2. LITERATURE REVIEW

2.1 Optimizing Kiln Drying Schedules: Overview

Trial and error has been used for the development of kiln drying schedules in the past (Campbell, 1980; Mills, 1991). Thereafter, more rational approaches have been undertaken for the optimization of kiln drying schedules. Optimized kiln drying schedules have been developed from simulations (Cronin *et al.*, 1997, 2002, 2003) that have only considered the variability of final moisture contents. Continuous kiln drying schedules (Booker, 1994; Alexiou, 1993; Langrish *et al*., 1997) have also accounted for stress, strain, and checking/cracking. Pordage (2006) and Pordage and Langrish (2000) developed a kiln drying schedule that considered the variability of timber properties, using very limited data on variability from Doe and Innes (1999). The remaining challenges in optimizing kiln drying schedules include getting sufficient data on the variability of timber properties, and optimizing both to minimize cracking and to minimize the range of final moisture contents.

2.1.1 Optimizing Kiln Drying Schedules to Minimize the Dispersion of Final Moisture Contents

Cronin *et al*. (2003) examined the effects that a single set—point drying schedule and a double set-point drying schedule had on the distribution of final moisture contents for Irish Sitka Spruce. The dry and wet-bulb temperatures were not altered in the single set-point schedule. On the other hand, the dry and wet bulb temperatures were modified in a stepwise fashion during drying for the double set-point schedule. The probabilistic drying models used in this work involved the development of empirical expressions that predict the mean and standard deviation of the board moisture contents as a function of time.

The drying model used was equivalent to linear kinetics, in the sense that the rate of drying at any time was assumed to be a linear function of the difference between the equilibrium moisture content (EMC) for the climate within the kiln, and the instantaneous timber board moisture content. EMC is the moisture content at which the timber neither gains nor loses moisture from the surrounding atmosphere. The following expression for timber moisture content, *X*, was developed:

$$X(t) = (X_i - X_e)e^{-kt} + X_e \tag{2.1}$$

The index of the exponential function, *k*, is the drying-rate constant (h^{-1}), X_i is the initial moisture content, and X_e is the EMC. Since the model was empirical, *k*, which represents a number of internal and external thermo-physical drying mechanisms, was found experimentally. In addition, *k*, from physical considerations, was shown to be related to the diffusion of water in the timber, hence the transport mechanism for moisture movement in this model was basically assumed to be diffusion. In the diffusion based model, *k* is expected to exhibit a strong dependence on the timber temperature. The magnitude of X_e was estimated using the kiln wet bulb depression, i.e. the difference between the dry bulb and wet bulb temperatures, applied to approximate formulae. It may be more accurately determined using sorption isotherms charts for timber species (Cronin *et al*., 2003).

The model was manipulated empirically to suit the conditions of the double set-point schedule, to predict the mean moisture content and the dispersion in the timber moisture contents when the dry and wet-bulb temperatures were altered (hence the EMC) in a stepwise fashion within the drying process (i.e. at some time *t*). Since the drying-rate constant may be affected by kiln conditions, two drying-rate constants, k_1 and k_2, are required for the separate drying periods that have EMCs equal to X_{e1} and X_{e2}, respectively (Cronin *et al*., 2003). It was also assumed that the rate constants are independent of the equilibrium moisture contents, i.e. no relationship exists between X_e and *k*. Thus, the drying models that were used for the two specific EMCs were:

$$X(t) = (X_i - X_{e1})e^{-k_1 t} + X_{e1} \qquad 0 \le t \le t_1 \tag{2.2}$$

$$X = (X_i - X_{e1})e^{-k_1 t_1} e^{-k_2 (t - t_1)} + (X_{e1} - X_{e2})e^{-k_2 (t - t_1)} + X_{e2} \qquad t_1 \le t \le t_f \tag{2.3}$$

Equation (2.2) was used to calculate the timber moisture content before the dry and wet-bulb temperatures changes for the double set point schedule, while equation (2.3) was used to evaluate the timber moisture content after the step change. These equations, along with equation (2.1) for the single set—point drying schedule, were used throughout the drying process to determine the mean timber moisture content and its standard deviation.

An optimum double set point schedule was developed further. A Monte Carlo drying analysis of the commercial drying schedule for the same timber species was carried out. The purpose of this was to compare the distribution of final moisture contents at the end of drying for the commercial schedule with the dispersion of final moisture contents for both the single set point and an optimum double set point drying schedule. The single set point schedule gave a mean moisture profile very similar to that achieved by the commercial schedule, whereas the mean moisture content for the double set point fell more rapidly until a certain point and then remained constant thereafter, as shown in Figure 2.1. The optimal double set point schedule produced a smaller final moisture content standard deviation, i.e. σ_{xf} = 0.0165 kg/kg, seen in Figure 2.2, compared with the commercial schedule, σ_{xf} = 0.021 kg/kg and the single set point schedule, σ_{xf} = 0.02 kg/kg. The reason behind the small deviation of the final moisture contents was that there was little variability in the equilibrium behaviour, and the drying behaviour at the end of drying is dominated by equilibrium considerations. Additionally, it was evident that kiln schedules influenced the distribution of final moisture contents. Cronin *et al.* (2003) showed that it is possible, theoretically, to develop a kiln schedule that will minimize the variability of final moisture contents within a stack of timber. However, the average moisture content was the only parameter modelled in Cronin *et al.* (2003). This makes it difficult to see how stress, strain, and hence cracking, could be modelled using this approach.

