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OPTIMISING DRYING SCHEDULES FOR HARDWOOD TIMBER IN SOLAR KILNS

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ABSTRACT

An optimised schedule has been developed using a model predictive control technique for drying 43-mm-thick (green) *Eucalyptus pilularis* Sm. boards, based on an original schedule generally recommended for greenhouse solar kilns equipped with good control of temperature and relative humidity. The predicted drying time for this schedule was 14% shorter than the original schedule using the drying model. Experimental tests confirmed this, with drying time in laboratory kiln being 10% shorter for this schedule (the initial moisture content was 10% higher) than the original schedule. The original schedule produced boards with a large number of end splits, a few surface checks, and some distortion, when drying from an initial moisture content of 60% to a final moisture content of 12%. In comparison, the optimised schedule produced boards with less degrade, from an initial moisture content of 70% to a final moisture content of 12%. Overall, the quality was slightly better and the drying time shorter for the optimised schedule than for the original schedule.

Keywords: hardwood; solar kiln; drying schedule; optimisation; *Eucalyptus pilularis*.

INTRODUCTION

A major timber drying challenge for researchers and industries is to reduce the drying time without loss of product quality. The task of schedule development has often been based on experience, essentially using trial and error approaches. Generally, longer drying times (low temperatures and high humidities in the early stages of drying, with a corresponding slow drying rate) for refractory hardwoods such as eucalypts result in less product loss, and vice versa. An optimised drying schedule (a strain-limited drying schedule) may trade off between these two opposing objectives (quality and productivity). Once developed, this schedule can be implemented based on either moisture content or time. Product quality is indicated by the absence of any cracks or splits on the surface and the ends of the boards. The optimised schedule dries the timber in the fastest possible time, subject to a maximum strain level at which it is unlikely that timber cracking will occur. Unfortunately, this procedure can be very expensive if achieved by trial and error due to the time required for testing.

Many researchers have attempted to develop optimised schedules based on modelling of drying and on simulation. Salin (1988) developed an optimised schedule for Scots pine (*Pinus sylvestris* L.) and spruce (*Picea abies* (L.) H.Karst.) for drying in batch and progressive kilns. Doe *et al*. (1996) developed a PC-based kiln-control system called the Clever Kiln Controller (CKC) which 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 sensors on sample boards in the kiln to indicate stress level, and an "acoustic emission threshold" was specified. Doe *et al*. (1996) incorporated a strain model to predict surface strain, and controlled the strain below an upper control limit that was usually 50–75% of the estimated ultimate value of 0.02 m/m for Tasmanian hardwoods. The CKC continually "looks ahead" to find a schedule using the historical kiln data (temperature, humidity, air velocity), and holds the surface strain below the specified maximum value, so it effectively develops an adaptive optimised drying schedule on-line. Carlsson & Esping (1997) also formulated the drying process as an optimisation issue. The objective was to minimise drying time while maintaining moisture content (below a certain level) and constraining cupping. Checks were not permitted in their formulation. The developed schedule was applicable only to the boards these researchers dried, and was not assessed for a timber stack in a kiln. Thus, the robustness of this model prediction for drying a stack of timber is uncertain.

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 4-hour schedule time step was chosen by Langrish *et al*. (1997), since the moisture transport dynamics are slow for the long timber-drying processes involved in drying hardwood (about 137 hours in a conventional kiln for timber from *Eucalyptus sideroxylon* A.Cunn ex Woolls. and 90 days in a solar kiln for green *E. pilularis* timber). 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 fewest checks with a reasonably fast drying time). In summary, all these previous approaches used a drying model for process simulation and a stress model to predict drying quality.

The diffusion model used in this study assumes moisture content gradient as a driving force and was applied successfully by Wu (1989), Doe *et al*. (1994), and Langrish *et al*. (1997). The thermal energy transport is described by a partial differential equation. These equations of the drying model were reported by Langrish *et al*. (1997) and Haque (2002). The present work uses this modelling and simulation approach to timber drying for developing the optimum combinations of dry- and wet-bulb temperatures for use in an industrial greenhouse solar kiln. Over the years more advanced solar kiln designs have evolved (equipped with auxiliary heating, water spray, vents, and automatic control) and are operating commercially (Haque 2002). The temperature and humidity can be precisely controlled in these solar kilns.

