$). The fitted results for $D_E$ and $D_r$ are shown in Table 3.6. The diffusion coefficients of other species generally found and reported by other workers have been compared in section 2.5.2.
Table 3.6: Fitted parameters for a stack of timber dried in a laboratory kiln.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Original</th>
<th>Initial optimised</th>
<th>Improved optimised</th>
<th>Repeat trial (improved)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activation energy (D_E)</td>
<td>3730</td>
<td>3762</td>
<td>3738</td>
<td>3776</td>
<td>K</td>
</tr>
<tr>
<td>Reference diffusion coefficient (D_f)</td>
<td>1.151×10^{-5} (across grain)</td>
<td>1.146×10^{-5} (across grain)</td>
<td>1.151×10^{-5} (across grain)</td>
<td>1.148×10^{-5} (across grain)</td>
<td>m² s⁻¹</td>
</tr>
</tbody>
</table>

The fitted moisture contents and experimentally obtained values as a function of time with dry and wet-bulb temperatures for these drying tests using initial optimised and improved optimised schedules are shown in Figures 3.20 to 3.22.

Figure 3.20: Drying test data using the initial optimised (FSP is temperature independent) drying schedule.
Figure 3.21: Drying test data using the improved optimised schedule.

Figure 3.22: Repeat drying trial using the improved optimised schedule.

There is only a very slight difference between these fitted values of the reference diffusion coefficients and activation energies (Table 3.6) for the drying tests using the original schedule, the initial optimised schedule and the improved optimised schedules. This result indicates that the variability, in terms of the diffusion coefficient between the
three groups of boards involved in the three drying tests, was probably small. However, four sets of samples are not a satisfactory basis for a confident statistical assertion. The sample boards were taken from only two logs of blackbutt timber. The small amount of variation may be due to this reason.

### 3.7.2 Drying Time and Quality Comparison

The drying times for the original, the initial optimised, the improved optimised schedules and the repeat trial were 81.5 days, 91.5 days, 73.5 days, and 80.5 days, respectively. The initial and final moisture contents for the batch of timber using the original schedule were 60% and 12%, respectively, while they were 64% and 12% for the initial optimised schedule and 70% and 12% (dry basis) for the improved optimised schedule. The initial and final moisture contents for the repeat trial using the improved optimised schedule were 65% and 10%. The drying time was 76 days for this repeat trial to a moisture content of 12%, so the variation between this repeated trial (76 days) and the first trial of the improved optimised schedule (73.5 days) was small. This indicates that these results are repeatable and that there is a significant benefit in using the optimised schedules compared with the original one (81.5 days). These initial and final moisture contents were determined by oven-drying method and also were in close agreement with the moisture contents recorded by the kiln balance and computer control system and the moisture meter.

Tables 3.7 to 3.10 show the timber quality after drying using the original, the initial optimised and the improved optimised schedules. All green boards were clear, without any surface checks, end splits or distortion before drying. These boards were observed before and after drying for end splits, surface checks, cupping and similar distortions. The
boards were cut after drying as shown in Figure 3.23 for internal checks with a band saw. All crosscut sections for the middle and end parts of the board were examined for internal checks.

Table 3.7: Timber quality after drying using the original schedule.

<table>
<thead>
<tr>
<th>Board number</th>
<th>End splits</th>
<th>Surface checks</th>
<th>Cupping</th>
<th>Collapse</th>
<th>Internal checks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>3</td>
<td>Absent</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Nil</td>
<td>Absent</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>Nil</td>
<td>Absent</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Nil</td>
<td>Absent</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>6</td>
<td>38</td>
<td>1</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
</tbody>
</table>

Table 3.8: Timber quality after drying with the initial optimised schedule.

<table>
<thead>
<tr>
<th>Board number</th>
<th>End splits</th>
<th>Surface checks</th>
<th>Cupping</th>
<th>Collapse</th>
<th>Internal checks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nil</td>
<td>3</td>
<td>Absent</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>2</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Present</td>
<td>Nil</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Nil</td>
<td>Absent</td>
<td>Absent</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Nil</td>
<td>Nil</td>
<td>Absent</td>
<td>Absent</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
</tbody>
</table>

Table 3.9: Timber quality after drying with the improved optimised schedule.

<table>
<thead>
<tr>
<th>Board number</th>
<th>End splits</th>
<th>Surface checks</th>
<th>Cupping</th>
<th>Collapse</th>
<th>Internal checks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nil</td>
<td>4</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>2</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>3</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>4</td>
<td>Nil</td>
<td>2</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>5</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>9</td>
<td>Absent</td>
<td>Absent</td>
<td>Nil</td>
</tr>
</tbody>
</table>
Table 3.10: Timber quality after drying with the improved optimised schedule for the repeat trial.

<table>
<thead>
<tr>
<th>Board number</th>
<th>End splits</th>
<th>Surface checks</th>
<th>Cupping</th>
<th>Collapse</th>
<th>Internal checks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>2</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>3</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>4</td>
<td>Nil</td>
<td>Nil</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td>Present</td>
<td>Absent</td>
<td>Nil</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>1</td>
<td>Absent</td>
<td>Absent</td>
<td>Nil</td>
</tr>
</tbody>
</table>

Figure 3.23: Cutting pattern of dry boards for internal checks.