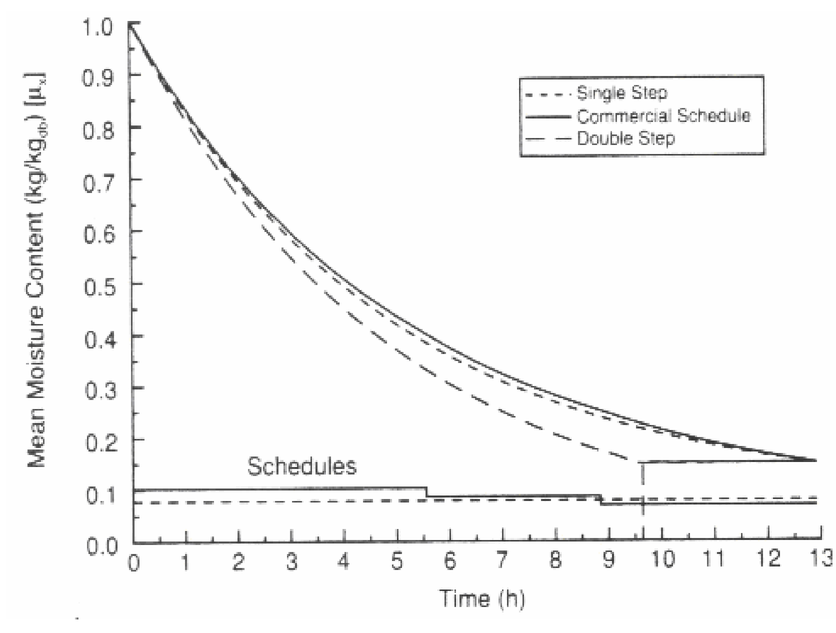

Figure 2.1. Mean moisture content as a function of time for a single set point schedule, double set point schedule, and commercial schedule (Cronin *et al*., 2003).

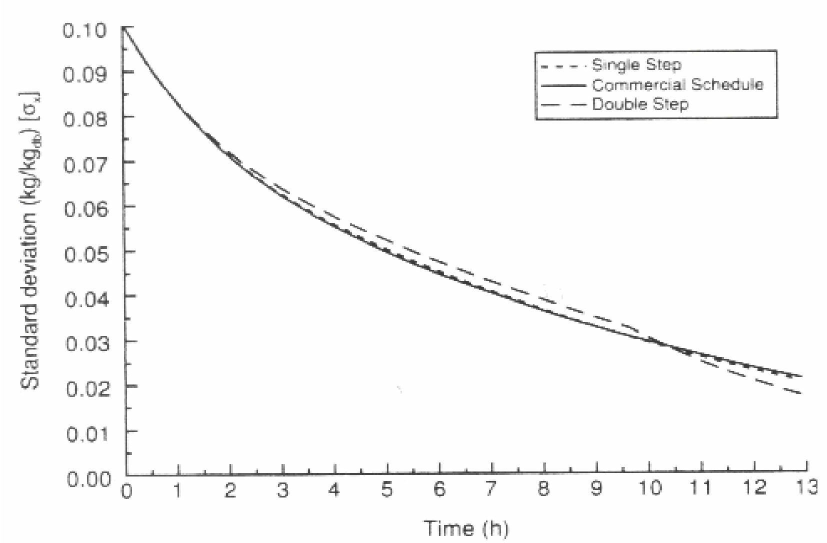

Figure 2.2. Standard deviation of moisture content as a function of time for a single set point schedule, double set point schedule, and a commercial schedule (Cronin *et al*., 2003).

2.1.2 Optimizing Kiln Drying Schedules to Minimize Checking or Cracking in Dried Timber

As timber dries, a moisture content gradient develops between the drier outer part of the timber and the wetter core (or inner part) of the timber. This then leads to the uneven shrinkage of the timber from the centre to the surface of the board. Under these circumstances, a variation in shrinkage results in differential stresses right through the board. Shrinkage at the surface of the timber leads to tension stress, which can then result in surface checking or cracking (AS/NZS 4787:2001). Internal checking occurs during the later stages of drying when the surface fibres are in compression and the core is in tension (Walker, 1993). Therefore, it is also important that drying schedules are capable of controlling the moisture content gradient, and the development of stresses in timber to prevent checking or cracking.

Boards intended for appearance grade use must be absent from both types of checking. On the other hand, structural timber may be able to tolerate some checking.

Different methods for optimizing drying schedules to minimize checking or cracking have been applied in the past. Key features of previous work include using acoustic emissions, and trial and error (Booker, 1994; Alexiou, 1993); the study of more specific stages during the drying process, for example the conditioning phase (Salin, 2001) to reduce the development of cracking or internal checking; using average timber properties as a basis for optimization (Langrish *et al*., 1997), and optimized drying schedules that allow for a representative mixture of sapwood and heartwood (Carlsson and Tinnsten, 2002). However, the methods mentioned were either applied only to a particular timber species, e.g. the work of Booker (1994) for Tasmanian eucalypt, Alexiou (1993) for blackbutt, and Langrish *et al.* (1997) for ironbark; or required validation because they were only predictions, e.g. Salin (2001); or lastly, were simulations that were based on assumptions that are improbable in practice, e.g. Carlsson and Tinnsten (2002), with the assumption that drying started from fibre-saturation point. Most importantly, the variability in timber properties was not accounted for in these previous works.

The works of Booker (1994), Langrish *et al* (1997) and Wu (1989), which will be discussed later in this chapter) based their drying model on Fick's Second Law of diffusion. This model can be represented by:

$$\frac{\partial X}{\partial t} = \frac{\partial}{\partial z}\left(D \ \frac{\partial X}{\partial z} \right) \tag{2.4}$$

where X = moisture content, kg.kg^{-1};

t = time, seconds;

z = distance from the surface, m;

D = average diffusion coefficient, m^2.s^{-1}.

For hardwood timber, the relationship between the average diffusion coefficient and the absolute temperature was found by Bramhall (1979), and a similar trend was reported by Schaffner (1981), as follows:

$$D = D_r e^{-\frac{D_E}{T}} \tag{2.5}$$

where D_r = reference diffusion coefficient, m^2 s^{-1};

D_E = activation energy for diffusion divided by the gas constant R (8.314 J/mol.K), K;

T = temperature of the board; K.

D_r and D_E characterize the drying behaviour of the corresponding timber board.