A modified approach to that of Langrish *et al*. (1997) was taken to develop a practically applicable optimised drying schedule. Model parameters, such as the diffusion coefficient and activation energy, were obtained from experimental data using a fixed schedule provided by the supplier of the solar kiln. The stress model parameters were determined from experiments reported by Haque (2002). The work reported in this paper was an attempt to apply the systematic technique to optimising and improving the original drying schedule in an industrial context in that the original fixed schedule was selected from the practice of an industrial solar kiln. The optimisation exercise was undertaken based on this fixed schedule. Testing of the optimised schedule (i.e., temperature and relative humidity) in a laboratory kiln is described. The objective of the development of this schedule was to implement it in an industrial solar kiln equipped with temperature and humidity control.

MATERIALS AND METHODS

Procedure

The optimisation formulation was implemented within the Matlab programming environment using a moving time horizon of 4 hours (established from the previous study), which is small compared with the overall drying time of over 2 months. The objective was to minimise the moisture content over successive time steps, subject to a constraint of a maximum strain level. The set points of dry- and wet-bulb temperatures calculated for each time step (satisfying the constraints) were part of the optimised schedule. This optimised schedule was 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 became the first constraint and was held at that level for faster drying as long as the dry-bulb temperature (the second constraint) did not exceed the upper limit (specified value of 60°C for a solar kiln). 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 programme was run in such a way that when the instantaneous strain reached its maximum level, the optimisation routine started and the constraints were satisfied at each time step.

Experimental Apparatus

The main experimental apparatus used for the determination of the drying behaviour of *E. pilularis* was a steam-heated kiln in the Department of Chemical Engineering at the University of Sydney. The kiln was a pilot-scale tunnel dryer with air circulation. The working section had a height of 0.45 m, a cross-stream width of 0.9 m, and a stream-wise length of 0.4 m, with a volumetric capacity of 0.162 m^3. A simplified schematic diagram of the kiln is shown in Fig. 1. The timber stack could be weighed as the kiln was running, by means of a 200 kg (± 5 g) capacity platform balance under the stack. This information was used to give an estimate of the moisture content of the timber as drying progressed. A centrifugal fan with a constant motor speed of 1400 rpm provided a uni-directional airflow of about 1 m/s across the timber stack. Dry-bulb and wet-bulb temperatures were monitored by two sets of resistance sensors, which were mounted in pairs at both sides of the kiln, upstream of the stack. Output signals were recorded on a PC connected via a datalogger. The stacking of boards in the kiln is described below.

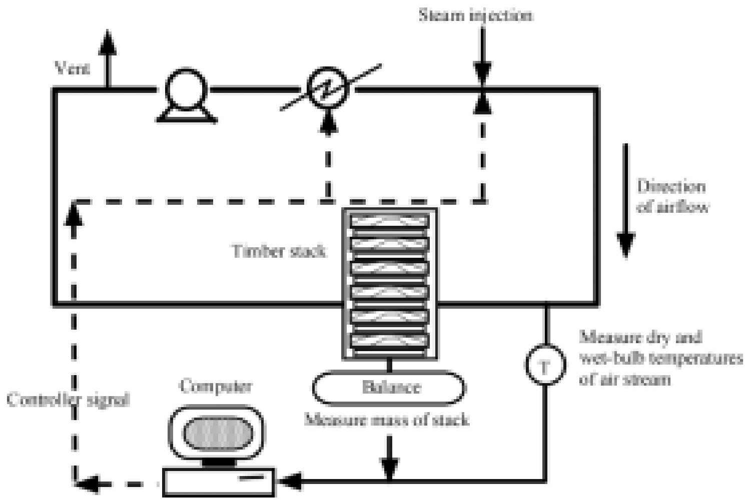

FIG. 1–Schematic diagram of the pilot scale timber drying kiln.

Sample Preparation

The *E. pilularis* timber used in this experiment was sawn at Boral Timber's Herons Creek Timber Mill, NSW, Australia. All boards were taken from one log to reduce the variation. The boards were 43 × 270 × 590 mm (green), backsawn, and wrapped as soon as they were cut to prevent premature moisture loss. Before the start of the experiment, the end of each board was coated with Timber End Sealer, supplied by Trend Timbers Pty Ltd, NSW, which can be used on wet timber. This helped to simulate the effect of a longer board by reducing longitudinal moisture flow, and also reduced end splitting. Samples were taken from each batch to determine initial moisture content by the oven-dry method.

