6. DRYING SCHEDULE EVALUATION AND OPTIMIZATION: THE EFFECTS OF THE CORRELATIONS BETWEEN THE PHYSICAL, TRANSPORT, AND MECHANICAL PROPERTIES ON DIFFERENT DRYING SCHEDULES

6.1 Principal Components Analysis

For all the experiments, the possibility that there is a correlation between high initial moisture contents, higher diffusion coefficients, low basic densities, and low green modulus of elasticity's (MOE) was assessed using principal components analysis (PCA). Principal components analysis is a multivariable analysis of correlation. The technique identifies patterns within a given set of data, and then expresses the data in such a way to highlight similarities and differences between variations in each parameter (Smith, 2002). A key feature of PCA is its ability to find correlations between variables without assuming that particular variables are dependent or independent of each other. PCA seeks orthogonal correlations between combinations of variables. Once these correlations are found in the data, the data is compressed by reducing the number of dimensions without much loss of information. Data compression in PCA involves calculating the covariance matrix of the given data and calculating the eigenvectors and eigenvalues of the covariance matrix. The eigenvector with the highest eigenvalue is the principal component of the data set. Thereafter, the notion of data compression and reduced dimensionality is applied where a new data set, with fewer dimensions, is derived using the principal component so that the maximum variability is visible. In effect, this procedure is a systematic way of assessing which parameters or variables are most strongly correlated without assuming that particular variables are dependent or independent.

The physical reason for seeking such a correlation is that timber boards with high densities mean that there is more wood material per unit volume, which would also tend to increase the stiffness of the timber (high MOE). This may be due to relatively large cell volumes and/or more cell—wall material compared with lower density timbers, leaving less space for water to occupy, which explains the low initial moisture contents for timber boards with high densities (Keey *et al*., 2000; Walker, 1993). In addition, more wood material means a higher resistance to diffusive transport of moisture (Walker, 1993), thus the diffusion coefficient is expected to be low in high density wood. Moreover, it is also possible that collapse (as mentioned in **Chapter 5.2**) has an effect on tortuosity, hence on the diffusivity. Keey (1992) states that tortuousity is expected to have an effect on diffusivity in loose and particulate materials. However, the fact that timber is not a loose and particulate material does not diminish the relevance of this discussion. Collapse is likely to make pathways within timber for moisture movement more tortuous or convoluted. This feature is likely to reduce the diffusion coefficient. Collapse was not significant for blackbutt samples studied in this thesis, and possibly this timber species in general, but it may be significant for other eucalyptus species such as collapse-prone *Eucalyptus regnans* F. Muell (mountain ash) (Chafe *et al*., 1992; Innes, 1996). This potential limitation means that care is needed in applying the relationships found in this thesis to collapse—prone species.

A principal components analysis was performed on the four parameters: the basic density, the initial moisture content, the diffusion coefficient, and the green MOE. If these parameters are closely correlated, then the PCA should result in only one large principal component, and one large eigenvalue and eigenvector. The results of the PCA showed that the principal component for the within—tree and between—trees test accounted for 93% and 94% (for regrowth), and 92% and 90% (for plantation), respectively, of the total amount of variation within these parameters, giving some support for the mentioned correlation between the parameters. The correlations that result from the PCA are presented later in this section.

Figures 6.1 and 6.2 are typical plots showing the three dimensional relationship between the diffusion coefficient, the basic density, and the initial moisture content, and the three dimensional relationship between the green MOE, the basic density, and the diffusion coefficient, for the within—tree test of regrowth blackbutt material. The plots were drawn in this orientation to show the pattern of the actual data and how closely they are aligned with the principal eigenvector. Appendix 6 shows the three—dimensional plots for the between—trees tests of regrowth and plantation blackbutt, and for the within—tree test of plantation blackbutt timber. Figures 6.1 and 6.2, including the three—dimensional plots in Appendix 6, show that boards with low basic densities have low green MOEs, have high diffusion coefficients, and high initial moisture contents. From the PCA and the ANOVAs in **Chapters 4** and **5**, basic density may be the link between the modulus of elasticity and the diffusion coefficient. It was mentioned in **Chapter 5.3** that microfibril angle is possibly a better indicator of stiffness and strength, as expressed by MOE, compared with the basic density (Cave and Walker, 1994; Evans and Ilic, 2001). This suggests that calculating the MOE of a timber board using the basic densities may not be as accurate as an equation that uses the timber board’s microfibril angles. However, basic density is significantly easier to measure than microfibril angle and the relationship of the basic density and the MOE for blackbutt in this work and the regrowth blackbutt material

Alexiou (1993) studied showed that the basic density was representative of the timber board's MOE. The significance of the microfibril angle for the MOE and the diffusion coefficient is unclear. Future actual measurements of the microfibril angle of blackbutt timber are recommended to clarify this situation.

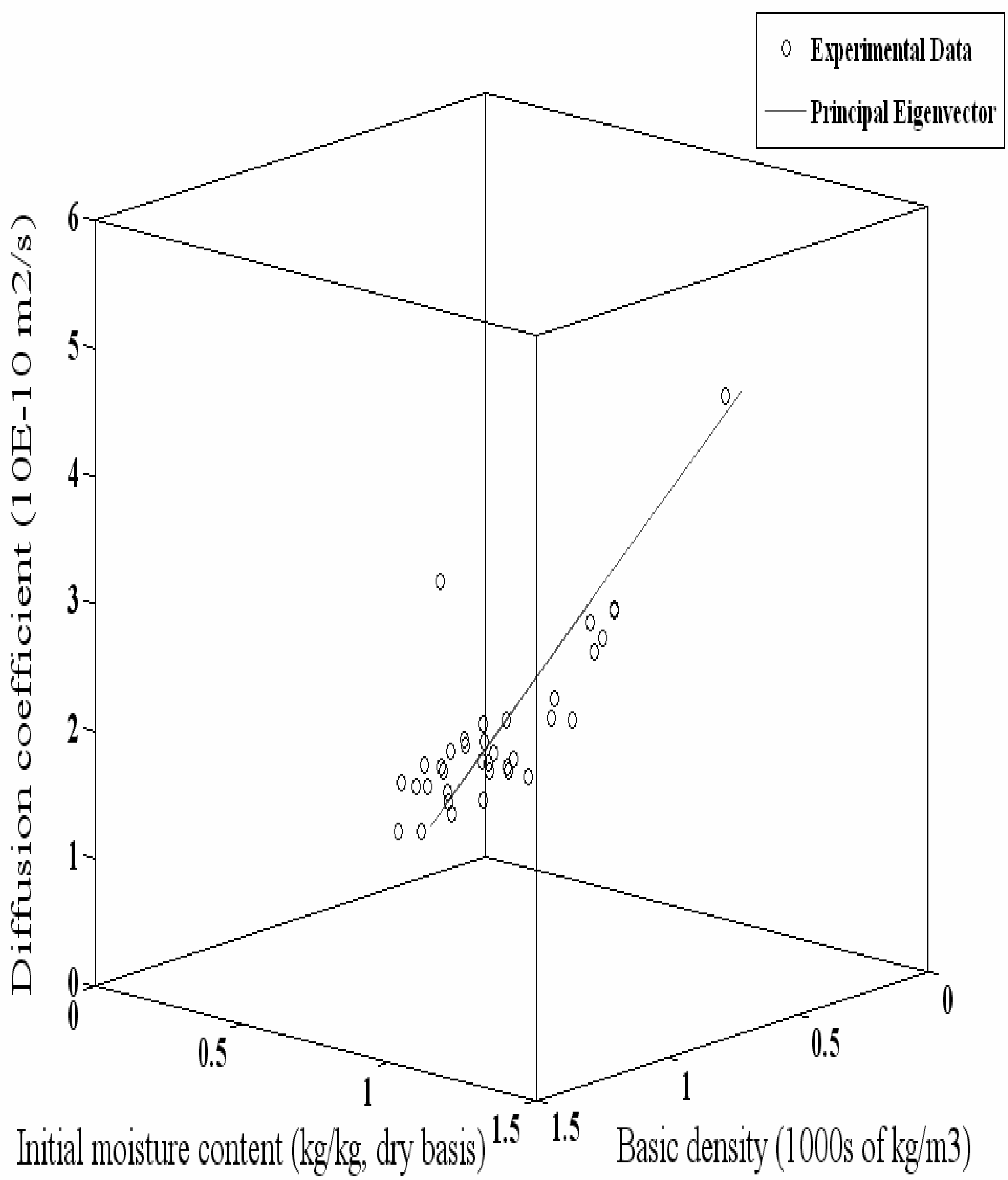

Figure 6.1. Three—dimensional plot of the relationship between the diffusion coefficient, the initial moisture content, and the basic density from the PCA, together with the principal eigenvector (regrowth blackbutt: within—tree test).

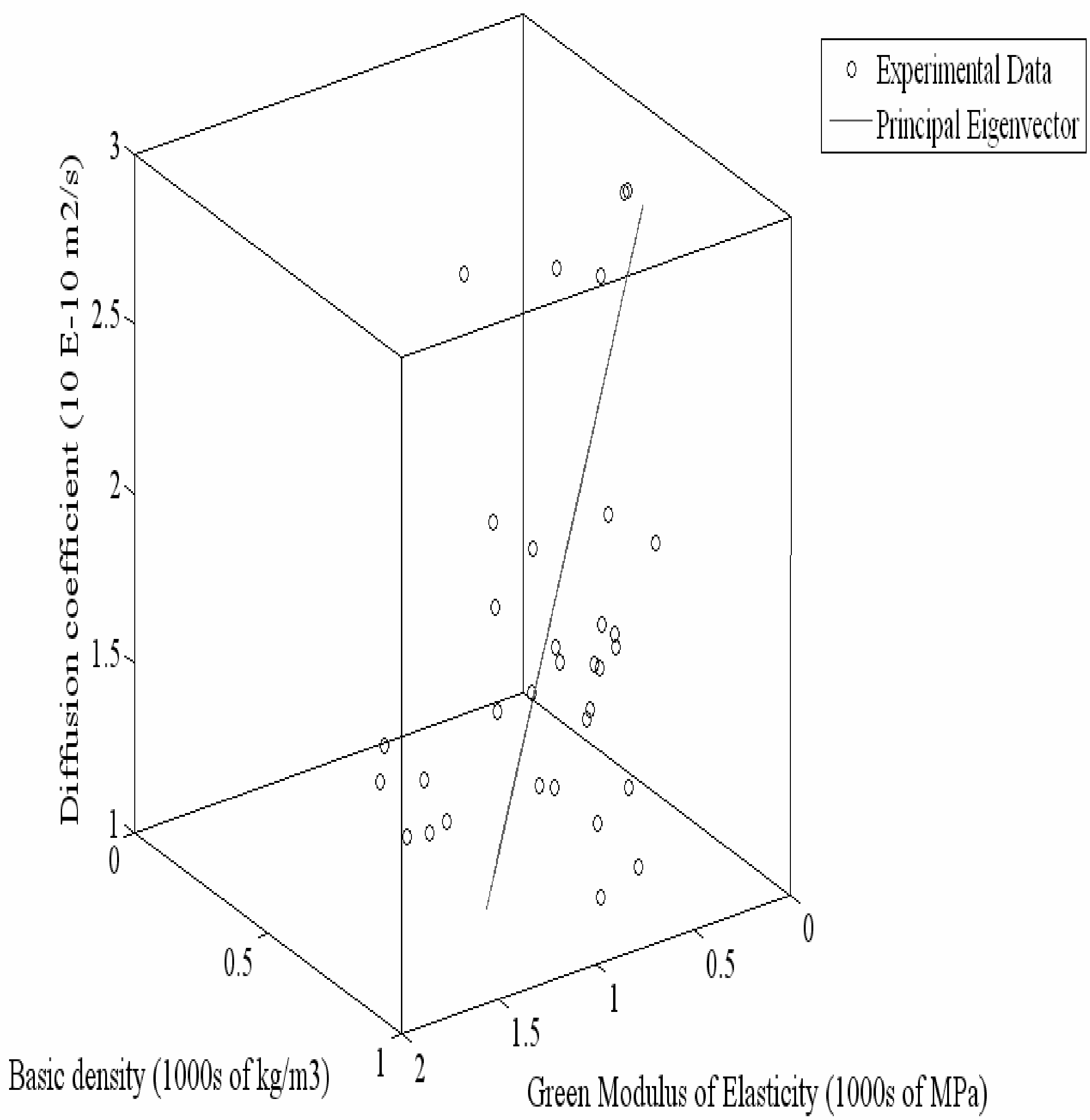

Figure 6.2. Three—dimensional plot of the relationship between the diffusion coefficient, the basic density, and the green MOE from the PCA, together with the principal eigenvector (regrowth blackbutt: within—tree test).