Booker (1994) applied acoustic emission (AE) in drying Tasmanian eucalypt boards to measure the occurrence of cracks developed, online, during drying. AE is a non-destructive tool to test materials for fatigue, cracks, and fracture. He suggested that there was a possible association between AE, the severity of the drying conditions, and the development of surface checking (Becker, 1982; Noguchi *et al*., 1987). Booker (1994) suggested that AE was generated by the irregular slips in the crystalline regions of the cellulose microfibrils in the cell walls. He also reported that the measured AE increased when the elastic strain approached the proportional limit. However, the anisotropic features of timber made it difficult to develop a clear picture of the stress release processes in timber. Lastly, Booker (1994) found that AE activity was associated with the complex interactions between changes in temperature/humidity and the instantaneous strain at the surface of the timber. This is due to his finding that the level of AE was much greater under harsh drying conditions compared with the AE measured from the same timber species subject to mild drying conditions.

He developed the program SMARTKILN from Oliver’s (1991) KILNSCHED program to develop optimum drying schedules based on the calculated surface instantaneous strain (Booker, 1994). KILNSCHED is based on a diffusion model. KILNSCHED simulates arbitrary drying conditions, allowing the user to experiment with different kiln schedules, and understand the fundamental process of timber drying. On the other hand, SMARTKILN is a modified version of KILNSCHED. What makes the SMARTKILN program different from the program KILNSCHED is that it incorporates an iterative logarithm that automatically optimizes a particular drying schedule based on the acoustic emission measured during drying. This controls the drying conditions to maintain the calculated surface instantaneous strain below the ultimate value of the instantaneous strain.

SMARTKILN control begins with a simple drying schedule. SMARTKILN, like KILNSCHED, then uses data logged real time drying conditions to simulate the drying behaviour of the sample boards in the kiln, by solving Fick’s Law of diffusion for mass transfer and the Fourier equation describing heat conduction for heat transfer. The process of moisture transfer was assumed to be a nonlinear, one-dimensional flow of moisture and heat from the centre to the wide surfaces because sufficient data on edge—drying was not yet available (Booker, 1994). Stress/strain theories were also applied in the model, where the instantaneous strain was the strain component compared with the failure criterion. The form in which the nonlinear stress/strain curve was integrated into KILNSCHED means that the ultimate strain was used as the criterion of surface checking. The calculated drying behaviour was continuously compared with the measured drying behaviour in the following ways. The AE and moisture content profiles were measured regularly by slicing sample boards so that he could compare these with the predicted moisture content and AE profiles. Once the fitted and measured drying behaviour matched, and the AE approached the 'AE checking threshold' (i.e. the AE rate when the surface checks began to develop), SMARTKILN automatically adjusted the drying conditions, by changing either the dry-bulb or wet-bulb temperatures, hence changing the air humidity to prevent surface checking. The optimized drying schedule was directly applied to the kiln. Overall, these optimized drying schedules calculated by SMARTKILN prevented collapse (shrinkage which occurs above fibre saturation point, usually 30% moisture content), reduced drying time from 1430 hours to 1320 hours, and controlled the strain on the surface of the boards. The work of Booker (1994), therefore, shows that AE measured within timber can be used to optimize kiln drying schedules to reduce cracking, but he did not try to minimize the dispersion of final moisture contents. The use of SMARTKILN was only tested on eucalyptus species. An issue is whether it is better to spend the money, time and effort on installing and using an AE sensor, or spend the money, time and effort on measuring the variability in timber properties and allowing for it.

Langrish *et al*. (1997) showed that optimizing drying schedules to minimize cracking using average timber properties gave improvements compared with conventional schedules (Campbell, 1980) based on trial and error. An optimized kiln schedule for Australian Ironbark timber (*Eucalyptus paniculata*) was based on a simple Fickian diffusion model for drying, and stress/strain models. The resulting optimized drying schedule set gentler drying conditions, smaller wet-bulb depressions during the initial stages of the drying process, and more aggressive conditions towards the end of drying compared with the conventional schedule. The drying time for the optimized drying schedule was reduced by 10% (122 hours) compared with the conventional one (137 hours) for a target average moisture content of 15%. The number of small and medium-sized cracks were 25% lower than what was observed for the conventional schedule (CSIRO), shown in Figure 2.3. Overall, 90% of the timber from the optimized schedule was suitable for high-value products such as furniture, whereas for the conventional schedule, only less than half of the amount of dried timber was appropriate for such uses. However, the dispersion of final moisture contents was again not minimized.

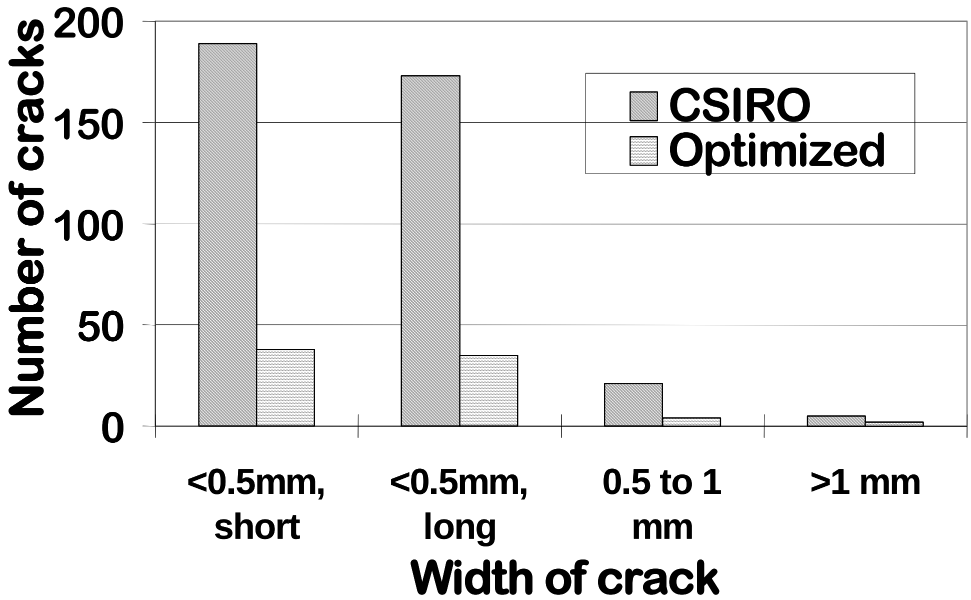

Figure 2.3. Comparison of checking obtained from the conventional and optimized drying schedules (Langrish *et al*., 1997).