The boards were stacked in the kiln through the access door. Dry and painted stickers of 25 × 25 × 300 mm of the same timber species were placed between boards, similar to the stacking arrangement in a commercial kiln. In total, six boards were used for each drying run. The total weight and average moisture content of the boards were entered into the kiln control software. The weight of the stickers in the kiln was also entered, and it was assumed that the stickers had a constant weight throughout the drying run. The changing weight of the stack (as recorded by the load cell) was used to estimate the moisture content of the boards as drying proceeded.

Drying Test

The drying schedule was entered as a look-up table using a moisture-content-based schedule so that, as the estimated moisture content of the stack was updated, the temperature setpoints were also updated and implemented by the control strategy of the kiln control system. The progress of the drying run was monitored by the computer, which controlled the temperature and humidity to predefined set-points. The drying run was terminated when the desired final moisture content was reached, which was specified to be 12% (average). After drying, the boards were allowed to cool for 6 hours. Moisture content was measured at the centre of each board with a Protimeter™ resistance moisture meter, and by the oven-drying method at the end of the experiment. The boards were cross-cut to give a 50-mm section from the end for internal-check inspection, and samples of the 50-mm block were taken for oven-dry moisture content tests. The cracks in each board were counted and classified according to size.

Drying Quality

The dried timber was classified according to the Australian and New Zealand Standard AS/NZS 4787 (Standards Australia/New Zealand 2001) for surface, internal, and end checks, and collapse caused by drying. According to this standard, there are five quality classes — A to E. Class A caters for specific end uses and applies to very particular 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 service environment is clearly defined. Class D applies when the final service environment is more clearly defined but 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 requirement is minimal. For example, for surface checks, if less than 0.5% of the full board surface is affected by checks (for 90% of samples observed), the quality class is Class A. No end check is acceptable for class A. If the maximum length of end check is less than 50 mm (for 90% of samples 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. No internal checks are acceptable for Classes A and B. Total collapse for both faces should be zero for Classes A and B.

RESULTS

The objectives of the first trial (Fig. 2) using the original schedule (Table 1) were to observe the drying behaviour of *E. pilularis* timber in the laboratory kiln, and to establish a base case of the final timber quality and the drying time for later comparison with an

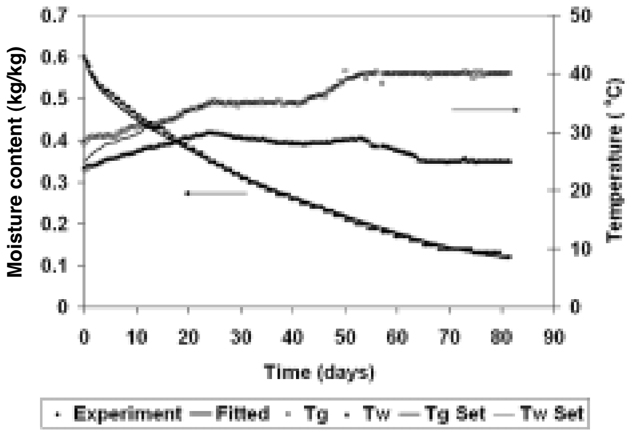

FIG. 2–Experimental and fitted moisture contents for a stack of timber using original schedule (Tg, actual dry-bulb; Tw, actual wet-bulb; and set-point temperatures).

TABLE 1–Original moisture-content-based schedule for drying 43-mm-thick (green) *E. pilularis* boards.

Initial moisture content (%)	Dry-bulb temperature (°C)	Wet-bulb temperature (°C)	Relative humidity (%)	Equilibrium moisture content (%)
70	25	24	85	18.0
60	25	23	80	16.0
45	30	27	75	14
35	35	30	70	12.5
30	35	29	65	11.3
25	35	28	55	9.5
20	40	29	45	7.8
15	45	29	30	5.7
14	45	26	22	4.0
13	55	26	15	2.0
10	55	25	12	1.5
Recondition	45	40	75	12.8

optimised drying schedule. These data were also used to estimate transport properties (the diffusion coefficient and activation energy) for the diffusion model used in the optimisation routine (as detailed by Haque 2002). The fitted parameters were then used to develop an optimised drying schedule. The physical, mechanical, and transport properties of *E. pilularis* timber used for drying simulation are summarised in Appendix 1.