The strong correlation between the diffusion coefficient, D, and the basic density, ρ_D; the diffusion coefficient and the initial moisture content, X_i; and the diffusion coefficient, D, and the modulus of elasticity, E_G, are represented by Equations (6.1) to (6.12), respectively. It should be noted that Equations (6.1) to (6.3) represent the same principal component. The same situation exists for Equations (6.4) to (6.6), (6.7) to (6.9), and (6.10) to (6.12).

Regrowth Blackbutt Timber

1) Within—trees (accounting for 93% of the total amount of variation) (Figures 6.1 and 6.2):

$$D = (-6\times10^{-13})\rho_D + (6\times10^{-10}) \tag{6.1}$$

$$D = (6\times10^{-10})X_i - (2\times10^{-10}) \tag{6.2}$$

$$D = (-1\times10^{-13})E_G + (3\times10^{-10}) \tag{6.3}$$

2) Between—trees (accounting for 94% of the total amount of variation) (Figures A6.1 and A6.4):

$$D = (-1\times10^{-12})\rho_D + (9\times10^{-10}) \tag{6.4}$$

$$D = (6\times10^{-10})X_i - (2\times10^{-10}) \tag{6.5}$$

$$D = (-6\times10^{-13})E_G + (4\times10^{-10}) \tag{6.6}$$

Plantation Blackbutt Timber

1) Within—trees (accounting for 92% of the total amount of variation) (Figures A6.2 and A6.5):

$$D = (-2\times10^{-12})\rho_D + (2\times10^{-9}) \tag{6.7}$$

$$D = (9\times10^{-10})X_i - (3\times10^{-10}) \tag{6.8}$$

$$D = (-1\times10^{-12})E_G + (7\times10^{-10}) \tag{6.9}$$

2) Between—trees (accounting for 90% of the total amount of variation) (Figures A6.3 and A6.6):

$$D = (-8\times10^{-12})\rho_D + (5\times10^{-9}) \tag{6.10}$$

$$D = (3\times10^{-9})X_i - (2\times10^{-9}) \tag{6.11}$$

$$D = (1\times10^{-13})E_G + (1\times10^{-10}) \tag{6.12}$$

Analysis of variance (*F* significance test - Spiegel and Stephens, 1999) was conducted to determine if the equations from within—tree and between—trees tests, and regrowth blackbutt and plantation blackbutt tests, were significantly different. Since the equations from each test represented the same principal component, it was not necessary to do the *F* significance test on all equations. Therefore, Equations (6.1), (6.4), (6.7), and (6.10) were chosen for the *F* significance test. The way in which this significance test was carried out will now be explained.

For each case (i.e. regrowth blackbutt within—tree, regrowth blackbutt between—trees, plantation blackbutt within—tree, and plantation blackbutt between—trees), the differences between the experimental data and the principal component was quantified by transforming the experimental data so that the eigenvectors were the axes. Figure 6.3 shows the experimental data for the within—tree test of regrowth blackbutt and the respective eigenvectors, and Figure 6.4 shows the transformed data. This transformation had the effect of aligning all the data sets with a common axis, thereby allowing the different data sets to be compared on a common basis.

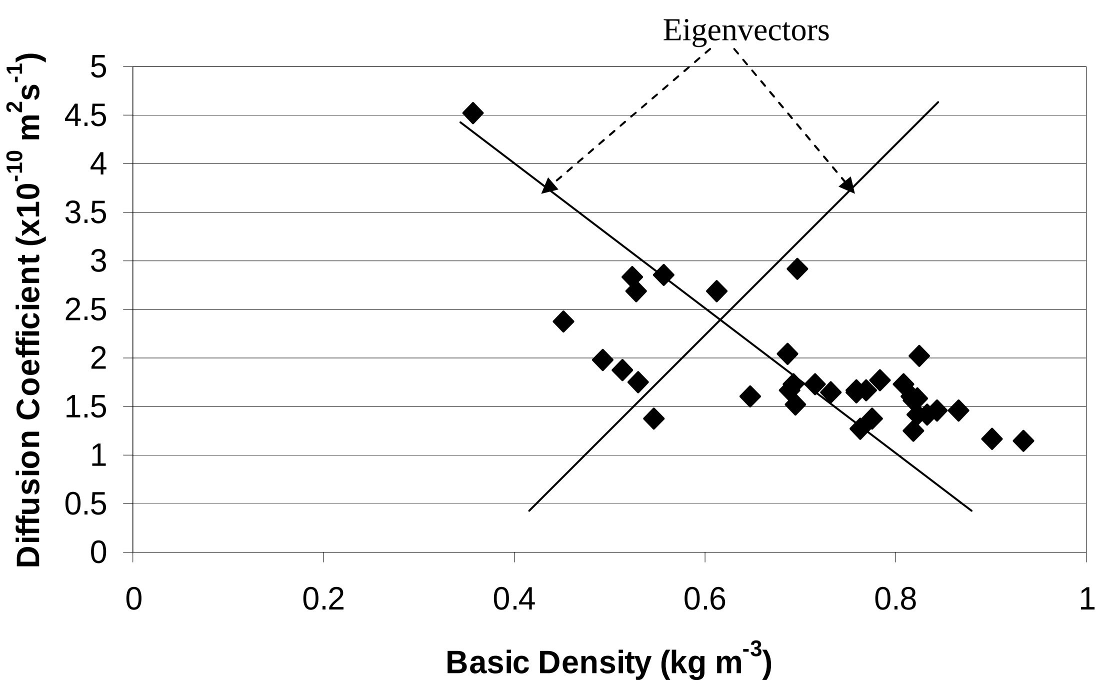

Figure 6.3. Experimental data for the within—tree test of regrowth blackbutt and their respective eigenvectors.

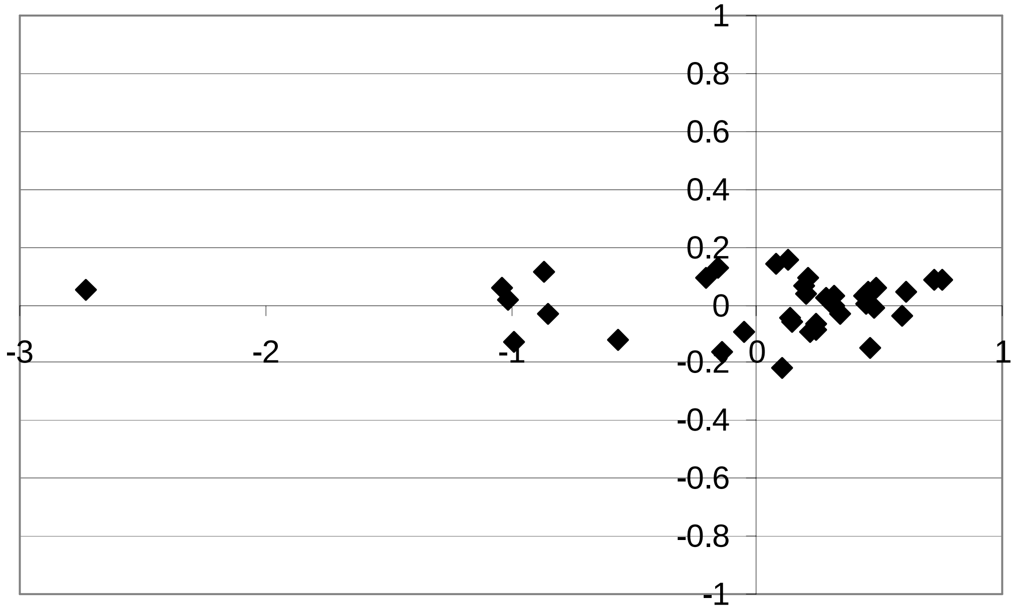

Figure 6.4. Transformed experimental data for the within—tree test of regrowth blackbutt timber, with the eigenvectors as axes.

The experimental data were transformed using Equation (6.13).

$$Transformed\ Data = Row\ Feature\ Vector \times Row\ Data\ Adjust \qquad (6.13)$$

Row Feature Vector is the matrix with the transposed eigenvectors from columns into rows, with the principal eigenvector at the top, and *Row Data Adjust* is the transposed mean—adjusted data, i.e. the data items are in columns, with each row holding a separate dimension. Overall, the transformation of the experimental data was based on the method described by Smith (2002).

Based on Figure 6.4, the difference between the *x* axis (i.e. the principal eigenvector/component) and each transformed data point was measured and squared. The sum of all the squared 'transformed' data points was calculated. The summation represented the variance of the within—tree test of regrowth blackbutt, S_1^2. The same procedure was used to calculate S_2^2 (between—trees test of regrowth blackbutt), S_3^2 (within—tree test of plantation blackbutt), and S_4^2 (between—trees test of plantation blackbutt). Table 6.1 shows the variance and the number of data points for each test. Thereafter, the variances were used in Equation (6.14).

$$F_{\nu_1,\nu_2} = \frac{S_x^2}{S_y^2} \tag{6.14}$$

where $S_x^2 > S_y^2$, ν_1 is the degrees of freedom in the numerator and ν_2 is the degrees of the denominator.

Table 6.1. The calculated variances and the number of experimental data points for each test.

	Variance (S_i^2)	**Number of Experimental Data Points**
S_1^2	0.29	36
S_2^2	0.00292	24
S_3^2	0.017	24
S_4^2	0.023	20

Table 6.2. Results of the *F* significance test, showing the calculated *F* values for each test.

Test	F_{actual}	$F_{expected}$ (at a 0.05 significance level)
1. Regrowth Blackbutt: Within—tree compared with Between—trees (S_1^2/S_2^2)	100	1.96
2. Plantation Blackbutt: Within—tree compared with Between—trees (S_4^2/S_3^2)	1.35	2.13
3. Within—tree Variability: Regrowth blackbutt compared with Plantation Blackbutt (S_1^2/S_3^2)	17.35	1.96
4. Between—Trees Variability: Regrowth Blackbutt compared with Plantation Blackbutt (S_4^2/S_2^2)	7.79	2.13

Table 6.2 shows the calculated *F* values for each significance test. The result of test 2 was the only result that showed there was no significant difference between the within—tree and between—trees variability of plantation blackbutt timber. A possible reason for this finding is that the boards from test 2, hence the trees, were all felled from one location. On the other hand, the other tests compared boards that were taken from trees felled from different locations, including the regrowth blackbutt within trees compared with between trees. The results of the significance tests imply the likelihood that boards taken from one location, whether they are within—tree and between—tree samples, have come from the same overall population. Hence using any of the correlations (within—tree or between—trees for plantation blackbutt) would be suitable to estimate the diffusion coefficient of other plantation blackbutt samples at the same location. Figure 6.5 further emphasizes the

impact that the location where the trees were felled had on the boards' timber properties. Figure 6.5 also shows that the pattern of the experimental data and the direction of the principal component for each test were similar to each other. Therefore, the results of the *F* significance test and Figure 6.5 are evidence that the variability of the timber properties was affected by boards taken from logs felled at different locations. In addition, the offset between the principal components of regrowth and plantation blackbutt timber supports the suggestion made in **Chapters 4** and **5** that there was a significant difference between the timber properties (except for the initial moisture content, tangential and radial shrinkages) of plantation blackbutt timber and that of regrowth blackbutt timber.