Salin (2001) used an optimization procedure to improve the conditioning phase at the end of the timber drying process. Conditioning involves increasing the relative humidity within the kiln so that the equilibrium moisture content of the timber is raised to correspond to the desired or specified moisture content at the end of the drying process. Since timber shrinks as it dries, tensile stress develops on the surface of the board, as mentioned earlier. This stress, combined with a change in moisture content, results in what is known as mechano-sorptive creep. If the drying process is stopped immediately once the average moisture content of the timber stack reaches the target moisture content, i.e. without a conditioning phase, it is likely that there will be significant internal moisture content gradients within the timber boards. These gradients level out very slowly at normal temperatures. Since most of the mechano-sorptive creep developed during drying is likely to remain in the timber, internal stresses are eventually created because of the internal moisture content gradients, and then cause deformations when the boards are machined (Salin, 2001). It was suggested that the traditional conditioning method was not able to completely remove the deformations produced during the drying process. The optimized schedule allowed varying set points (in the schedule) during conditioning. This new schedule was developed using a timber drying simulation. The one-dimensional simulation was based on a simple diffusion equation (Salin, 2001). It was found that there was a possibility that high internal tensile stresses were developed during the conditioning phase, especially if this phase is not optimized. Thus, measurements of the deviation in the timber stack's average moisture content from the target moisture content, the uniformity of the internal moisture profiles of the boards, and a measure of the elongation of mechano-sorptive creep on the timber surface were all integrated into the new optimization procedure to avoid internal checking and deformation after drying. Overall, Salin (2001) showed theoretically that it was possible, with acceptable accuracy, to use timber drying simulation models to solve problems such as reducing cracking/checking of dried timber. The optimized drying schedule was not tested experimentally, or any such test was not reported.

A mixture of boards with different proportions of sapwood and heartwood was taken into account by Carlsson and Tinnsten (2002) in their optimization procedure. A two-dimensional orthotropic drying model was used in the moisture transport and structural analysis. Moisture transport was based on diffusion, and the total strain rate was assumed to be the sum of the shrinkage strain rate, the elastic strain rate, and the mechano—sorptive strain rate. Visco-elastic creep (without moisture content change) was neglected because it was assumed to be significantly smaller than the other strains. Shrinkage strain is the shrinkage in wood that occurs below fibre—saturation point (moisture content of 0.3 kg water/kg dry wood). It arises due to the diameters of the wood fibres shrink because bound moisture is lost from the cell walls (Keey *et al*., 2000). Elastic strain is the time—dependent movement of wood in the absence of any change in moisture content. Lastly, mechano—sorptive strain is also time—dependent, independent of temperature, and it is the effect due to the interaction between the changes of volume due to a change in moisture content and that due to an applied stress (Keey *et al*., 2000; Doe *et al*., 1994).

Moreover, the variations of transport and structural parameters in the radial and tangential directions were also considered by Carlsson and Tinnsten (2002) in their drying model. They assumed that the stress/strain distribution had no influence on the moisture transport, and that drying started from the fibre-saturation point in the simulations. Overall, the objective function of the drying model was to minimize the total drying time subject to the following constraints:

a) Moisture content of the dried product is between an upper and lower level after drying;
b) Deformation is between an upper and lower level after drying;
c) Stresses are below a certain level during the whole drying process, since the stress levels during drying were used as measure for the tendency of checks.

The resulting optimization technique worked well for a mixture of several boards, despite the constraints implemented in the analysis programs. The model was not reported to be tested in actual drying experiments. More information regarding the material parameters of timber boards was needed to overcome a significant limitation of this work, namely the assumption that drying started from the fibre—saturation point, which is almost never true in practice.

Alexiou (1993) developed an optimized kiln drying schedule for 50 mm thick blackbutt timber boards based on trial and error. The final, optimized drying schedule was developed based on data regarding strain gradients, moisture gradients, and on the amount of checking obtained from two conventional kiln runs, and from a first attempt at an accelerated drying schedule. The data gathered from the two conventional kiln runs were used as limits for the necessary relative humidity and temperature to develop an accelerated drying schedule in order to produce high quality timber. In the first trial of the accelerated drying schedule, the drying time was reduced to half the time of the conventional run. However, significant surface checks and unacceptable internal checking developed. This finding points clearly to the trade-off between drying speed and quality. The duration of drying, using the final optimized drying schedule, was reduced to 63% of the time that it took for the old kiln drying schedule to dry timber of the same species, same total length, maximum depth, and maximum width of face checking. In addition, there were small internal checks, but still acceptable, which developed in some boards using the final accelerated schedule. This suggests that the conditions of the final, optimized drying schedule are the most severe that can be used when drying timber without down-grading the dried timber's quality, but this conclusion is subject to the trial—and—error approach and limited number of experiments used. It is possible that a more systematic approach, using a combination of simulations and experiments, might have resulted in a better and very different drying schedule. This optimized kiln drying schedule was suggested (by Alexiou, 1993) to be further tested on other species and varying thicknesses as long as the acceptable levels of surface and internal checking have been defined.

Overall, Table 2.1 summarizes the main similarities and differences between the optimization procedures discussed.

Table 2.1. Similarities and differences between previous optimization methods.