The newly developed optimised schedule was tested in a laboratory drying trial and is shown in Fig. 3 with the original fixed drying schedule. The predicted reductions of moisture content as a function of time for both schedules are given in Fig. 4, and the predicted strain development during drying as a function of time for both schedules in Fig. 5.

The predicted moisture content profile and corresponding strains from the surface to the half thickness of a typical timber board are shown in Fig. 6 and 7 for the optimised schedule.

The optimised schedule for drying *E. pilularis* boards 43 mm in thickness is shown as a "look-up" table in Table 2.

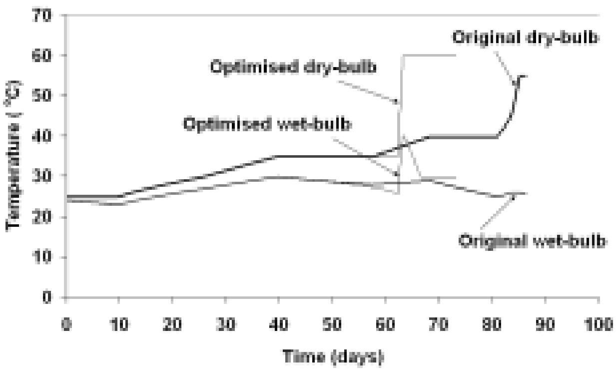

FIG. 3–The original and the optimised schedules, as a function of time.

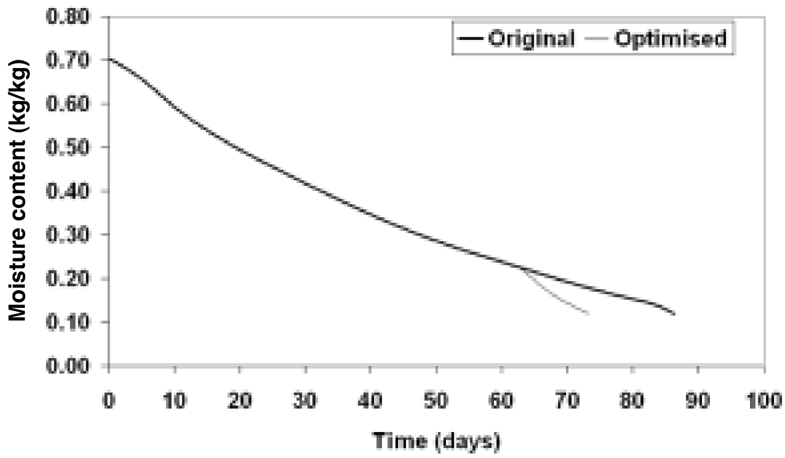

FIG. 4–Moisture contents as a function of time for the original and the optimised schedules.

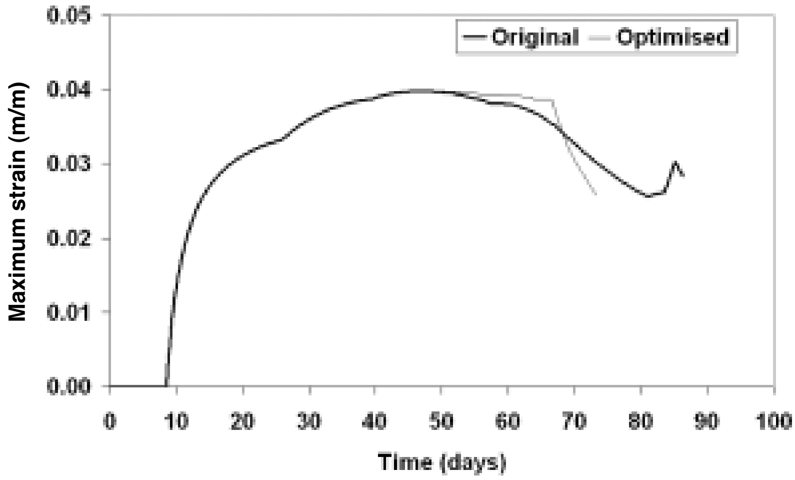

FIG. 5–Predicted strain as function of time for the original and the optimised schedules.