For the original schedule, Table 3.7 shows that almost all (five of the total six boards) boards had end splits. Two boards produced surface checks and cupping. None of these boards showed either any presence of collapse or internal checks. Board number 6 was removed from the drying tunnel before reconditioning (6 hours at dry and wet-bulb temperatures of 45°C and 44°C) for final moisture content measurement using the oven-drying method. Possibly this is why this board showed a large number of end splits. The surface checks and end splits were 5 to 80 mm long and 0.5 to 1.5 mm wide. The end-splits extended over the surface up to 80 mm from the edge of the board. The maximum cupping was 2.5 mm.
In comparison, for the *initial optimised* schedule (Table 3.8), one board showed end splits and surface checks. Three boards had cupping and internal checks. One board had some collapse. Board number 6 was removed before reconditioning in the same way as for the original schedule. However, this board only had a little cupping, whereas board number 6 for the original schedule had a large number of end-splits. The lengths of the surface checks for all the boards were from 7 mm to 34 mm, and the range for the widths was hairline (less than 0.5 mm) to 1 mm. The internal checks were 3 to 12 mm long and had a range for depths from hairline to 1.2 mm. The maximum cupping was 1.5 mm.

For the *improved optimised* schedule (Table 3.9), only one board had end checks, and two boards showed surface checks. The range of the length of end checks was 7 to 25 mm, and the depths were from hairline to 0.65 mm. Board number 6 was removed in the same way for the original schedule. This board had both end and surface checks. Almost all boards had some cupping. The range of cupping was 1.5 to 2 mm. None of these boards showed other defects such as collapse or internal checks. The drying time was 10% shorter for the *improved optimised* schedule compared with the *original* schedule (and the initial moisture content was 10% lower for the *original* schedule) and 18% shorter than the *initial optimised* schedule for a similar reduction in moisture content.

For the repeat trial of the *improved optimised* schedule (Table 3.10), three boards had end checks, and two boards showed surface checks. The range for the length of end checks was 5 to 20 mm, and the depths were hairline or less than 0.5 mm. Board number 6 was removed in the same way as for the other trials. This board had both end and surface checks. Almost all boards had 1 mm cupping. None of these boards showed other defects such as collapse or internal checks. The drying time was 7% shorter for the repeat
trial of the improved optimised schedule compared with the original schedule for a similar reduction in moisture content (e.g. from 60% to 12%).

In summary, the original schedule dried boards with a large number of end-splits but with few surface checks, little cupping and with no collapse and internal checks. For the initial optimised schedule, half of the dried boards had cupping and internal checks, and one board showed collapse. The improved optimised schedule dried boards with cupping and a few surface checks, and the boards had no other defects. The drying time was similar for a similar reduction of moisture content for the original and the initial optimised schedule but shorter for the improved optimised schedule compared with both other schedules.

Dried timber was classified according to the Australian and New Zealand Standards (AS/NZS 4787, 2001) for surface, internal, end checks and collapse caused by drying. According to this standard, there are five quality classes, i.e. classes A to E. Class A caters for specific end uses and applies to very specific requirements for drying quality. Class B applies where tight control over drying quality is required to limit in-service movement resulting from changes in equilibrium moisture content. Class C applies where higher drying quality is required and the final use environment is clearly defined. Class D applies when the final use environment is more clearly defined but again the drying quality requirements are not considered high. Class E applies when the final use and final environment can accept a product with a wide range of moisture contents and the drying quality requirements are not high. For example, for surface checks, if only 0.5 percent of the full board surface is affected by checks (for 90% of samples observed), the quality class is Class A. None of these schedules (used here) produced surface checks over more
than 0.5% of the surface. For end checks, no end check is acceptable for class A. If the maximum length of end check is less than 50 mm (for 90% of sample observed), the drying quality is Class B. If the maximum length is more than 50 mm and less than 100 mm, then the quality class is Class C. For internal checks, no internal checks are acceptable for classes A and B. For collapse, total collapse for both faces should be zero for Classes A and B. According to this classification, the class of dried timber is shown in Table 3.11 for all the tests.

**Table 3.11:** Classification of timber based on drying quality.

<table>
<thead>
<tr>
<th>Schedules</th>
<th>Surface checks</th>
<th>End checks</th>
<th>Internal checks</th>
<th>Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>Class A</td>
<td>Class C</td>
<td>Class A</td>
<td>Class A</td>
</tr>
<tr>
<td>Initial optimised</td>
<td>Class A</td>
<td>Class B</td>
<td>Class C</td>
<td>Class C</td>
</tr>
<tr>
<td>Improved optimised</td>
<td>Class A</td>
<td>Class B</td>
<td>Class A</td>
<td>Class A</td>
</tr>
<tr>
<td>Repeat (improved optimised)</td>
<td>Class A</td>
<td>Class B</td>
<td>Class A</td>
<td>Class A</td>
</tr>
</tbody>
</table>