Author	***Simulations***	***Basis of Model Used***	***Experiments***
Booker (1994)	✓	Diffusion/One-dimension	✓
Langrish *et al*. (1997)	✓	Diffusion/One-dimension	✓
Salin (2001)	✓	Diffusion/One-dimension	x
Carlsson and Tinnsten (2002)	✓	Diffusion/Two-dimensions	x
Alexiou (1993)	x	-	✓

2.1.3 Optimizing Drying Schedules Based on the Biological Variability of Timber Properties

Pordage (2006) developed a technique to use information on the biological variability of timber properties to optimize drying schedules. Firstly, quantitative measurements of the variations in properties were identified because these were necessary to develop optimized drying schedules. Four biological parameters predicted to have significant impacts on the drying time and maximum board strain were the reference diffusion coefficient, the activation energy, the shrinkage coefficient and the initial centre moisture content (Pordage, 2006;

Pordage and Langrish, 2000). From this sensitivity study, optimized drying schedules were developed that accounted for biological variability. The results of the optimization procedure predicted that the original optimized drying schedule (i.e. without variability) had a total drying time of 100 hours compared with 152 hours for the new optimized drying schedule (i.e. with variability). This result suggested that longer drying times are required if the variability in the timber properties is taken into account and if a large percentage of high quality timber is desired. The optimization technique developed by Pordage (2006) is described in **Chapter 6**.

An analysis of trade—off between quality and productivity was also conducted by Pordage (2006). Productivity is defined as the amount of high quality (uncracked) timber divided by the total drying time. If the quality requirement increases, the total drying time also increases because gentler conditions are required to achieve a specific timber quality. Pordage (2006) predicted that there is a particular point when this increase in drying time will outweigh the enhancement in quality, which a trade—off is found experimentally by Alexiou (1993) through trial and error. The productivity will thus peak at some value of the intended quality, and decrease dramatically beyond that point.

Furthermore, a trade—off between the amount of high quality timber and the total drying time was predicted to exist, as discussed above. Pordage (2006) and Pordage and Langrish (2000) predicted that about 90% was an optimal economic point for the maximum amount of good quality timber that can be produced from a single drying run, as shown in Figure 2.4.

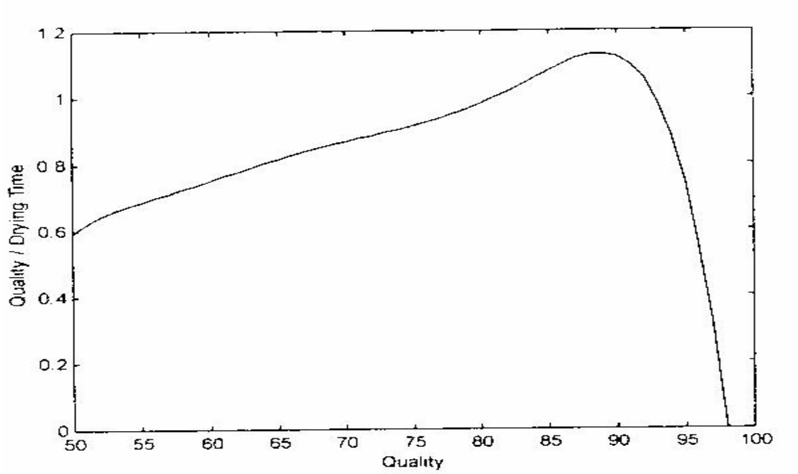

Figure 2.4. Trade—off between drying time and quality (Pordage, 2006; Pordage and Langrish, 2000).

This trade—off was based on limited information about the variability in drying and stress/strain parameters measured by Doe and Innes (1999) for *Eucalyptus obliqua* (messmate). If more than 90% of high quality timber was desired, the total drying times increased significantly, reducing the productivity. In Figure 2.4, it is notable that the penalty in aiming too high, at too high a quality level, is much greater than the penalty in being too conservative, being under or below the optimum quality level. The trade—off between productivity and quality was dependent on the timber species and the variability of its biological parameters.

Overall, the works of Pordage (2006) and Pordage and Langrish (2000) were only a prediction and a very limited amount of validation was carried out. In addition, the information on the variability of biological parameters was very limited, was assumed to be normally distributed, and the parameters were assumed to be uncorrelated with one another.

There is little information about the variability in timber properties with respect to drying, including how strongly they are correlated.

2.1.4 Conclusions

The previous section has reviewed work on optimized drying schedules to either reduce cracking/checking or minimize the dispersion of final moisture contents. Drying schedules that aim for both a reduction of checking/cracking and a small dispersion of final moisture contents are yet to be further developed. The use of drying simulations has proved feasible to optimize drying schedules. However, more information regarding the material properties of the timber boards, and the covariance between the parameters, is required, so that the information will be considered in the optimization procedure, and possibly increase the robustness and flexibility of optimized kiln drying schedules. It is important for sawmillers to have robust drying schedules because they are under pressure both to increase its throughput and reduce wastage (Langrish *et al*., 1997), especially when dealing with the increased amount of variability in the timber properties for hardwood plantation timber. An important gap to note is the absence of a comprehensive database of information about the transport, mechanical and other physical properties of any timber that allows the variability in these properties to be evaluated and used.

2.2 Variability in Hardwood Timber Properties and the Effects on Timber Quality Within Trees and Between Trees

2.2.1 Hardwood Timber Properties

Pordage (2006) and Pordage and Langrish (2000) performed a sensitivity analysis for which biological parameters are most important in the optimization of drying schedules. The four parameters that had the highest impact on the drying time and maximum strain are as follows:

1. Shrinkage coefficient (used to predict the strain during the drying process), β;
2. Reference diffusion coefficient, D_r (m^2/s);
3. Activation energy, D_E (K);
4. Green centre moisture content, X_c (kg/kg).

In addition, basic density, failure stress, failure strain, and modulus of elasticity are also considered important, due to the possible correlation they have with the other mentioned parameters (Siau, 1984; Alexiou, 1993; Andrews and Muneri, 2002; Cave and Walker, 1994; Kretschmann and Green, 1996). For example, basic density is likely to be correlated to both the initial moisture content of the timber, and with the stiffness of the timber (modulus of elasticity).

The following subsections present what trends have been found regarding the variability the above properties, and possible correlations between variables.

In this section, the key works in this area will be reviewed, with an emphasis on hardwood timber because blackbutt, the target timber for this study, is a hardwood.