The fitted moisture contents and experimentally obtained values as a function of time, with dry- and wet-bulb temperatures, for the drying tests using the optimised schedule are shown in Fig. 8 and 9.

Timber quality after drying using the original schedule, and after the first and second tests using the optimised schedule, is indicated in Tables 3 to 5. All green boards were clear, without any surface checks, end splits, or distortion before drying. These boards were assessed after drying for end splits, surface checks, cupping, and similar distortions, and cross-cut for observation of internal checks.

The class of dried timber according to AS/NZS 4787 (Standards Australia/New Zealand 2001) is shown in Table 6 for all the tests.

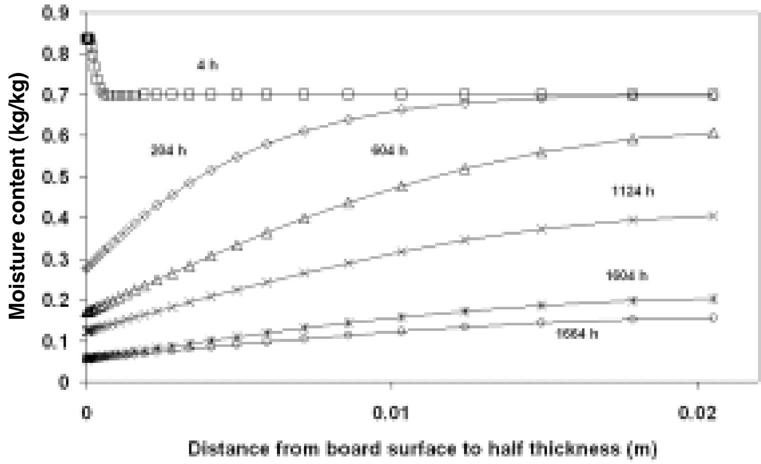

FIG. 6–Predicted moisture content profiles in a typical board for the optimised schedule at different times (t in hours) during drying.

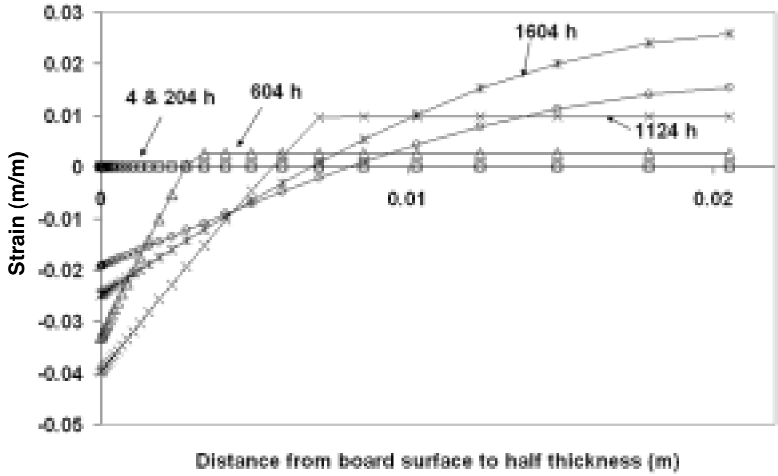

FIG. 7–Predicted strain profile in a typical board for the optimised schedule at different times (t) during drying.

DISCUSSION

At the start of the experiment maintaining very low wet-bulb depressions proved to be difficult, but apart from that the control of both dry- and wet-bulb temperatures was very good (Fig. 2). This was particularly so for the wet-bulb temperature where the differences between the actual values and the set points were barely noticeable except in the first 2 days. It is worth noting that the effect of the optimised schedule (Fig. 3) was to cut off some of the long "tail" of the original schedule. The long "tail" in the moisture content curve (Fig. 4) arose 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

TABLE 2–Moisture-content-based optimised schedule for drying 43-mm-thick (green) *E. pilularis* boards.