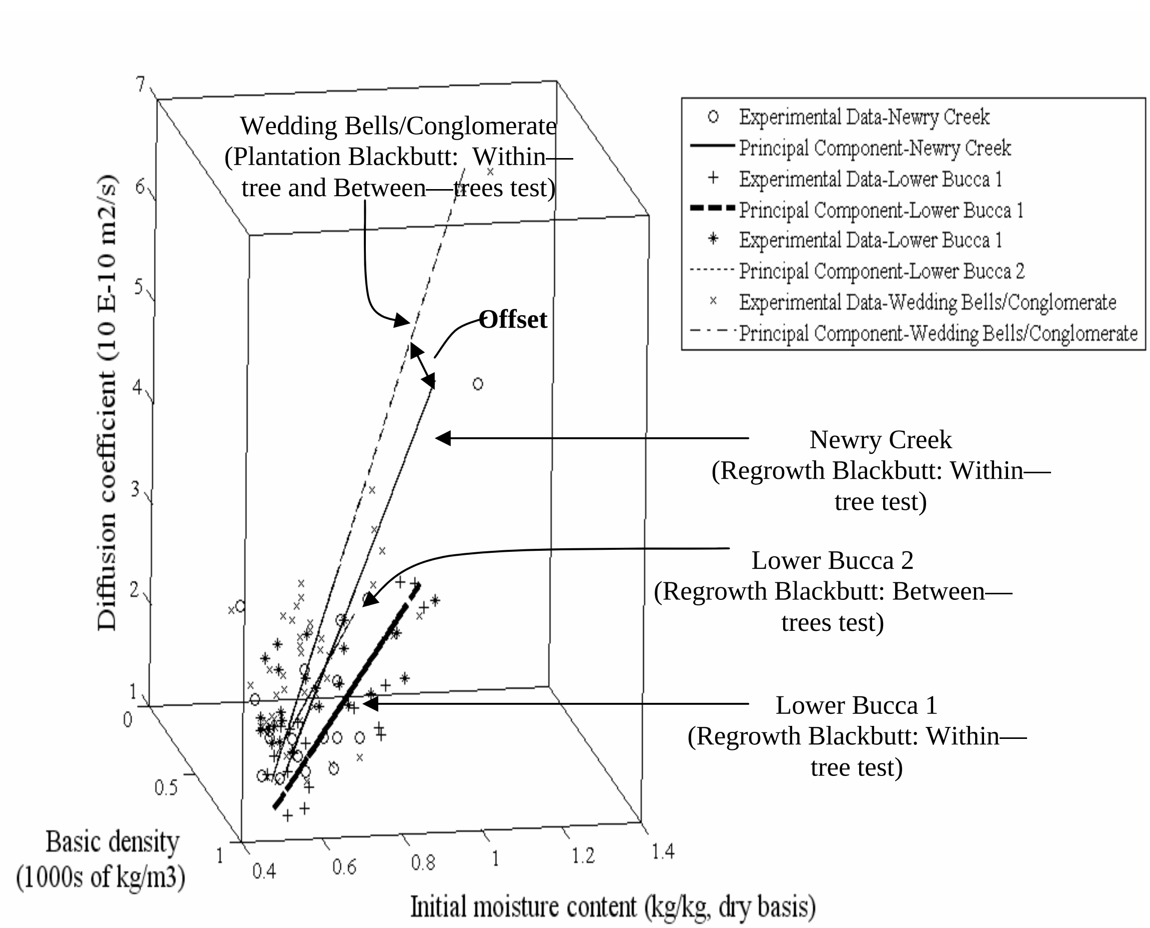

Figure 6.5. Three—dimensional plot showing the experimental data and the principal component for each test based on the location where the trees were felled.

Overall, these empirical equations can be used to estimate important drying properties of other regrowth and plantation blackbutt samples, such as the diffusion coefficient, using easily measured properties, like the initial moisture content or the basic density, as long as the boards were taken from the same age group (i.e. regrowth or plantation) and the same location. Thereafter, the blackbutt timber boards may be segregated based on their respective diffusion coefficient values, i.e. boards with high diffusion coefficient represent one group, while the other group consists of timber boards with low diffusion coefficients. Hence a suitable drying schedule should be chosen for each group.

Moreover, PCA was applied to determine the correlation between five properties: the basic density, the initial moisture content, the diffusion coefficient, the green MOE and the failure strain. The results of the PCA showed that the principal components both for the within—tree and between—trees test of regrowth blackbutt accounted for 93% of the total amount of variation within these parameters. In addition, the principal components of the within—tree and between—trees tests of plantation blackbutt accounted for 92% and 90% of the total amount of variation, respectively. These results suggest that a strong correlation exists between the physical properties (the basic density and the initial moisture content), the drying property (diffusion coefficient) and the mechanical properties (the green MOE and the failure strain).

Acoustic methods to measure stiffness are currently being applied in the timber drying industry (Andrews and Muneri, 2002). The predicted longitudinal MOE, E_L, as shown in Table A3.4 in Appendix 3 for the within—tree test of regrowth blackbutt timber, for example, was calculated using the following equation (Andrews and Muneri, 2002):

$$E_L = \rho_G V^2 \tag{6.15}$$

The average value of the parameters was taken for all the ‘A’ and ‘E’ boards to represent the properties of each full length board. Using PCA again, the diffusion coefficient and basic density of each 4.8 m regrowth timber board were analysed alongside the other data, first with E_L (longitudinal modulus of elasticity) (as shown in Figure 6.6), V (acoustic speed), and lastly, ρ_G (green density).

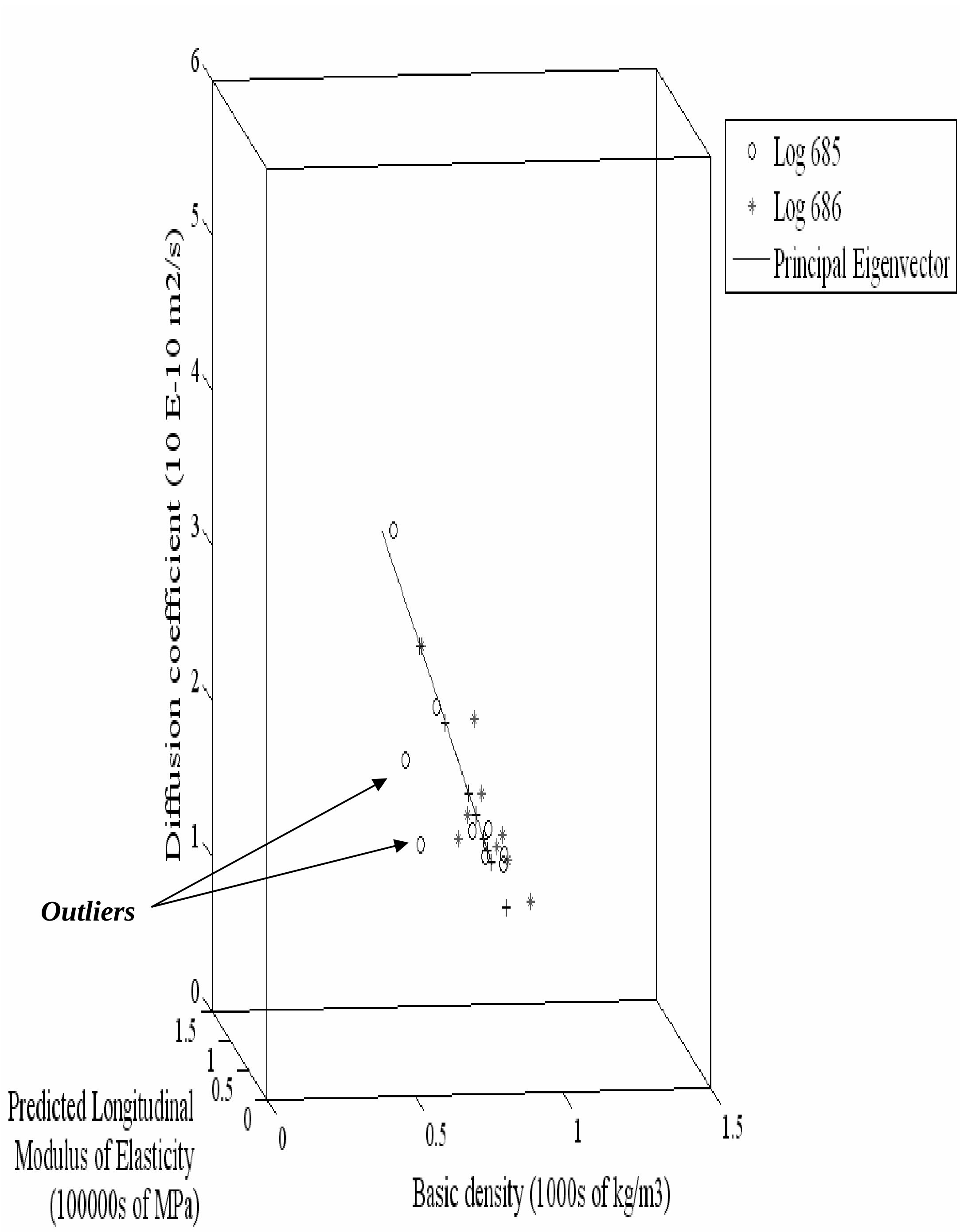

Figure 6.6. Three-dimensional plot of basic density, longitudinal modulus of elasticity (predicted using acoustic methods), and diffusion coefficient from Principal Components Analysis (PCA), together with the principal eigenvector (regrowth blackbutt: within—tree test).

The outcomes of the three separate analyses were common: the first and largest eigenvalue accounted for 98% of the total amount of variation within these parameters. This finding suggests that a strong correlation exists between D, ρ_D, E_L, V, and ρ_G, i.e. high basic density (also high green density) meant a faster acoustic speed, thus a high longitudinal MOE, from Equation (6.15). An explanation for this is that a denser timber means that sound travels much faster within the timber, and this is correlated to the stiffness of the timber in the longitudinal direction. Two boards were considered outliers. These boards, though it had a high basic density, had a high diffusion rate which was possibly due to the crack present throughout the length of the board. However, the presence of cracks has not increased the apparent diffusion coefficients by an order of magnitude. Therefore, through the use of acoustic methods, the correlation between the diffusion coefficient and the longitudinal MOE (and basic density) is Equation (6.16):

$$D = (-3\times10^{-14})E_L + (7\times10^{-10}) \tag{6.16}$$

Since acoustic methods are widely accepted and used by the timber drying industry, with the use of correlations such as Equation (6.16), important drying properties such as diffusion coefficients can possibly be estimated. This step also allows the prediction of the drying behaviour of a particular timber board prior to kiln—drying. With this in mind, a suitable drying schedule may then be chosen to dry a given stack of boards, since previous work has developed drying schedules based on trial and error (Mills, 1991), or on simulations (Langrish *et al*., 1997; Brooke, 1999) for commercial species, such as Australian Ironbark timber (*Eucalyptus paniculata*). However, a challenge that is addressed here is accounting for the variability of both the drying and the mechanical properties in the development of better drying schedules.

6.2 Drying Schedule Evaluation

6.2.1 Preliminary Drying Schedule Evaluation (12 Boards)

A preliminary drying schedule evaluation was conducted to investigate the effects of different drying schedules on the variability of final moisture contents based on the measured regrowth blackbutt timber properties, i.e. the reference diffusion coefficient, the green MOE, the shrinkage coefficient (calculated from the tangential shrinkage), and the initial moisture content, when the average moisture content within a stack of timber reached 15%. The same drying model (**Chapter 3.3**) was used in this evaluation. In addition, the maximum strain attained by the timber boards was also predicted by including the stress/strain model used by Langrish *et al*. (1997) in the assessment. Tables 6.3 to 6.5 show the drying schedules used for this comparison. These drying schedules were used by Kärki (2002), whose experiment dried European aspen (hardwood), Innes and Redman (2003) to dry six different regrowth hardwoods including blackbutt, and for this preliminary evaluation, a revised drying schedule by adding 5^{o}C to the dry and wet-bulb temperatures to the drying schedule in Table 3.3. The results from these drying schedules have then been compared, in terms of the dispersion of the final moisture contents and the maximum strain reached, with the drying schedule used for the drying experiments in this thesis (Table 3.3). The data used with the 12 timber boards chosen for this simulation were the boards with the highest and lowest initial moisture contents from each regrowth blackbutt drying experiment.

Table 6.3. Drying schedule used by Kärki (2002) to dry European aspen.

Time (hours)	Dry-Bulb Temperature (^oC)	Wet-Bulb Temperature (^oC)
0	20	18
20	50	47
40	50	46
60	50	45
80	55	47
100	60	49
120	65	50
140	70	52
160	70	52
180	55	50

Table 6.4. Drying schedule used by Innes and Redman (2003) to dry blackbutt timber.

Time (hours)	Dry-Bulb Temperature (^oC)	Wet-Bulb Temperature (^oC)
0	23	21.5
168	23	21
336	24	21.5
504	24	21
840	25	20.5
1008	25	20

Table 6.5. Revised drying schedule, for this study, by using the drying schedule from Mills (1991) to dry 25 mm thick blackbutt timber and adding 5^oC to the temperatures.

Time (hours)	Dry-Bulb Temperature (^oC)	Wet-Bulb Temperature (^oC)
0	60	57
120	65	61
192	70	65
240	70	62
288	75	65
360	75	60

Table 6.6. Statistical analysis of the predicted final moisture contents and maximum strains using the different drying schedules and the properties of 12 regrowth blackbutt boards.