2.2.2 Green (Initial) Moisture Content

Green (initial) moisture content is an important factor that affects the drying time and drying rate. Swett and Milota (1999) and Choong and Fogg (1989) suggested that sorting by green moisture content before drying may narrow the distribution of the final moisture contents within a stack of timber. The variability of green moisture content is dependent on the tree species, the portion of the log from where it is taken between sites, between genetic variation and environment (Wimmer, 2000). Dinwoodie (2000) proposed that it might also be correlated with the season of the year when the tree is felled.

Most evidence from the literature indicates that the green moisture content values, between sapwood and heartwood within most hardwoods, are not significantly different from each other. The moisture contents of hardwoods such as yellow birch (*Betula lutea*) and shining gum (*Eucalyptus nitens*) are 75% (heartwood) and 70% (sapwood), and 115% (heartwood) and 125% (sapwood), respectively (Walker, 2003). However, Shupe *et al.* (1995a) found that two yellow-poplar trees exhibited a general decrease of green moisture content from heartwood to sapwood. The moisture content for heartwood varied with height but was generally higher than the sapwood. In another experiment, Shupe *et al*. (1995b) observed that the green moisture content of the heartwood of a single eastern cottonwood tree (*Populus deltoides*) was almost three times greater, 170.4%, than the green moisture content of the sapwood, 67.7%, despite being cut at the same time. The large difference between the moisture contents of the heartwood and sapwood was possibly due to seasonal variation (Dinwoodie, 2000). In addition, the negative correlation of green moisture content with basic density, as found by Shupe *et al*. (1995b) may also be an explanation for the large difference in moisture contents between the heartwood and sapwood. The basic density of the eastern cottonwood tree increased from heartwood to sapwood, and since there was less wood material per unit volume in the heartwood, it is possible that the heartwood's moisture content was significantly higher because the vacant spaces may be occupied with water. The analysis of variance failed to detect what effect e.g. height, radial, etc. caused the variation in green moisture contents (Shupe *et al*., 1995b).

Kayihan (1993) assumed that there was no correlation between the green moisture content and the drying-rate parameters. He did not have data for the drying-rate parameters of his experimental samples, and thus could not assess the covariance between the drying-rate parameters and the green moisture content. On the other hand, Siau (1984) suggested that there was a possibility that the variability in green moisture content may be correlated with the variability in timber density. This hypothesis by Siau (1984) has yet to be confirmed.

2.2.3 Basic Density

It has been suggested that basic density, which is the oven-dried weight (kg) divided by the volume of green wood (m^3), may be correlated with the variations of green moisture content and/or modulus of elasticity (MOE) (Siau, 1984; Alexiou, 1993; Andrews and Muneri, 2002). However, Andrews and Muneri (2002) and Cave and Walker (1994) found that basic density is not enough to explain the variation in the MOE. The reason for this will be discussed in more detail in section ***2.2.5 Mechanical Properties***.

The basic density of hardwoods varies radially. Olson (2003) studied the wood properties of New Zealand silver beech (*Nothufagus menziesii*) and found that the density of the heartwood was slightly higher than that of the sapwood. The two yellow-poplar trees examined by Shupe *et al*. (1995a) showed a general increase of basic density from pith to bark. More specifically, Andrews and Muneri (2002) reported that the density at the ‘bark’ was estimated to be 1.4 times the density at the pith, for blackbutt timber.

In addition, Bao *et al*. (2001) studied the timber properties of both plantation-grown and naturally-grown lemon eucalyptus and lankao paulownia. Their results showed that the juvenile wood of the trees had a significantly lower basic density than the mature part (i.e. the older part and outer section) of the tree. A possible explanation for this finding was that juvenile wood, which is the younger part and is found in the inner section of the tree, has significantly shorter fibres or tracheids with substantially thinner cell walls. In general, Bao *et al*. (2001) found that naturally-grown juvenile and mature wood had a higher basic density than plantation-grown juvenile and mature wood.

2.2.4 Diffusion Coefficients

The most important direction for the movement of moisture in the drying of timber is across the grain (Keey *et al*., 2000). The main reason is that the distance for moisture to move across the grain in a board is typically much smaller than the distance along the grain. Another reason is that the cross-sectional area for the movement of water is much greater than along the grain, despite longitudinal moisture transport being much faster per unit area. Longitudinal moisture movement is only confined to the ends of the board which dry faster than the majority of the board. Therefore, slow-drying hardwoods are sometimes end-sealed to reduce longitudinal moisture transport, and hence further decrease the influence of longitudinal transport in drying (Keey *et al*., 2000), so that longitudinal moisture content gradients do not further contribute to the development of stresses in the timber.

It is probable, on the basis of previous studies in the literature (Keey *et al*., 2000) about the drying of hardwoods, that the main transport mechanism of moisture movement within hardwoods is diffusion. This is due to hardwoods consisting mainly of heartwood. Cells are aspirated within heartwood, thus, water cannot flow by convection through these cells. In addition, it is important to know the rate at which moisture leaves a timber board because it helps predict the development of stresses and strains within the timber. The water molecules tend to diffuse from an area of high moisture concentration (inside the timber) to a region of low moisture concentration (outside it). This reduces the steepness of moisture gradients, and hence reduces stresses and strains within the timber (Keey *et al*., 2000).

Keey *et al*. (2000) reported that most measured transverse average diffusion coefficients lie within the range of 10^{-8} m^2s^{-1} and 10^{-10} m^2s^{-1}, using Fick's Second Law of Diffusion as the basis of the diffusion model. Furthermore, the effect of moisture content on the diffusion coefficient was not considered in this thesis for a number of reasons. The diffusion coefficient is expected to decrease with decreasing moisture content (Keey *et al*., 2000; Walker, 1993).