However, it is difficult to conclude that one schedule is superior to another regarding quality. Cupping, collapse and internal checks are more serious forms of degrade because the product loss is higher for those types of degrade compared with end splits and surface checks (industry experience). The reason for the occurrence of these types of degrade using the *initial optimised* schedule may be that the kiln control (Figure 3.20) was poor in the beginning of drying for the *initial optimised* schedule (Figure 3.20) because it is difficult to achieve very low temperature and high relative humidity (i.e. dry-bulb temperature 25°C and 90% relative humidity) during the summer months (when average day temperature is above 25°C) in this equipment. This affected the timber quality (Tables 3.8 to 3.10) compared with timber dried using the original drying schedule.
Collapse usually occurs above the fibre saturation point (Innes, 1996). Since both these drying schedules dried boards using the same drying conditions down to a moisture content of 25%, this collapse may be due to the lack of good kiln control in the early stages of drying. Other types of distortion like cupping occur due to shrinkage anisotropy. Types of degrade such as end-splits and surface checks can occur due to uneven drying (Desch and Dinwoodie, 1996). It may be possible that the initial optimised schedule dried boards slightly more evenly than the original schedule, since there were fewer end splits and surface checks for the boards produced from the initial optimised schedule compared with the original schedule.

Overall the drying time was 10% shorter for the improved optimised schedule compared with the original schedule. This is expected, since Figure 3.5 shows how the optimised schedule, with its higher temperatures towards the end of drying, cuts off some of the long "tail" of moisture content reduction.

### 3.8 CONCLUSIONS

Optimised schedules have been developed for drying 43 mm thick (green) blackbutt timber boards in solar kilns using model predictive control techniques. The improved optimised schedule was predicted to reduce the drying time by about 12% compared with the original drying schedule. The original schedule was used to dry a batch of board in a laboratory kiln. This schedule produced dry boards with large number of end splits, a few surface checks and some distortion, for drying from an initial moisture content of 60% to a final moisture content of 12%. The improved optimised schedule was tested in the laboratory. This schedule produced boards with some cupping and only a few surface checks for a couple of boards. The actual drying time was 10% shorter for this schedule.
(though the initial moisture content was 10% higher) than the original schedule compared with an expected reduction in drying time of 14%. Overall the quality was slightly better and the drying time was shorter for the improved optimised schedule compared with the original schedule.

The sensitivities of the improved optimised schedule to variations in the board thickness (within the common production range and due to imperfect cutting), the mechanosorptive coefficient, the diffusion coefficient and the shrinkage coefficient have been assessed. It was predicted that the board thickness significantly influences the drying rate. The developed optimised schedule here is suitable for 43 mm thick boards. This schedule may also be used for 54 mm thick boards since the maximum instantaneous strain is only predicted to exceed the limit by a very small amount (0.5%), which is unlikely to cause the timber to crack. However, the schedule is predicted to be 33% slower for 54 mm boards compared with 43 mm thick boards, and the drying rate is predicted to be higher for 30 mm thick boards. This schedule can be used for thicker boards due to imperfect cutting (42 to 46 mm), because the maximum strain development was predicted to be very close to that for 43 mm thick boards.

The mechanosorptive coefficient is predicted to have a significant effect on the development of maximum instantaneous strain. For the improved optimised schedule, the maximum instantaneous strain is likely to be 62% lower when including the mechanosorptive effect, compared with neglecting this effect. This finding indicates that the current optimisation procedure, which neglects the mechanosorptive effect, is conservative in the sense that it predicts strains that are higher than those which are actually likely. The variability in the mechanosorptive coefficient means that setting it to
zero is the safest and most conservative option because non-zero values might result in more severe drying schedules being suggested by the optimisation procedure.

The diffusion coefficient had a significant effect on the predicted drying time. The drying time was 8% longer for a 10% lower reference diffusion coefficient than the base case ($1.145 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$). The lower diffusion coefficients mean a larger resistance to moisture transport and also steeper moisture content gradients between the centre and the surface of the board. The shrinkage coefficient has a significant effect on the development of maximum instantaneous strain. A 10% reduction from a shrinkage coefficient of 0.348 for blackbutt determined from experiment produced about a 10% lower maximum instantaneous strain. A drying schedule with a lower shrinkage coefficient will be harsher than a drying schedule using a higher shrinkage coefficient, since a lower shrinkage coefficient means lower strains for the same drying conditions.

Overall, the production of a successful optimised drying schedule has been carried out, and implementation of this schedule in industrial practice is recommended. The reduction in drying time through the use of this optimised drying schedule for blackbutt (10%) is similar to that achieved by Langrish et al. (1997) for ironbark timber, confirming the usefulness of model predictive techniques to optimising timber drying schedules.

The timber properties, i.e. diffusion and shrinkage coefficients used in this chapter, have also been used in solar kiln model development in the next chapter and in the kiln model validation in Chapter 5.
REFERENCES


Personal communication (2001). Email communication with Professor Peter Doe.