Drying Schedule Used	**Time (hours)**	**Final Moisture Content (kg/kg)**			**Maximum Strain (mm/mm)**		
		Average	*Standard Deviation*	*Coefficient of Variation*	*Average*	*Standard Deviation*	*Coefficient of Variation*
1.Original drying schedule	396	0.15	0.013	0.087	0.0472	0.018	0.381
2.Kärki (2002)	255	0.15	0.029	0.193	0.0639	0.024	0.376
3.Innes and Redman (2003)	1386	0.15	0.014	0.093	0.0624	0.025	0.401
4.Original drying schedule + 5^{o}C	378	0.15	0.013	0.087	0.0428	0.017	0.397

Table 6.6 shows the different effects of each drying schedule on the time that it takes for the timber stack to reach an average moisture content of 0.15 kg/kg, the dispersion of final moisture contents, and the maximum strain reached. These results show a trade off between the shortness of the drying schedule and the dispersion of final moisture contents. Drying schedule 2 gave the shortest time for the stack of timber to reach the target average moisture content, but its conditions produced the largest dispersion of final moisture contents and the highest average value for the maximum strain. Drying schedule 3 gave the longest drying time, but the dispersion of final moisture contents was two times smaller (0.093) compared with the dispersion of final moisture contents from drying schedule number 2 (0.193). On the other hand, the conditions of drying schedules

1 and 4 seem to be similar in terms of the distribution of final moisture contents. On the other hand, increasing all the temperatures in drying schedule 1 by 5^{o}C (which is drying schedule 4) reduced both the drying time and the maximum strain level. Elevated temperatures increase the diffusion coefficient and hence the drying rate, decreasing the drying time. Increasing the rate for moisture transport also produces flatter moisture content gradients and therefore reduces the strain level. Doe *et al*. (1994) suggest that the cracking of this type of hardwood timber occurs above a strain level of 0.02 mm/mm, and all four drying schedules produced a maximum strain above this target level. In addition, the average maximum strains estimated in this preliminary drying schedule evaluation are greater than the value (0.02 mm/mm) reported by Doe *et al*. (1994) and the average maximum strains measured and reported in the actual drying experiments in this thesis, i.e. 0.0092 mm/mm (regrowth: within—tree), 0.0146 mm/mm (regrowth: between—trees), 0.0156 mm/mm (plantation: within—tree) and 0.0139 mm/mm (plantation: between—trees). The results from the preliminary drying schedule evaluation will now be further investigated by studying the effects of different drying schedules on sample boards chosen in random and the effect of taking into account possible correlations between the timber properties on the drying behaviour of the boards.

6.2.2 Drying Schedule Evaluation: Random Sampling (30 Boards)

The purpose for the 'random sampling' evaluation was to assess the drying behaviour of regrowth and blackbutt timber boards in different drying schedules and the effects of the potential correlations between the diffusion coefficient (*w*), the green MOE (*x*), the shrinkage coefficient (calculated from the tangential shrinkage) (*y*), and the initial moisture content (*z*) has on the quality of the timber boards. In this evaluation, the timber properties of the boards used for the simulation were based on the covariance of the measured timber properties in **Chapters 4** and **5**. Figure 6.7 shows the overall procedure that led to the 'random sampling' evaluation of different drying schedules.

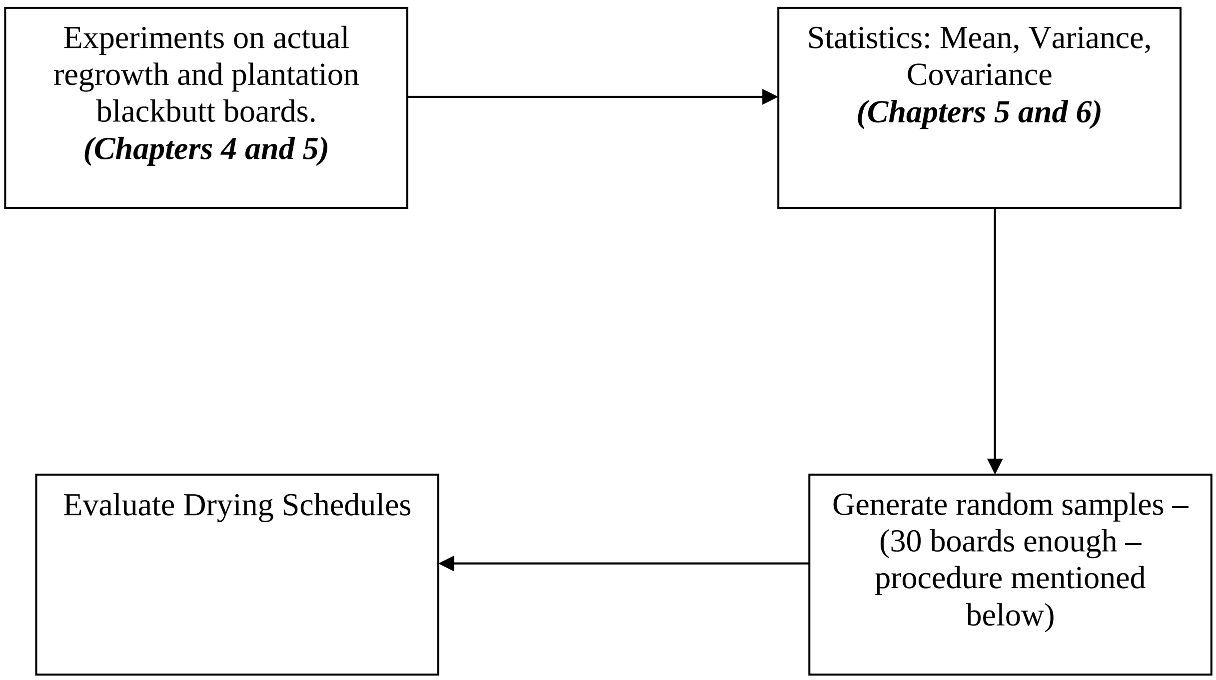

Figure 6.7. The overall procedure for evaluating different drying schedules accounting for the variability of regrowth and plantation blackbutt timber.

The method applied for the 'random sampling' evaluation of different drying schedules will now be explained. Firstly, the covariance matrix, *C*, for each variability test, i.e. regrowth within—tree, regrowth between—trees, plantation within—tree, and plantation between—trees, was calculated using Equations (6.17) and (6.18) (Smith, 2002).

$$\operatorname{cov}(X,Y) = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{(n-1)} \tag{6.17}$$

$$C = \begin{pmatrix} \text{cov}(w,w) & \text{cov}(w,x) & \text{cov}(w,y) & \text{cov}(w,z) \\ \text{cov}(x,w) & \text{cov}(x,x) & \text{cov}(x,y) & \text{cov}(x,z) \\ \text{cov}(y,w) & \text{cov}(y,x) & \text{cov}(y,y) & \text{cov}(y,z) \\ \text{cov}(z,w) & \text{cov}(z,x) & \text{cov}(z,y) & \text{cov}(z,z) \end{pmatrix} \tag{6.18}$$

Where *w*, *x*, *y* and *z* are the data sets, $\bar{W}$, $\bar{X}$, $\bar{Y}$, and $\bar{Z}$ are the means of each data set, and *n* is the total number of samples. In this case, four data sets were used, thus the covariance matrix had four rows and four columns. Thereafter, a number of trial simulations were conducted to determine the smallest number of samples so that the sample statistics (i.e. the dispersion of the final moisture contents and the maximum strain reached) were within ±1% of the population statistics.

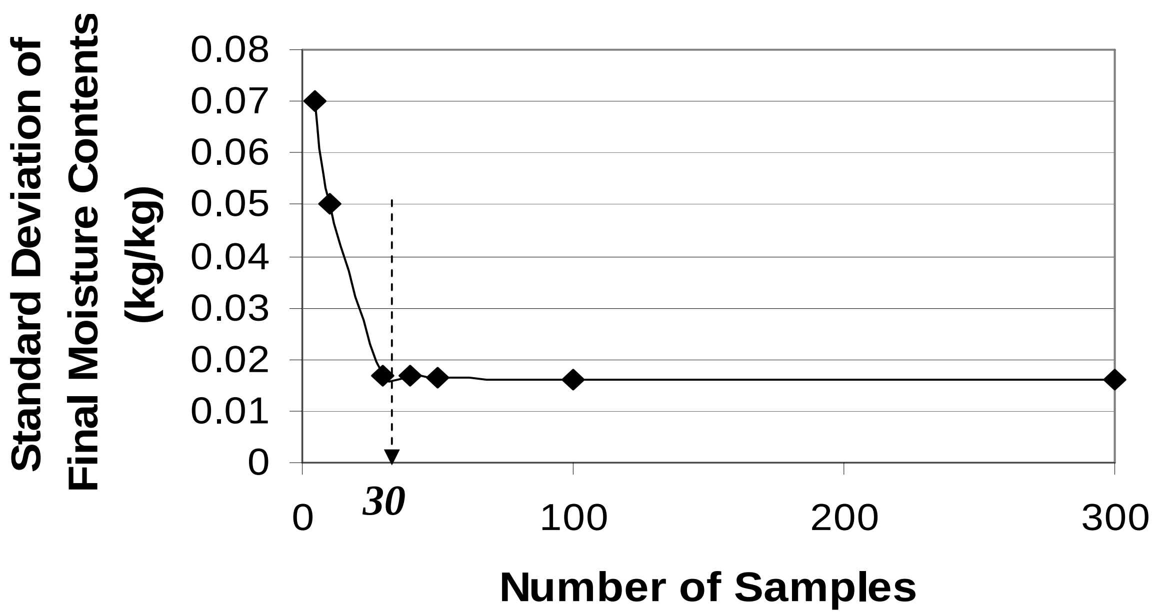

Figure 6.8. The dispersion of final moisture contents as a function of the number of samples.

Figure 6.8 shows that the dispersion of final moisture contents stabilizes beyond 30 samples. Hence, 30 samples was a reasonable sample size to use for the evaluation of different drying schedules. The same result was obtained for the maximum strain in which the standard deviation of the maximum strains (0.018 mm/mm) stabilized around 30 to 300 samples. The different drying schedules used for this 'random sampling' evaluation were the altered dry—bulb and wet—bulb temperatures of the drying schedule used in the experiments for this thesis, i.e. increasing and decreasing the original drying schedule (Table 3.3) by 5^{o}C and 10^{o}C. The sensitivity of the outcomes of regrowth blackbutt, accounting for within—tree variability is recorded in Table 6.7. Appendix 7 shows the results for the between—tree variability sensitivity tests of regrowth and plantation blackbutt timber and the within—tree variability sensitivity test of plantation blackbutt timber.

Table 6.7. Statistical analysis of the predicted final moisture contents and maximum strains using the different drying schedules for the within—trees test of regrowth blackbutt timber.

Drying Schedule Used	**Time (hours)**	**Final Moisture Content (kg/kg)**			**Maximum Strain (mm/mm)**	
		Average	*Standard Deviation*	*Coefficient of Variation*	*Average of Maximum Strains*	*Maximum Strain Reached*
1.Original drying schedule –10°C	391	0.15	0.012	0.079	0.060	0.468
2.Original drying schedule –5°C	317	0.15	0.054	0.361	0.051	0.093
3.Original drying schedule	294	0.15	0.045	0.297	0.037	0.060
4.Original drying schedule +5°C	285	0.15	0.031	0.208	0.038	0.066
5.Original drying schedule +10°C	269	0.15	0.034	0.228	0.037	0.068

Table 6.7 shows the different effects of each drying schedule on the time that it takes for the timber stack to reach an average moisture content of 0.15 kg/kg, the dispersion of final moisture contents, and the maximum strain reached. These results show that, for regrowth blackbutt timber and accounting for within—tree variability, there is no relationship between the length of the drying schedule and the dispersion of final moisture contents. As the temperatures increased, the dispersion of the final moisture contents had no consistent trend (Table 6.7). In addition, the results present the possibility that simply increasing or decreasing the temperature does not decrease the dispersion of final moisture contents. It is also possible that the non—existence of a trend is due to the

different locations where the logs used for the within—tree test of regrowth variability were taken. On the other hand, the between—tree variability sensitivity tests for both regrowth and plantation blackbutt timber and the within—tree variability sensitivity test for plantation blackbutt timber show a relationship between the length of the drying schedule and the dispersion of final moisture contents (Appendix 7). The dispersion of the final moisture contents decreased as temperatures increased. Generally, the '+10^{o}C' drying schedule gave the shortest time for the stack of timber to reach the target average moisture content and its conditions produced the smallest dispersion of final moisture contents. It was also interesting to observe, however, that for all sensitivity tests, that as the temperature of the drying schedule increased, the average of the maximum strains reached decreased. This is a very unusual result, because normally the strains and stresses would be expected to increase with increasing temperature.