Most water molecules are strongly held by hydrogen bonding to the hydroxyl groups in the cell wall at low moisture contents. Therefore, for these water molecules to migrate to another adsorption site, significant thermal energy is required to break the hydrogen bonds. Hence, this behaviour is reflected in a very low diffusion coefficient at these low moisture contents (Walker, 1993). Simultaneously, timber starts to shrink as it dries. Shrinkage of the timber shortens the pathway for diffusion and this will allow the diffusion coefficient to increase somewhat (Schaffner, 1981). Overall, the effects of changing both the moisture content and shrinkage cancels out, and thus the effect of moisture content on the diffusion coefficient may not change greatly. The work of Wu (1989) on Tasmanian eucalypts supports this hypothesis, when he used a diffusion model in which the diffusion coefficient was taken to be independent of the moisture content but was assumed to be only temperature dependent. His results showed a good fit of the diffusion model to the moisture—content profiles within the timber at various drying times shown in Figure 2.5. A similar result was found by Doe *et al*. (1996) and Langrish *et al*. (1997) in terms of fitting average moisture contents as functions of time for their study of Tasmanian eucalypt hardwoods, and Australian ironbark timber, respectively.

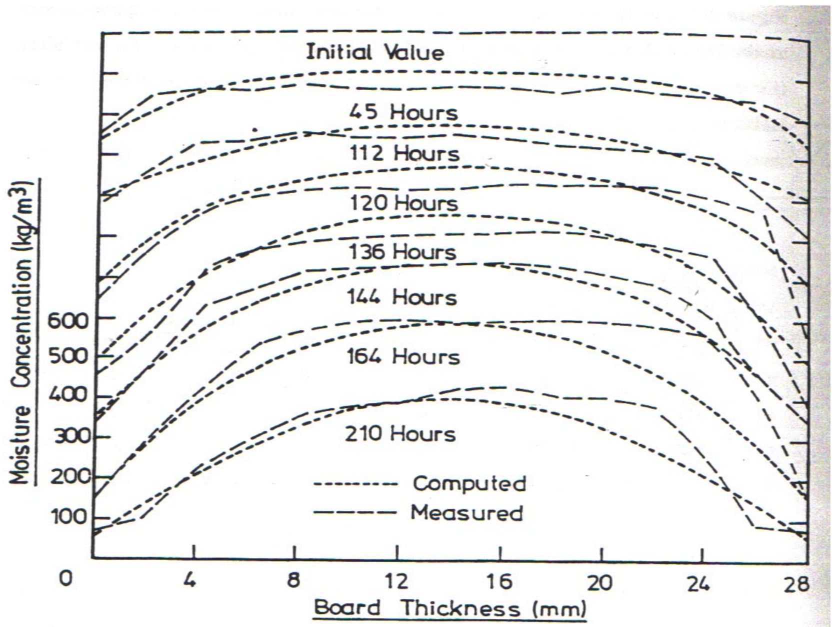

Figure 2.5. Parabolic moisture profiles, throughout the drying process of Tasmanian eucalypt timber, predicted by the diffusion model and measured experimentally (Wu, 1989).

The work of Haque (2002) considered the average diffusion coefficients within 38 mm thick blackbutt boards using the same diffusion model. The calculated average diffusion coefficients were 4.5 x10^{-11} m^2s^{-1} at a temperature of 300 K, and 7.6 x 10^{-11} m^2s^{-1} at a temperature of 313 K. However, Haque (2002) did not report how much the diffusion coefficients varied within a tree or between trees.

2.2.5 Mechanical Properties

One of the most important mechanical properties for solid timber applications is the modulus of elasticity, MOE (Yang and Evans, 2003). The mechanical properties of timber, such as MOE, are potentially dependent on species, variations in moisture content, and the characteristics of the wood fibres (Alexiou, 1993; Cave and Walker, 1994; Kretschmann and Green, 1996; Omarsson *et al*., 2000). Many researchers have suggested that variations in specific gravity or density may explain (or be strongly correlated with) the variations of mechanical properties (Kretschmann and Green, 1996; Yang and Evans, 2003). In addition, the majority of failures observed for timber structures are due to tension perpendicular to the grain (Jönsson and Thelandersson, 2003). The elastic (and other) properties of timber perpendicular to the grain are important because they are a critical aid to understanding how internal stresses are developed during drying (Alexiou, 1993).

Kretschmann and Green (1996) found that the interaction between density and changes in moisture content accounted for some of the observed variability in mechanical properties, MOE being one of them. A multiple regression analysis was used to assess the effect of density and moisture content on the mechanical properties, such as MOE (perpendicular to the grain). The calculated R^2 values for the correlation between the parameters ranged from a low value of 0.37 to a high value of 0.95 (Kretschmann and Green, 1996). MOE in tension perpendicular to the grain increased from the green moisture content to about 6 % (moisture content). Alexiou (1993) found a similar result, but slightly lower R^2 values. For green blackbutt, MOE and failure stress in tension perpendicular to the grain were affected by basic density. On the other hand, the failure strain was independent of basic density. The effect of moisture content and basic density accounted for up to 79% of the variation in the data for failure strain, failure stress, and MOE. His results for green and 14% moisture content blackbutt are shown in Table 2.2.

Table 2.2. Mechanical properties of blackbutt (Alexiou, 1993; Haque, 2002).

	Alexiou (1993)		*Haque (2002)*
	At green moisture content	***At 14% moisture content***	***At green moisture content***
Strain at failure (mm/mm)	0.0138	0.015	0.0131-0.0156
Stress at failure (MPa)	4.7	6.5	4-4.96
Modulus of elasticity (MPa)	678	881	368-432

Alexiou (1993), however, only tested blackbutt trees that were felled in one location, Whian Whian State Forest, near Lismore, New South Wales. Haque's (2002) blackbutt study also resulted in similar failure stresses and strains for green timber to Alexiou's results. Haque's (2002) green blackbutt timber had lower MOE's than Alexiou's data. He suggested that the difference between his calculated MOE's and that of Alexiou (1993) might have been due to biological differences between the same timber species from different regions, and not only because of different basic densities. Timber studied by Haque (2002) was felled from Heron's Creek, while Alexiou's timber came from Lismore. Moreover, Andrews and Muneri (2002), using acoustic methods, found that MOE increased from pith to bark. Their results supports those of Alexiou (1993) and Haque (2002), suggesting that basic density was proportional to MOE, but they also reported that the increase in density was not enough to explain the rise in MOE.