Initial moisture content (%)	Dry-bulb temperature (°C)	Wet-bulb temperature (°C)	Relative humidity (%)	Equilibrium moisture content (%)
70	25	24	85	18.0
60	25	23	80	16.0
45	30	27	75	14
35	35	30	70	12.5
30	35	29	65	11.3
25	35	28	55	8.5
23	35	26	46	8.1
22	53	37	38	6.0
20	60	37	24.5	4.0
18	60	30	11	2.1

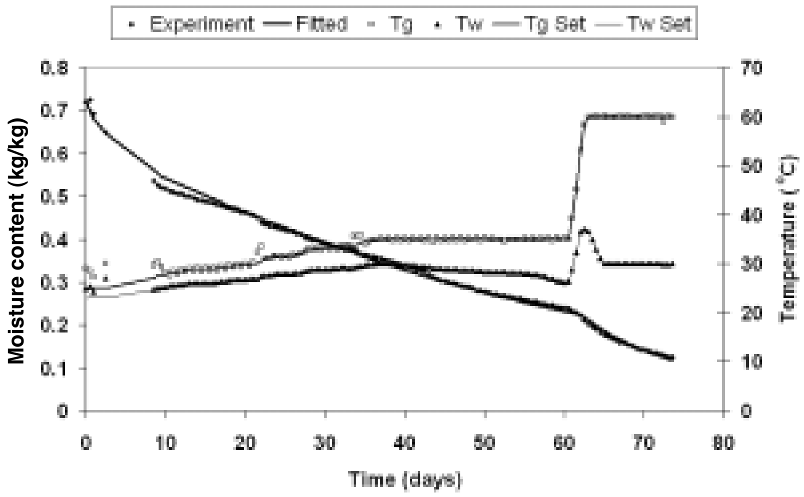

FIG. 8–Drying test data using the optimised schedule (Tg, actual dry-bulb; Tw, actual wet-bulb; and set-point temperatures).

calculations of Pordage & 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.

The procedure described here 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 and other degrade such as collapse may occur. After 3 weeks of drying, the dry-bulb temperature rose above 30°C. After 6 weeks, the dry-bulb temperature reached 35°C, which was held for another week. Both original and optimised schedules are the same until this stage (until 7 weeks). The moisture contents after 3 weeks, 6 weeks, and 9 weeks of drying were 0.48 kg/kg, 0.33 kg/kg, and 0.23 kg/kg, respectively,

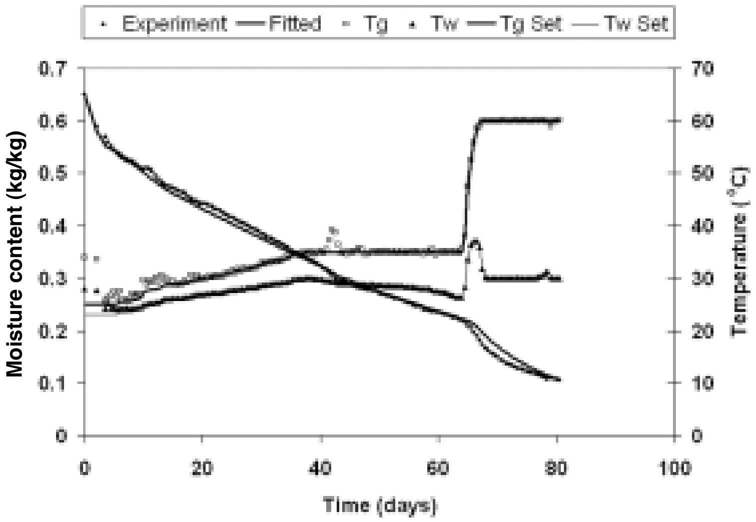

FIG. 9–Repeat drying trial using the optimised schedule (Tg, actual dry-bulb; Tw, actual wet-bulb; and set-point temperatures).

TABLE 3–Timber quality after drying using the original schedule

Board No.	End splits	Surface checks	Cupping	Collapse	Internal checks
1	Nil	Nil	Present	Absent	Nil
2	8	3	Absent	Absent	Nil
3	3	Nil	Absent	Absent	Nil
4	2	Nil	Absent	Absent	Nil
5	1	Nil	Absent	Absent	Nil
6	38	1	Present	Absent	Nil

TABLE 4–Timber quality after drying with the optimised schedule

Board No.	End splits	Surface checks	Cupping	Collapse	Internal checks
1	Nil	4	Present	Absent	Nil
2	Nil	Nil	Present	Absent	Nil
3	Nil	Nil	Present	Absent	Nil
4	Nil	2	Present	Absent	Nil
5	Nil	Nil	Present	Absent	Nil
6	5	9	Absent	Absent	Nil

TABLE 5–Timber quality after drying with the optimised schedule for the repeat trial