Further investigation was conducted on the within—tree test of regrowth blackbutt timber. The average, minimum and maximum values of the diffusion coefficient, the moisture content gradient, the shrinkage and the strain as a function of time (under the drying conditions of the '-10^{o}C' and '+10^{o}C' drying schedules) were plotted to show a possible explanation for why drying time and strain decreased as temperature increased. Elevated temperatures increase the diffusion coefficient (Figures 6.9 and 6.10) and hence the drying rate, decreasing the drying time. Increasing the rate for moisture transport also produces flatter moisture content gradients, i.e. the differences between the minimum and the maximum values of the moisture content gradient of the timber boards decreased over time, and the overall average moisture content gradients of the '+10^{o}C' drying schedule were less than the moisture content gradients of the '-10^{o}C' drying schedule (Figures 6.11

and 6.12). Moreover, the shrinkage values for the '+10^{o}C' drying schedule are lower compared with the shrinkage values of the timber boards using the '-10^{o}C' drying schedule (Figures 6.13 to 6.14). The lower shrinkage values for the '+10^{o}C' reduce the strain level as a function of time (Figures 6.15 and 6.16). It should be noted that the jumps in Figures 6.9 to 6.16 are due to the step changes in the drying schedule.

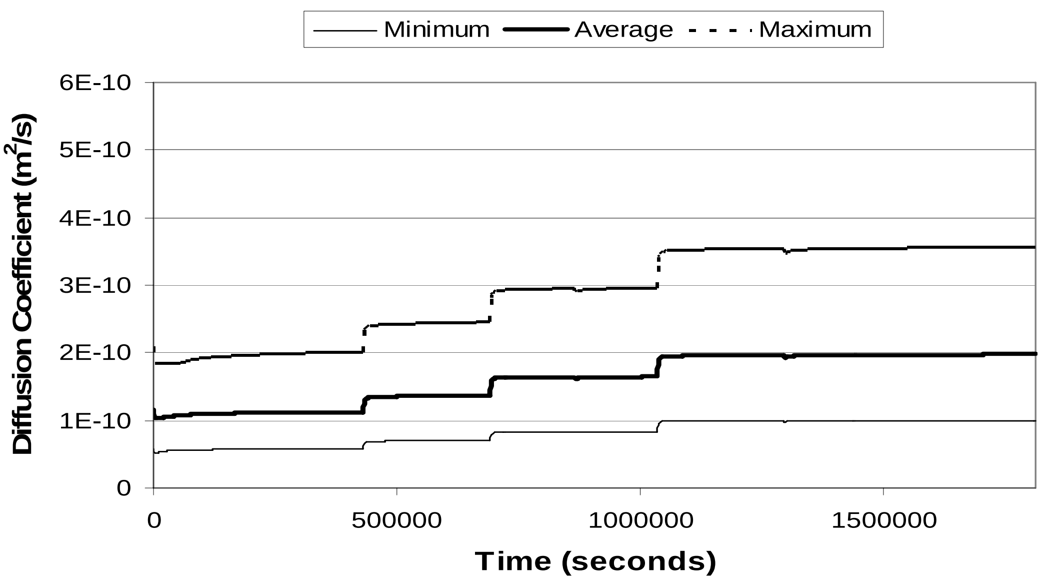

Figure 6.9. The minimum, maximum and average diffusion coefficient values of all 30 boards as a function of time, using the drying schedule with temperatures that were 10^{o}C lower than the original drying schedule (regrowth blackbutt timber: within—tree variability).

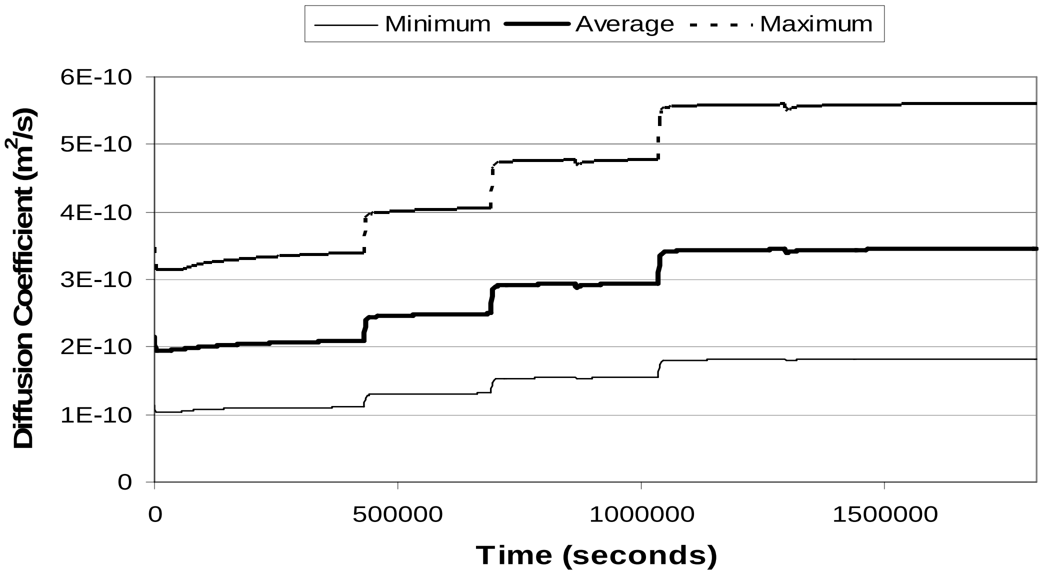

Figure 6.10. The minimum, maximum and average diffusion coefficient values of all 30 boards as a function of time, using the drying schedule with temperatures that were 10°C higher than the original drying schedule.

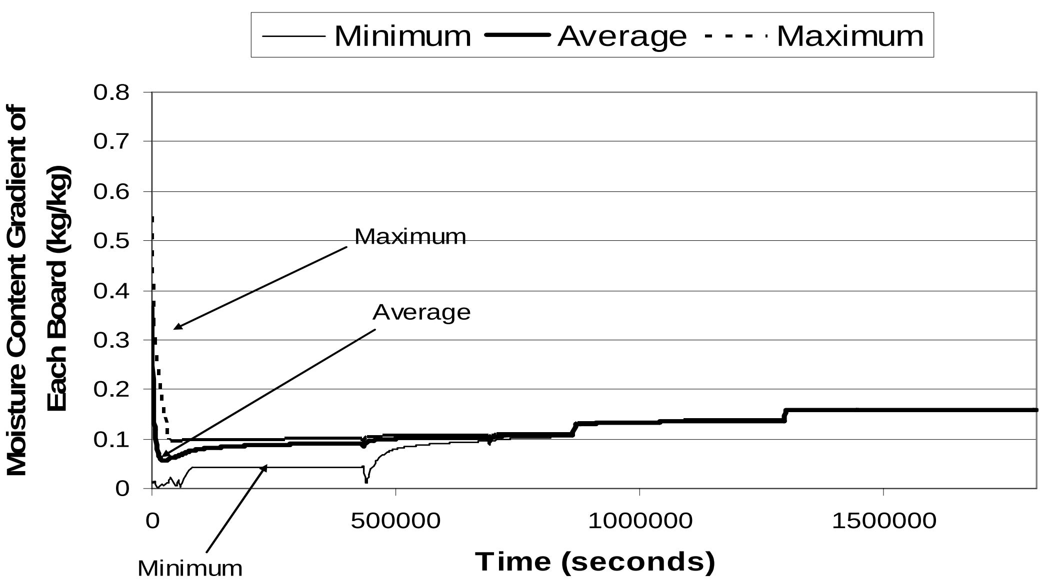

Figure 6.11. The minimum, maximum and average moisture content gradient values of all 30 boards, as a function of time, using the drying schedule with temperatures that were 10°C lower that the original drying schedule.

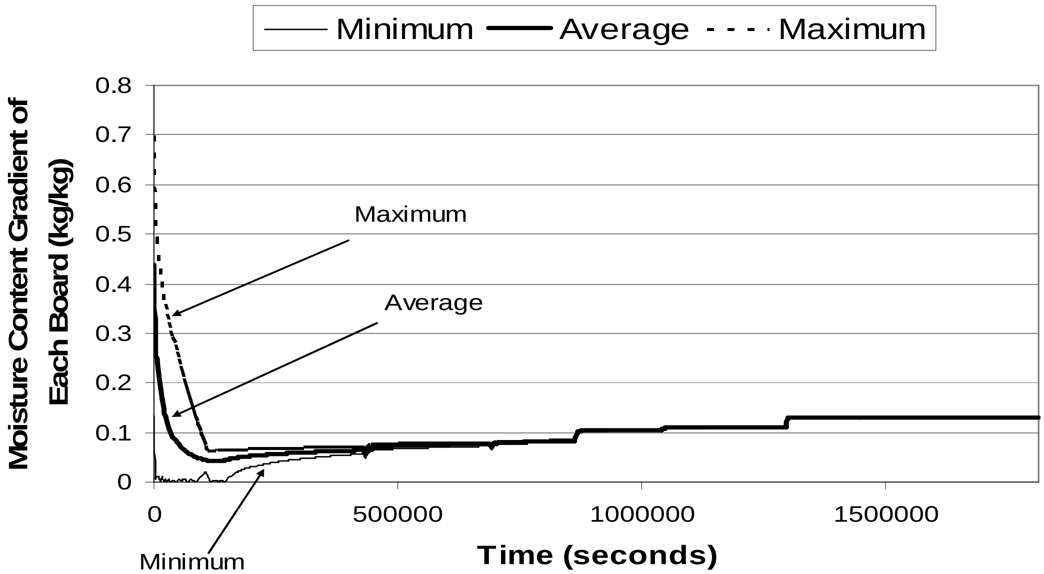

Figure 6.12. The minimum, maximum and average moisture content gradient values of all 30 boards as a function of time, using the drying schedule with temperatures that were 10°C higher than the original drying schedule.

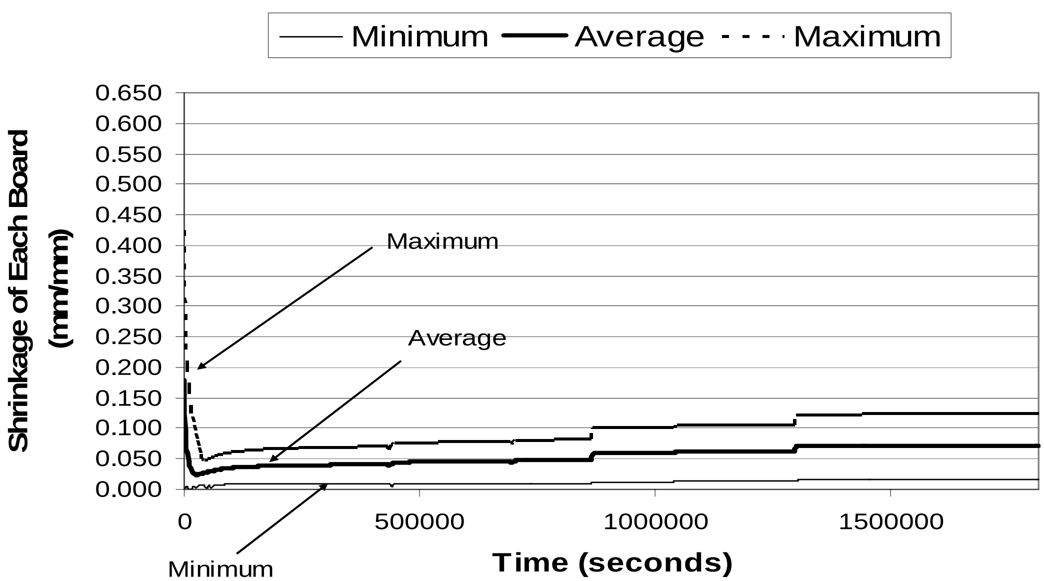

Figure 6.13. The minimum, maximum and average shrinkage values of all 30 boards as a function of time, using the drying schedule with temperatures that were 10°C lower than the original drying schedule.