The use of specific gravity or density to predict stiffness can be misleading at times, since various timbers of the same specific gravity can have a wide range of mechanical properties due to different grain lengths and microfibril angles (Cave and Walker, 1994; Andrews and

Muneri, 2002; Lichtenegger *et al*., 1999). The cellulose fibrils in the "S2" layer, the major part of the cell wall, run parallel to one another and follow a steep helix around the cell wall (Litchtenegger *et al*., 1999). The angle between this helix and the axis of the tree is known as the microfibril angle. These fibrils are responsible for the strength-producing portion of wood fibre (Logan, 2003). Microfibril angle decreased from the pith to the bark (Litchtenegger *et al*., 1999). It was found that timber with a large microfibril angle had low strength and stiffness, and vice versa (Logan, 2003). A large microfibril angle can be compared with a loose spring where it is very susceptible to flaws and damage, which hence makes it weaker (Evans, 1996). Overall, it has been shown both experimentally and theoretically that microfibril angle is just as, or even more, important as basic density in predicting the stiffness of hardwood and softwood timber (Evans and Ilic, 2001; Cave and Walker, 1994).

Failure strain is used as a criterion for checking because it has been found by Oliver (1991), Alexiou (1993), Booker (1994), Doe *et al*. (1994) and Langrish *et al*. (1997) to be a more constant measurement of the tendency for timber to fail than the maximum stress. Brooke's (1999) results for mechanical properties of Ironbark timber found that the effect of varying temperature was stronger for the failure stress than for strain at failure. Hence, Brooke (1999) used failure strain as a failure criterion because it was less affected by the specimen's temperature. In addition, Alexiou *et al*. (1989) used failure strain as a criterion because they found that it was independent of the basic density for the green timber. Afterwards, Alexiou (1993) found a similar result with his further study of blackbutt, that the failure strain was independent of density, more consistent (Table 2.2) and thus was a better criterion for surface checking.

With this in mind, the concept of fracture mechanics is possible to assess the propagation of cracks along an expected crack path. Daudeville's (1999) study of fracture in spruce (softwood) compared simulation results based on Linear Elastic Fracture Mechanics (LEFM) model, and experimental results of the three point bending test, showed that LEFM could predict the load-displacement curve of the specimen. Additionally, a simplified approach of Damage Mechanics for the analysis of cracking was able to correctly predict the load-deflection curve (Daudeville, 1999). The fracture energy, which is the dissipated energy per unit crack area, was also found to be the major parameter that governs fracture propagation in linear or in non-linear fracture studies. The concept of fracture mechanics is yet to be applied for predicting failure behaviour in hardwoods, in this case, for blackbutt timber. In future work, the study of fracture mechanics as a failure criterion may be a useful way to determine a better failure criterion for timber during drying.

2.2.6 Shrinkage

Shrinkage occurs in timber when bound water is lost from the cell walls (i.e. as soon as the moisture content falls below fibre saturation point, X_{fsp}) and results in the diameters of the fibres shrinking (Keey *et al*., 2000). Oliver (1991) found linear shrinkage strains of around 0.04 m m^{-1} for various Australian eucalypts in the radial direction. Bao *et al*. (2001) studied the shrinkage (both in the radial and tangential directions) of three plantation—grown hardwood species: lemon eucalyptus, lankao paulownia, and sanbei poplar. With the exemption of lemon eucalyptus, the transverse shrinkage of juvenile timber was higher than the transverse shrinkage of mature timber. A similar trend was also found for shrinkage in the tangential direction. However, lemon eucalyptus had the opposite result for tangential shrinkage, i.e. the tangential shrinkage for juvenile wood was smaller than the tangential shrinkage for mature wood. Though these results occurred, juvenile wood in most species has a considerably higher differential shrinkage, where differential shrinkage = (tangential/radial) shrinkage (Bao *et al*., 2001). This indicates that juvenile wood is less dimensionally stable compared with mature wood. Bao *et al*. (2001) suggested that the large differential shrinkage in juvenile wood may be caused by the larger microfibril angle in the juvenile wood, since differential shrinkage was reported to be closely related to the microfibril angle (Zhang and Zhong, 1992).

The study of eastern cottonwood by Shupe *et al*. (1995b) found that the sapwood had significantly greater radial and tangential shrinkages than the heartwood. This trend supports what Bao *et al*. (2001) found with their shrinkage results of lemon eucalyptus, i.e. radial and tangential shrinkages increased from pith to bark. This trend is yet to be assessed for blackbutt species.

2.3 Conclusions

Anecdotal evidence suggested that hardwoods taken from plantations are more variable with regards to their biological properties, compared with the properties of old growth or regrowth timber. This poses increasing challenges to timber drying companies, which have to deal with the variations and at the same time meet the requirements stated in the Australian/New Zealand Standard on the assessment of dried timber quality (2001). The definition of quality considered in this study is to both minimize the dispersion of the final moisture content, and to reduce cracking/checking. Conventional kiln drying is preferred to other drying methods such as air drying and solar kilns due to better control of the drying conditions and faster throughput. The higher costs of conventional kiln drying are compensated, relative to open—air drying, by the reduction in stock level and faster turnaround of green timber to dried timber. Blackbutt (*Eucalyptus pilularis*) has been chosen for this study because it is the most abundant hardwood species in New South Wales and the timber is marketable.

Previous studies and methods for optimizing drying schedules have been reviewed. These studies either developed optimized drying schedules to minimize the dispersion of the final moisture contents, or reduced cracking/checking. No schedule has been developed to satisfy both aspects of quality. In addition, only one report has taken into consideration biological variability in the development of an optimized drying schedule, but this approach has not been tested experimentally.

Finally, reports have showed that there are possible correlations between the timber properties, which can be taken into account in the development of optimized drying schedules. Previous timber drying studies have observed that biological variability had a significant effect on the timber quality, but the variability of the transport properties that are relevant to drying has not been studied in detail so far.