Board No.	End splits	Surface checks	Cupping	Collapse	Internal checks
1	6	Nil	Present	Absent	Nil
2	Nil	Nil	Present	Absent	Nil
3	Nil	Nil	Present	Absent	Nil
4	Nil	Nil	Present	Absent	Nil
5	1	2	Present	Absent	Nil
6	10	1	Absent	Absent	Nil

TABLE 6–Classification of timber based on drying quality

Schedules	Surface checks	End checks	Internal checks	Collapse
Original	Class A	Class C	Class A	Class A
Optimised	Class A	Class B	Class A	Class A
Repeat (optimised)	Class A	Class B	Class A	Class A

for both the optimised and the original schedules since the drying conditions until a moisture content of 0.23 kg/kg were the same.

In the final stage of drying, after about 9 weeks, the dry-bulb temperature reached its maximum of 60°C for the optimised schedule. By comparison, the original schedule dried the timber boards with lower dry-bulb temperatures in the final stages: the dry-bulb temperature was 40°C after 10 weeks, and the highest temperature of 55°C was used for a very short period after about 12 weeks. The drying rate was faster after 9 weeks for the optimised schedule than for the original schedule, since the dry-bulb temperature reached its maximum for the optimised schedule after this time (Fig. 3).

The predicted drying time for the original schedule is 86 days, whereas for the 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 the drying rate is significantly faster for the optimised schedule than for the original schedule (Fig. 4). This 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%.

The simulation program was formulated so 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, and so the maximum strain was considered as a constraint. While keeping the strain level equal to the maximum value (Fig. 5), the second constraint was applied to the dry-bulb temperature which was not allowed to exceed the limiting value of 60°C. This is the maximum dry-bulb temperature that can be achieved and maintained in a solar kiln equipped with an auxiliary heating source. The drying rate was faster than the original schedule at this period. The strain was predicted to reach its maximum value on the forty-seventh day when the moisture content was 0.30 kg/kg and continue until the sixty-seventh day when the moisture content was 0.17 kg/kg. The strain later started to decrease (Fig. 5) since the moisture content gradient after that time decreased rapidly, with the surface of the timber being close to the equilibrium moisture content and the moisture content in the centre decreasing. From below a moisture content of 0.22 kg/kg to the final moisture content, the optimisation routine maximised the drying rate within the constraints specified (particularly dry-bulb temperatures). The slightly harsher conditions (higher wet-bulb depressions) made little difference to the strain because large moisture content gradients are not possible in timber at these low average moisture contents. Hence, large stresses and strains were not predicted.

The development of strain 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 at about the half-thickness of the timber boards, since the boards are dried from both sides. At the beginning of drying (time t = 4 hours), there was some condensation at the surface, and the surface moisture content increased above the initial value (Fig. 6). The corresponding strain profile (Fig. 7) shows that there was no strain at that time, since the moisture contents were above the fibre saturation point throughout the timber board. After 8 days (t = 204 h), a small amount of strain (3×10^{-8} mm/mm) was predicted near the surface. After 25 days of drying (t = 604 h), the moisture content gradient was well developed from the surface (0.17 kg/kg) to the centre (0.61 kg/kg). 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 h), the moisture content gradient was significant (surface to centre 0.12 to 0.4 kg/kg), and this caused a very large amount of tensile stress (on surface) and compression stress (towards the centre). After 66 days (t = 1604 h), the moisture content gradient became shallower or milder than that for the early drying stages, resulting in lower strains. At the end of drying (t = 1664 h), the profile of moisture content became flattened, and the strains also reduced.

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

A simplified step-wise drying schedule based on moisture content can be implemented by extracting the values from the optimised schedule (Table 2). A step-wise drying schedule is convenient to apply for kiln operators with simple kiln control systems. Once the actual average moisture contents fall below 35%, then the dry-bulb temperature can be increased to 35°C, with a 5° or 6°C wet-bulb depression (Table 2). The dry-bulb temperature may be increased to 53°C, with a wet-bulb depression of 16°C, for drying below moisture content 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 content 25% to 12%, the new schedule predicts that in solar kilns 16 days may be necessary for drying if a constraint is put on the dry-bulb temperature (i.e., a maximum of 60°C for a solar kiln).