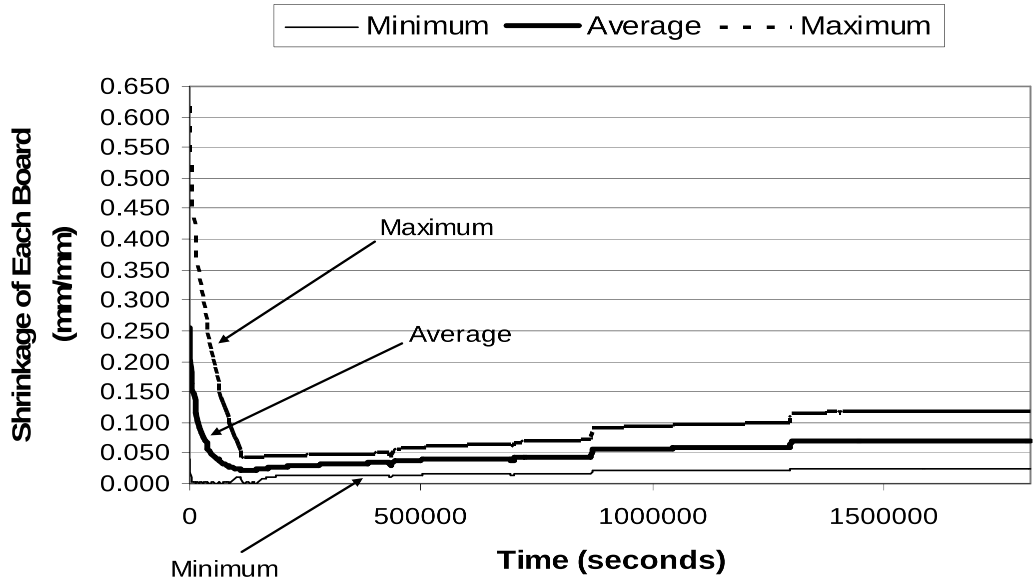

Figure 6.14. The minimum, maximum and average shrinkage values of all 30 boards as a function of time, using the drying schedule with temperatures that were 10^{o}C higher than the original drying schedule.

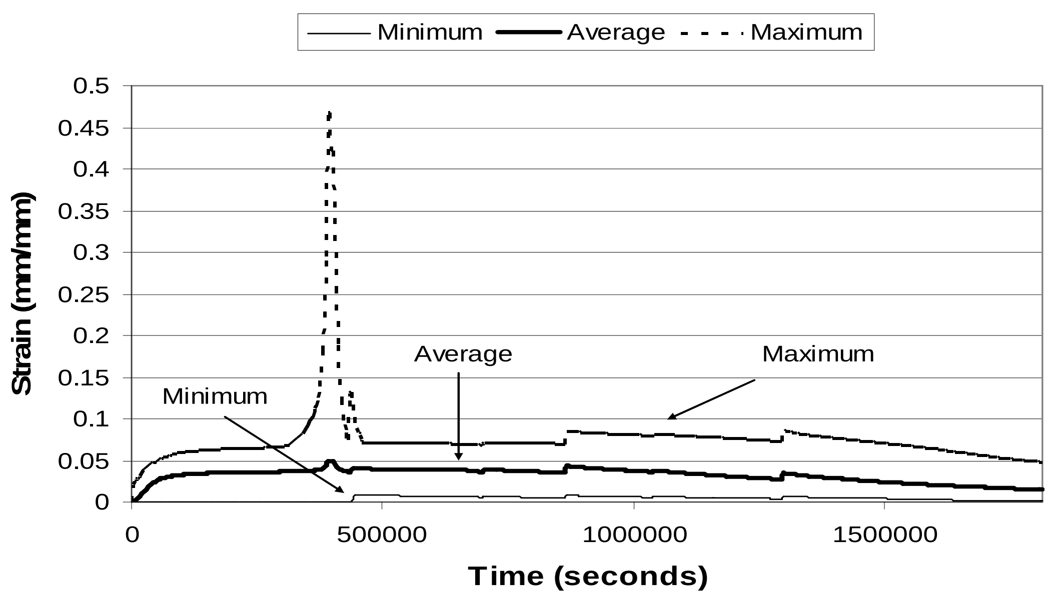

Figure 6.15. The minimum, maximum and average strain values of all 30 boards as a function of time, using the drying schedule with temperatures that were 10^{o}C lower than the original drying schedule.

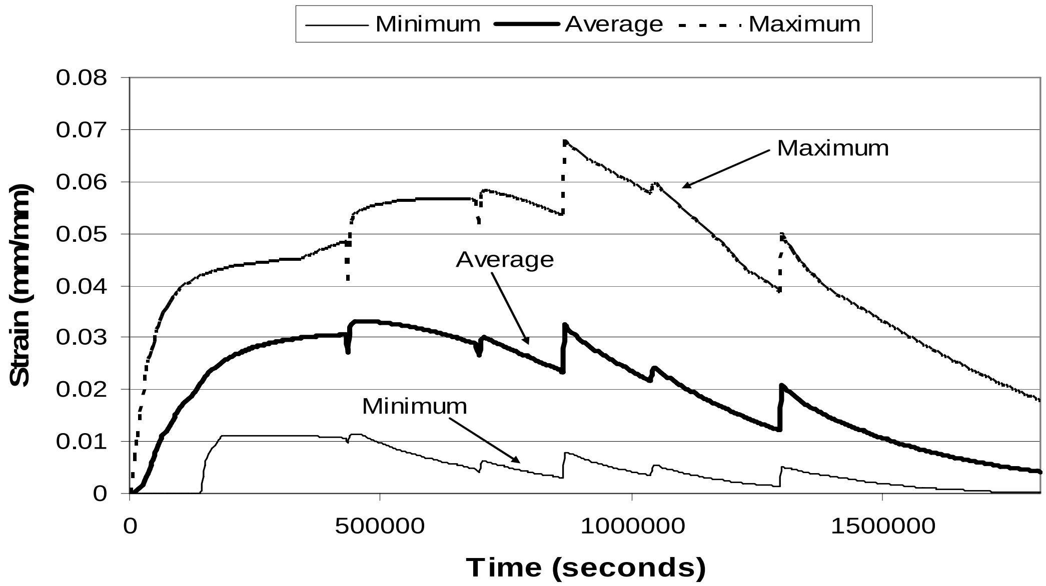

Figure 6.16. The minimum, maximum and average strain values of all 30 boards as a function of time, using the drying schedule with temperatures that were 10^{o}C higher than the original drying schedule.

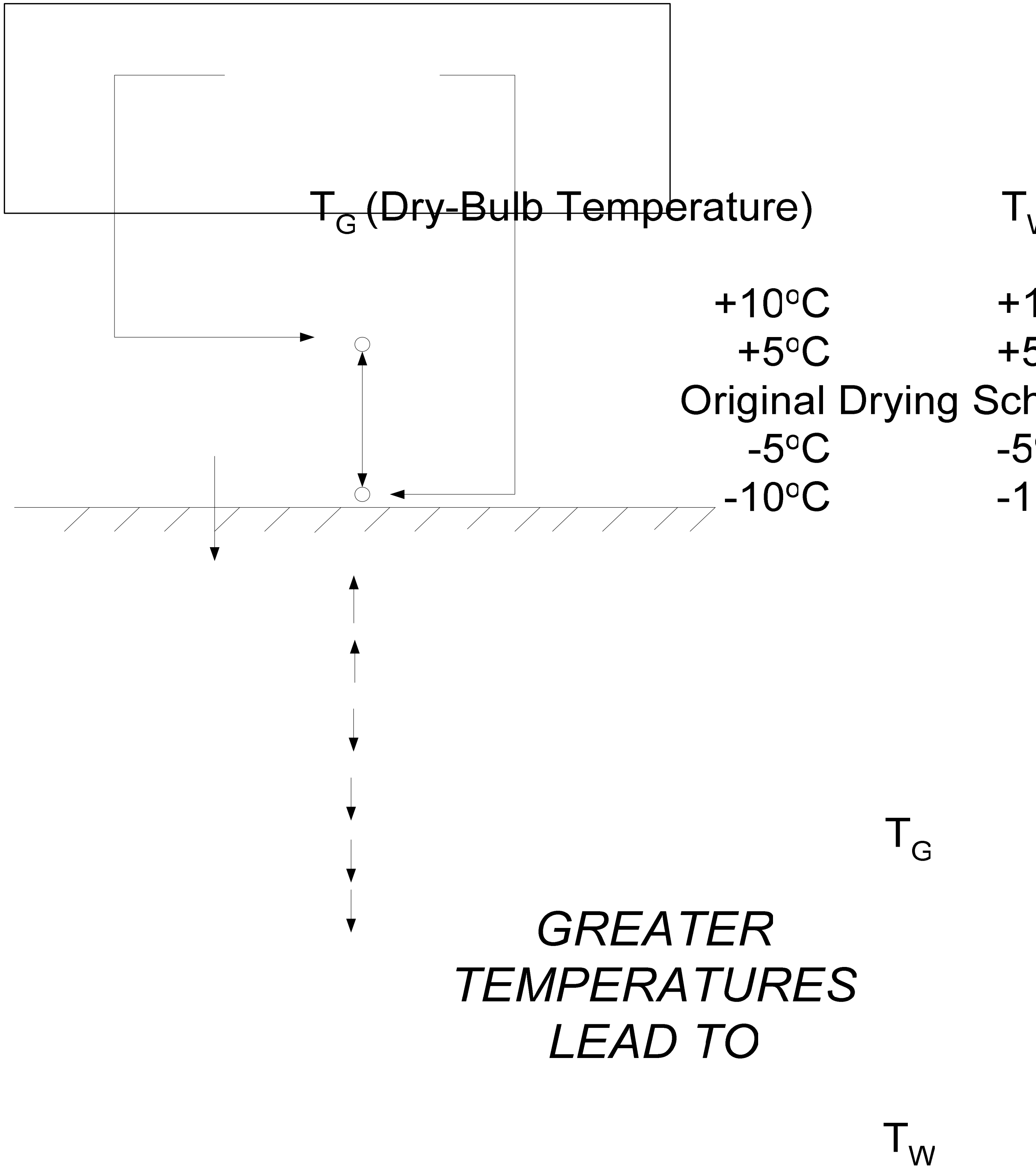

Figure 6.17. A possible reason as to why the average of the maximum strains reached and the drying time decreased with increasing dry and wet—bulb temperatures.

Figure 6.17 shows a possible general explanation for why the strain values decreased as the temperatures increased for regrowth and plantation blackbutt timber. There are limitations, however, associated when using high temperatures in kiln drying. Collapse is shrinkage in the timber at moisture contents above the fibre saturation point during drying, and many Australian eucalypt timbers are prone to collapse (Chafe *et al*., 1992; Innes, 1996). Innes (1995) used a stress—strain model to assess the stress and strain distributions within the fibre cell walls of Tasmanian eucalypt and found that the stresses and strains in the fibre cell wall were sensitive to small variations in temperature. In another study comparing three drying strategies aimed to avoid collapse checking for Tasmanian eucalypt, Innes (1996) suggested there was a “collapse threshold” temperature for any timber species, above which collapse was likely to be severe. In addition, due to reactions involving some constituents in the wood, along with the combined effect of high temperature and relative humidity (MTC, 2002c), sometimes discolouration of the timber occurs when kiln drying. The discolouration of the timber may become unacceptable, especially for appearance grade products (AS/NZS 4787:2001). McCurdy *et al*. (2003) reported that high drying temperatures (as high as 120^{o}C) enhanced the darkening of *Pinus radiata* sapwood boards and thus, both temperature and drying time were significant factors for timber discolouration during drying.

In general, based on all the findings from this study, it may be possible to develop a drying schedule that increases the productivity of timber, i.e. amount of good quality timber divided by the drying time, (Pordage and Langrish, 2000) by accounting for biological variability and considering the mentioned limitations (which were stress and strain constraints, and the maximum temperatures that can be reached before collapse and discolouration occurs). This development can be done by using the data for this variability in the diffusion coefficients (drying property), the initial moisture contents (physical property), and the shrinkage coefficients (mechanical property).

6.3 Representative Drying Schedule Optimization

6.3.1 Overview

The development of optimized timber drying schedules for both regrowth and plantation blackbutt timber has been conducted in this section. Pordage (2006) developed an optimization method that included the effect of biological variability. In this thesis, the optimized drying schedules were based on the variability of timber properties for both regrowth and plantation blackbutt timber measured in previous chapters (**Chapters 4** and **5**). In addition, the purpose of this section is to apply the optimization technique created by Pordage (2006), but improving it by using a large number of measurements to quantify the variability in the properties of blackbutt timber better. Pordage (2006) used published data, by Doe and Innes (1999), for various biological parameters from a number of *Eucalyptus obliqua* (messmate) logs to estimate variances and covariances. Section 6.3.2 presents a summary of Pordage's (2006) optimization technique that was used in this thesis. The reference diffusion coefficient, the initial moisture content and the shrinkage coefficient were reported by Pordage (2006) to have the greatest impact on the maximum strain and the total drying time, thus were included in the optimization technique that accounted for parameter variability. Thereafter, the optimized drying schedules are presented and evaluated based on the predicted total drying times, with a 95% confidence level that the constraints are not exceeded in comparison with previous work presented in the literature.

6.3.2 Development of an Optimization Technique Including the Effects of Biological Variability

The aim of the optimization technique is to develop drying schedules that reduce the total drying time and improve the amount of high quality timber. The method for the optimization of drying schedules including variability is summarized in Figure 6.18 (Pordage, 2006).

The way in which the optimization was carried out will now be explained. An equation is developed to represent the relationship between all the (n) values of all the timber properties that vary and the confidence level of this combination. The mean and the standard deviation for each parameter and the covariance between these parameters are used to develop an equation. This equation is then used to give the confidence level for any combination of parameters, which is a value within the range of 0 – 100%. Thereafter, the optimization goes through two main stages. The first stage involves finding the combination of timber properties within the *cl%* (95% in this case) confidence region for all properties which maximize the stress or strain constraints. The second stage is when, for this combination of properties, the drying schedule is found that dries the timber as quickly as possible without violating the stress and strain constraints.

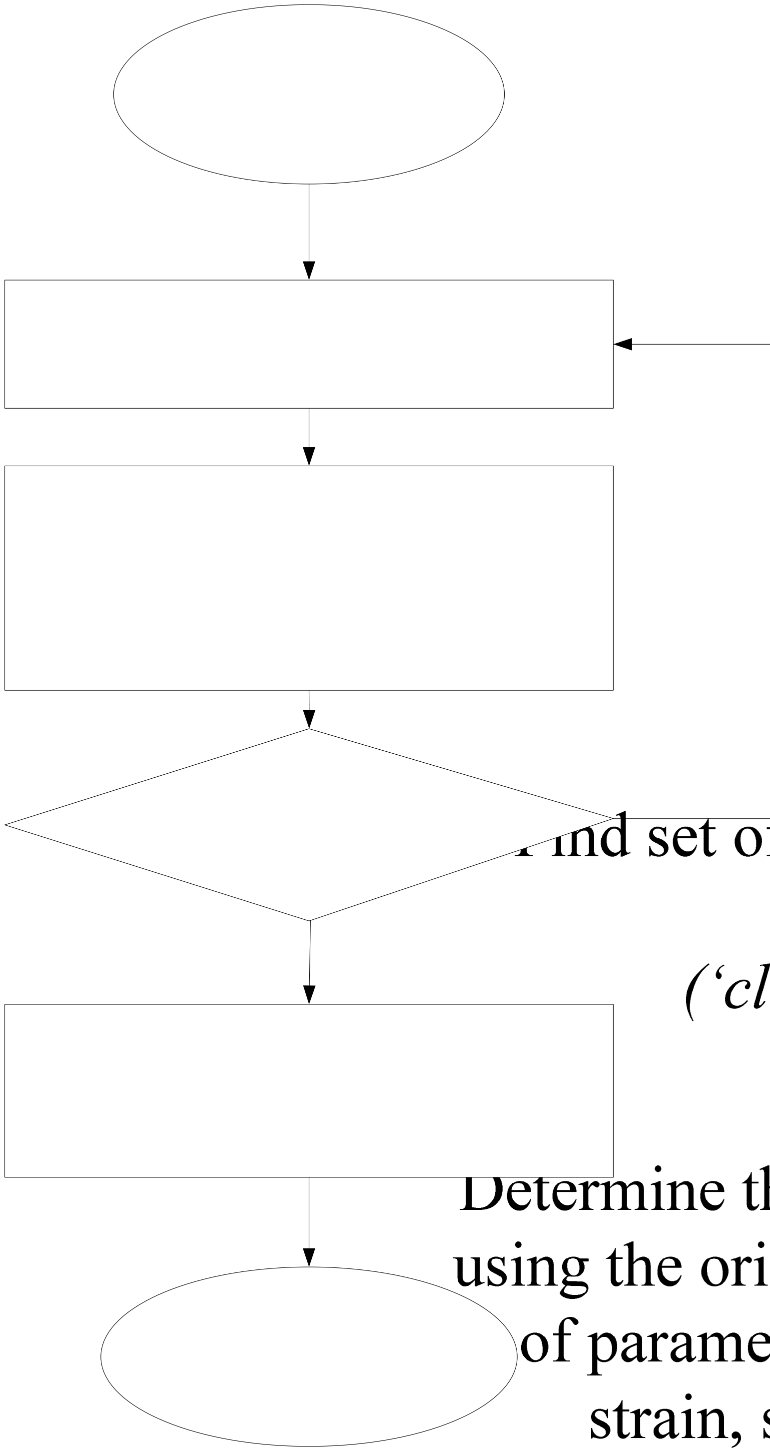

Figure 6.18. Summary of the optimization technique to develop optimized drying schedules that account for biological variability (Pordage, 2006).

The purpose of the constraint is to find the combination of timber property parameters that, while still being *cl%* likely, maximize the strain so that the subsequent optimization of the drying schedule can use these (worst—case) timber property parameters. These property parameters are worst case ones because they give the largest strains and hence would damage the timber most greatly. It should be noted that the drying conditions, i.e. temperatures, air velocities, etc., are not varied in this initial stage of the optimization. When the combination of parameters (i.e. initial moisture content, reference diffusion coefficient, and shrinkage coefficient) is found that maximizes the strains most greatly, the drying schedule optimization is re—run using this combination of parameters to give a new set of drying conditions, i.e. a new optimized drying schedule. This optimization technique, including the basic statistical technique that account for the variability, was the method developed and described by Pordage (2006).

6.3.3 Results and Discussion

Two separate simulation trials for optimization were conducted for regrowth and plantation blackbutt timber. The first simulation accounted for the between—tree variability of the biological parameters in regrowth blackbutt, and the second simulation accounted for both the within and between—tree variability of the timber properties in plantation blackbutt. Since location was observed as a main source of variability, the board properties used for each simulation were taken from the logs that were felled from the same location, i.e. regrowth between—trees timber properties from Lower Bucca 2 and plantation within and between—trees timber properties from the Wedding Bells/Conglomerate area. The constraints for these simulations were as follows:

1. The final average moisture content of the timber stack should be 0.12 kg/kg, since industrial users usually dry down to an average moisture content between 10% and 15% (Mills, 1991).
2. The average maximum strain of the timber stack should not exceed 0.015 mm/mm, which is the experimental value measured in both the regrowth and plantation blackbutt drying experiments.

The initial dry—bulb temperature chosen for the optimization of regrowth and plantation blackbutt was 40^{o}C, because this was the initial dry—bulb temperature used by Pordage (2006) in his optimization of drying schedules accounting for variability. In addition, this dry—bulb temperature and the wet—bulb temperature of 37^{o}C were used by Alexiou (1993) in his work to develop accelerated drying schedules for regrowth blackbutt timber based on trial and error. Table 6.8 shows the mean and the standard deviations of each timber property of regrowth and plantation blackbutt used for the simulations. These values and the covariance of the parameters, represented by covariance matrices, were used in the optimization.

Table 6.8. The mean and the standard deviation for the initial moisture content, the reference diffusion coefficient, and the shrinkage coefficient used for each 'blackbutt' simulation and used by Pordage's simulation (2006).

Type of Optimization	**Initial Moisture Content (kg kg^{-1})**		**Reference Diffusion Coefficient ($\times 10^{-5}$ m^{2}s^{-1})**		**Shrinkage [(mm/mm)/(kg/kg)]**	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Regrowth BBT	0.66	0.14	1.79	0.32	0.61	0.20
Plantation BBT	0.66	0.15	2.17	1.02	0.55	0.20
Pordage (2006)	1.01	0.17	4.37×10^{-11}	8.13×10^{-12}	0.06	0.005

The general form of the covariance matrix used in the optimization is represented by Equation 6.19.

$$C = \begin{pmatrix} a & \text{cov}(x,y) & \text{cov}(x,z) \\ \text{cov}(y,x) & b & \text{cov}(y,z) \\ \text{cov}(z,x) & \text{cov}(z,y) & d \end{pmatrix} \tag{6.19}$$

In the covariance matrix *C*, *x* is the initial moisture content, *y* is the reference diffusion coefficient, and *z* is the shrinkage coefficient. *a*, *b* and *d* are the variances of *x*, *y*, and *z* respectively. The other components in the covariance matrix, e.g. cov(*x,y*), represent the covariances between the parameters. The optimization technique developed by Pordage (2006) scaled the covariance matrices, in which he proved that scaling the covariances had a negligible change (<0.5%) in the sample mean and the sample standard deviation. The scaled covariance matrix was achieved by dividing all the parameters by the mean (Pordage, 2006). The final covariance matrices used for each optimization are shown below.

1. Regrowth Blackbutt

$$C = \begin{pmatrix} 0.0192 & 1.78e^{-7} & 0.0185 \\ 1.78e^{-7} & 1.03e^{-11} & 1.67e^{-7} \\ 0.0185 & 1.67e^{-7} & 0.0417 \end{pmatrix} \tag{6.20}$$

2. Plantation Blackbutt

$$C = \begin{pmatrix} 0.0224 & 1.08e^{-6} & 0.0172 \\ 1.08e^{-7} & 1.05e^{-11} & 3.10e^{-7} \\ 0.0172 & 3.10e^{-7} & 0.0380 \end{pmatrix} \tag{6.21}$$

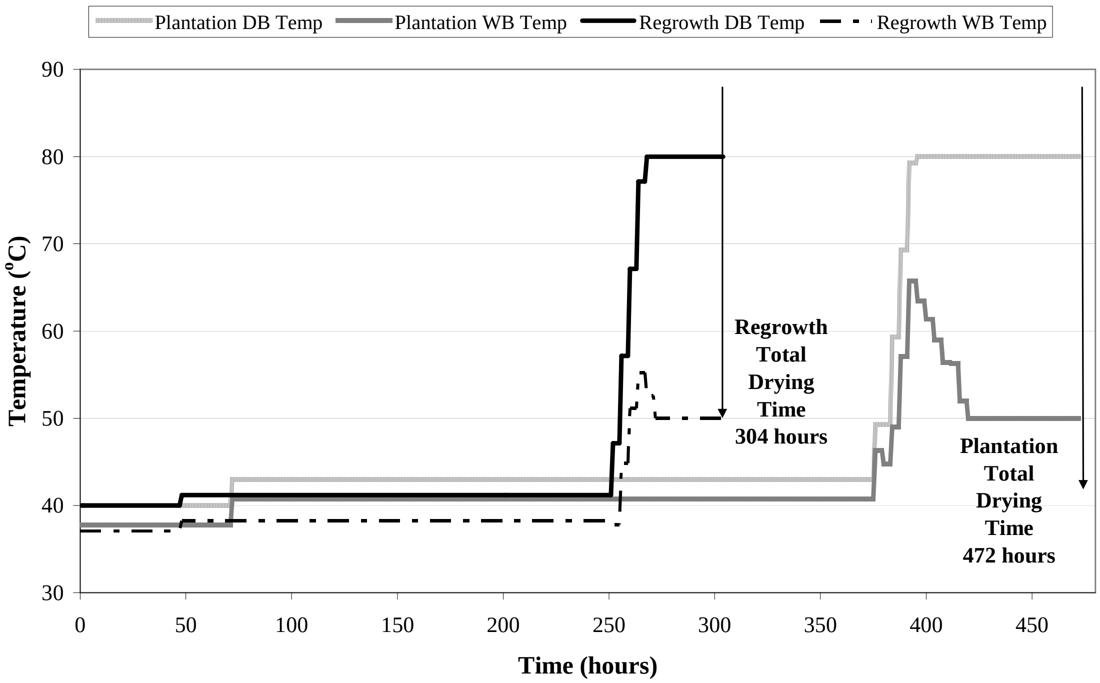

Figure 6.19. Optimized drying schedules as a function of time accounting for the variability of regrowth blackbutt boards (between—trees) and the variarbility of plantation blackbutt boards (within and between—trees).