For the original schedule, the average initial moisture content determined by the oven-drying method was 59.9% before drying. The average final moisture content was 11.4% determined by the moisture meter test and 11.8% using the oven-drying method. The final moisture content that was recorded by the control system based on the drying tunnel balance was 12.2%. There is therefore very good correspondence between the final moisture content estimated from the measurement of the stack weight by the balance in the drying tunnel, and independent measurements by the oven-dry method. So the mass balance for moisture loss is very good using the moisture meter, the oven-dry method, and the balance of the drying tunnel.

Drying Time and Quality Comparison

The drying times for the original, the optimised, and the repeated optimised schedules were 81.5 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, and 70% and 12% (dry basis) for the optimised schedule. The initial and final moisture contents for the repeat trial using the optimised schedule were 65% and 10%. The drying time was 76 days for this repeat trial to a moisture content of 12%, and so the variation between this repeated trial (76 days) and the first trial of the 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). The initial and final moisture contents were determined by the oven-drying method and were in close agreement with the moisture contents recorded by the kiln balance and computer control system and the moisture meter.

For the original schedule, almost all boards (five of the total six) had end splits (Table 3). Two boards produced surface checks and cupping. None of these boards showed any 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; that may be 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 amount of cupping was 2.5 mm.

In comparison, for the optimised schedule (Table 4) 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 without reconditioning in the same way as for the original schedule. This board had both end and surface checks. Almost all boards had some cupping. The range for the amounts 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 optimised schedule than for the original schedule (and the initial moisture content was 10% lower for the original schedule).

For the repeat trial of the optimised schedule (Table 5), 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 optimised schedule than for the original schedule for a similar reduction in moisture content (e.g., from 60% to 12%).

Based on the AS/NZS 4787 (Standards Australia/New Zealand 2001), all boards were suitable for superior Class A, except for end checks (Table 6). For end checks, boards dried using the original schedule met the quality criteria for Class C, whereas boards dried using the optimised schedule were in higher Class B. The numbers of end checks were higher because the board lengths were shorter than the industrial size. None of the schedules used here produced surface checks over more than 0.5% of the board surface. Thus, dried boards met the quality criteria for Class A.

In summary, the original schedule dried boards with a large number of end splits but with few surface checks, little cupping, and no collapse and internal checks. The optimised schedule produced timber of no worse and possibly slightly better quality than the original schedule. The drying time for the optimised schedule was shorter for a similar reduction of moisture content.

It should be noted that the boards were taken from the same log to reduce variation and make possible a comparison between runs. This may mean that the variability in wood has not been fully addressed in this study. The time horizon of 4 hours was based on a previous study by Langrish *et al*. (1997). The selection of 1 or 2 hours produced a similar result but the effect of a time over 4 hours was not assessed. Overall the drying time was 10% shorter for the optimised schedule than for the original schedule. This is expected since the optimised schedule, with its higher temperatures towards the end of drying, cuts off some of the long "tail" of the reduction in the moisture content (Fig. 3).

CONCLUSIONS

The optimised schedule developed for drying *E. pilularis* boards in a solar kiln equipped with an auxiliary heating system is expected to increase productivity and improve the product quality of Australasian hardwood processing companies. The potential of this optimised schedule for drying other hardwoods needs to be examined.

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APPENDIX 1

TIMBER PROPERTIES OF *EUCALYPTUS PILULARIS* FOR DRYING SIMULATIONS

Properties	*E. pilularis* values or formula	Units
Mechanical properties		
Modulus of elasticity (green) cross-grain	4.04×10^8 (present study)	Pa
Free shrinkage coefficient	0.35 (present study)	$\frac{m/m}{kg/kg}$
Free shrinkage strain	$\varepsilon_s = 0.35 \times$ (moisture content change in kg/kg from fibre saturation point) (present study) Maximum ε_s 0.05 (present study)	m/m
Physical properties		
Density	1100–1150 (unseasoned) 900 (seasoned) (Bootle 1994) 1125 (measured at 71% moisture content), 825 (measured at 12% moisture content) (present study).	kg/m^3
Fibre saturation point (FSP)	0.30–0.001 × (T-20) (°C) (Siau 1984)	kg/kg
Transport properties		
Reference diffusion coefficient	1.15×10^{-5} (across grain) present study 1.145×10^{-4} (along grain)	m^2/s
Activation energy	3730 (present study)	K