The total drying time of the optimized drying schedule of plantation blackbutt timber, shown in Figure 6.19, was longer (an additional 168 hours, i.e. 472 hours) compared with the total drying time of the optimized drying schedule of regrowth blackbutt timber (304 hours). Since plantation blackbutt timber has been found to have more variability in the diffusion coefficients compared with regrowth blackbutt timber (**Chapters 4, 5,** and **6**), the reason for the increase in drying time for plantation blackbutt may be due to this greater variability in plantation blackbutt timber. Table 6.8 shows that the dispersion of the reference diffusion coefficient for plantation blackbutt (1.02×10^{-5} m^2s^{-1}) was more than three times the value of the dispersion of the same parameter for regrowth blackbutt (0.32×10^{-5} m^2s^{-1}). An *F* distribution test was conducted to evaluate the variance of the reference diffusion coefficients between regrowth (between—trees) and plantation (within and between—trees) blackbutt timber. The results showed that there was a significant difference between the variances of the reference diffusion coefficients of between—trees regrowth and within and between—trees plantation blackbutt at a 0.05 significance level (F_{actual}, 10 > $F_{expected}$, 1.91). Due to the greater variability present in plantation blackbutt, gentler drying conditions for a longer period of time and thus slower drying is required for plantation blackbutt. Severe drying conditions for plantation blackbutt were applied after 375 hours while severe drying conditions for regrowth blackbutt were applied after 255 hours until the regrowth stack reached an average moisture content of 0.12 kg/kg. Figure 6.20 shows the average moisture content as a function of time for regrowth and plantation blackbutt timber. Pordage (2006) noted that the optimized drying schedules developed by this optimization technique are drying schedules for single boards. However, it can be represented by a stack of boards since it takes into account different timber properties from a population of a number of boards.

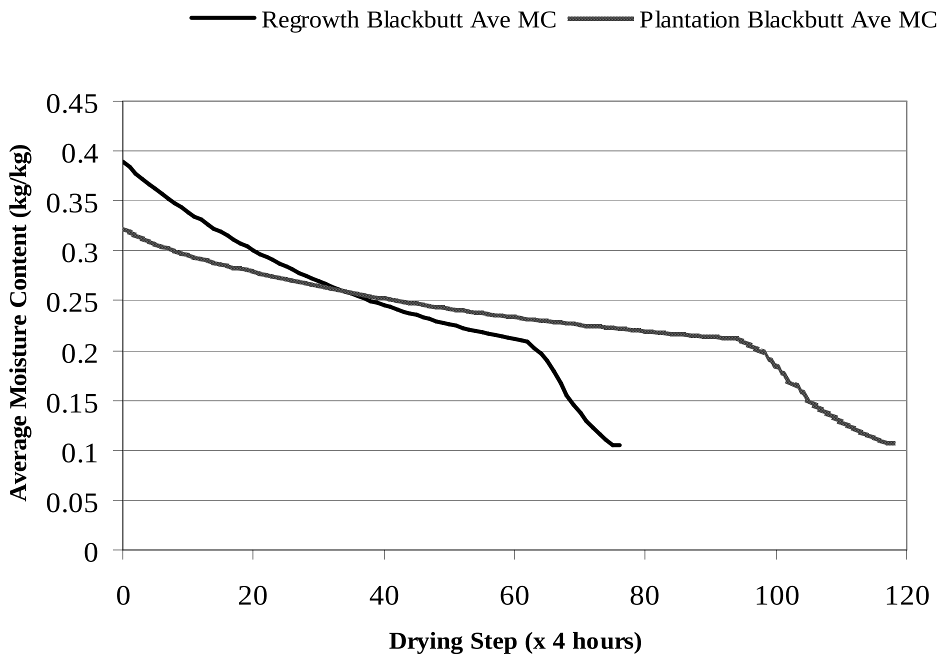

Figure 6.20. The predicted average moisture content as a function of time of regrowth and plantation blackbutt timber using the optimization procedure.

The total drying times from the 'regrowth blackbutt' optimization and the 'plantation blackbutt' optimization were shorter compared with the total drying time of the original drying schedule for 28 mm—thick mixed—sawn blackbutt boards, i.e. 504 hours (**Chapter 3**). The optimized drying schedules also have fewer step changes, i.e. maximum dry—bulb temperature of 40^{o}C and a wet—bulb temperature of 37^{o}C for the majority of the drying period down to a moisture content of 0.20 kg/kg (Figures 6.19 and 6.20). Then severe drying conditions were applied up to the end of drying (i.e. the average moisture content of the stack = 0.12 kg/kg), compared with the five step changes of the original drying schedule (shown in Table 3.3). It is possible that the reason behind having more step changes applied in the original drying schedule was to minimize the shock to the timber from having large step changes. The results of the optimization suggest that it may be possible to develop better drying schedules that account for biological variability, that have shorter drying times and at the same time produce high quality timber because each boards' drying behaviour does not exceed the constraints on strains.

The total drying times of the optimized drying schedules of regrowth and plantation blackbutt timber were greater than the total drying time (152 hours) predicted by Pordage's (2006) optimized drying schedule accounting for the variability of *Eucalyptus paniculata* (grey ironbark). It is possible that the difference between the predicted drying times of the optimized drying schedules in this thesis and that of Pordage's (2006) may be due to the fact that he used the diffusion coefficient variability values from Doe and Innes (1999) for *Eucalyptus obliqua* (messmate) and applied these values to the variability of the reference diffusion coefficient of grey ironbark (shown in Table 6.8). He had limited information on the variability of the parameters of grey ironbark and thus used an estimate from another eucalyptus species, whereas in this thesis, the variabilities for regrowth and plantation blackbutt used for the optimization technique were measured and part of the scope for this study. These results also suggest that the variability of timber properties is likely to be dependent on the species of eucalyptus. Furthermore, the results of an F significance test (at a 0.05 significance level) showed that the dispersion of the reference diffusion coefficient used by Pordage (2006) was significantly different from the dispersion of the reference diffusion coefficients used for the regrowth blackbutt 'between—trees' simulation (F_{actual}, 1.56×10^{11} > $F_{expected}$, 2.46), and the plantation blackbutt 'within and between—trees' simulation (F_{actual}, 1.57×10^{12} > $F_{expected}$, 2.34). These results suggests that the variabilities in the drying properties measured in the regrowth and plantation blackbutt boards studied in this thesis were greater than the variability in the drying properties used by Pordage (2006) for grey ironbark. Hence Pordage's (2006) optimized drying schedule had a total drying time shorter than the predicted total drying times of the optimized drying schedules for regrowth and plantation blackbutt in this work.

Overall, the optimized drying schedules for regrowth and plantation blackbutt in this thesis have shorter drying times compared with the original drying schedule used in the actual experiments. The total drying times of the optimized drying schedules for regrowth and plantation blackbutt were also significantly different from the drying time of the optimized drying schedule for ironbark by Pordage (2006). This is a typical application of data obtained in this thesis to the optimization of drying schedules.

6.4 Conclusions

A principal components analysis (PCA) presented the possibility that there was a strong correlation between the basic density, the initial moisture content, the diffusion coefficient, and the green modulus of elasticity (MOE). The results of the PCA showed that the principal component for the within—tree and between—trees test accounted for 93% and 94% (for regrowth), and 92% and 90% (for plantation), respectively, giving some support for the mentioned correlation between the parameters. Boards with low basic densities have low green MOEs, have high diffusion coefficients, and high initial moisture contents. In addition, basic density may be the link between the MOE and the diffusion coefficient. However, literature mentioned that microfibril angle is possibly a better indicator of stiffness and strength compared with the basic density. But the work of

Alexiou (1993) and the results in this thesis for blackbutt timber showed a relationship between the basic density and the MOE, and basic density is significantly easier to measure than microfibril angle. Actual measurements of the microfibril angle of blackbutt timber need to be further investigated.

An analysis of variance (*F* significance test) was conducted to determine if the strong correlations between the parameters, i.e. represented by empirical equations, from within—tree and between—trees tests, and regrowth and plantation blackbutt tests, were significantly different. The results of the *F* significance test showed there was no significant difference between the within—tree and between—trees variability of plantation blackbutt timber. But the results of the other significance tests showed that there was a significant difference between the within—tree and between—trees variability of regrowth blackbutt timber, the within—tree variabilities of regrowth and plantation blackbutt timber, and the between—trees variability of regrowth and plantation blackbutt timber. The results are evidence that the variability of the timber properties was affected by boards taken from logs felled at different locations. Overall, the empirical equations can be used to estimate important drying properties of other regrowth and plantation blackbutt samples, such as the diffusion coefficients, using easily measured properties, like the initial moisture content and the basic density, as long as the boards were taken from the same age group (i.e. regrowth or plantation) and the same location. Boards can then be segregated in groups based on their respective diffusion coefficient, hence a suitable drying schedule can be chosen for each group.

PCA was also applied to determine the correlation between five properties: the basic density, the initial moisture content, the diffusion coefficient, the green MOE and the failure strain. The results of the PCA showed that the principal components both for the within—tree and between—trees test of regrowth blackbutt accounted for 93% of the total amount of variation within the five parameters. In addition, the principal components of the within—tree and between—trees test of plantation blackbutt accounted for and 92% and 90% of the total amount of variation, respectively. These results further supports that a strong correlation exists between the physical properties (the basic density and the initial moisture content), the drying property (diffusion coefficient) and the mechanical properties (the green MOE and the failure strain).

Acoustic methods were another alternative to estimate the diffusion coefficient prior to kiln—drying. PCA showed that there was a possible correlation between the diffusion coefficient, the acoustic speed, and longitudinal MOE where the principal component accounted for 98% of the total variation within these parameters. However, a challenge that is addressed here is accounting for the variability of the drying and mechanical properties in the development of better drying schedules.

The effects of different drying schedules and the potential correlations between the diffusion coefficient, the green MOE, the shrinkage coefficient (calculated from the tangential shrinkage), and the initial moisture content on the variability of final moisture contents and the maximum strain reached, when the average moisture content within a stack of timber reached 15%, were predicted. A preliminary evaluation (12 boards) was conducted and then followed by an evaluation using timber samples chosen in random.

30 samples was a reasonable sample size for the 'random sampling' evaluation of different drying schedules. The results of both evaluations showed that, for regrowth blackbutt timber and accounting for within—tree variability, there is no relationship between the length of the drying schedule and the dispersion of final moisture contents. On the other hand, the between—tree variability sensitivity tests for both regrowth and plantation blackbutt timber and the within—tree variability sensitivity test for plantation blackbutt timber show a relationship between the length of the drying schedule and the dispersion of final moisture contents. The '+10^{o}C' drying schedule gave the shortest time for the stack of timber to reach the target average moisture content and its conditions produced the smallest dispersion of final moisture contents for the between—tree variability sensitivity tests for both regrowth and plantation blackbutt timber and the within—tree variability sensitivity test for plantation blackbutt timber. It was also observed for all the sensitivity tests that as the temperature of the drying schedule increased, the average of the maximum strains reached decreased. This is a very unusual result, because normally the strains and stresses would be expected to increase with increasing temperature.

Further investigation was conducted on the within—tree test of regrowth blackbutt timber to determine as to why the average of the maximum strains increased with temperature. The results of the investigation presented that possibly within a piece of timber (internal), as the temperatures increase, the diffusion coefficient will increase because the internal average temperature increases, the internal resistance to mass transfer decreases, which leads to the moisture content gradient decreasing, even though the drying rate may slightly increase. This decreases both the drying time and the maximum strain reached.

There are limitations, however, associated when using high temperatures in kiln drying such as collapse and timber discolouration.

The total drying time of the optimized drying schedule of plantation blackbutt timber was longer (an additional 168 hours, i.e. 472 hours) compared with the total drying time of the optimized drying schedule of regrowth blackbutt timber (304 hours). Due to the greater variability present in plantation blackbutt, slower drying is required. Moreover, the total drying times from the ‘regrowth blackbutt’ optimization and the ‘plantation blackbutt’ optimization (which both accounted for variability) were shorter compared with the total drying time of the original drying schedule for 28 mm—thick mixed—sawn blackbutt boards, i.e. 504 hours. On the other hand, the total drying times of the optimized drying schedules of regrowth and plantation blackbutt timber were greater than the total drying time (152 hours) predicted by Pordage’s (2006) optimized drying schedule accounting for the variability of *Eucalyptus paniculata* (grey ironbark). He had limited information on the variability of the parameters of grey ironbark and thus used an estimate from another eucalyptus species, *Eucalyptus obliqua* (messmate), whereas in this thesis, the variabilities for regrowth and plantation blackbutt used for the optimization technique were measured and part of the scope for this study. These results also suggest that the variability of timber properties is likely to be dependent on the species of eucalyptus. Overall, this is a typical application of the data obtained in this thesis to the optimization of drying schedules.