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Literature Review of Machine Stress Grading Accuracy Check Methods

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Literature Review of Machine Stress Grading Accuracy Check Methods

Prepared for the

Forest & Wood Products Research & Development Corporation

by

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Executive Summary

Given the heavy reliance of the Australian pine structural timber market on MGP the accuracy of the grading process requires ongoing validation. Plantation Timber Certification Pty Ltd (PTC) always anticipated that the current Australian QC methodologies, developed by PTC and CSIRO in 1996/97, would require review and ongoing refinement. This project was seen as a logical first step in achieving this with the initial focus being on the Accuracy Check method.

The primary aim of this project was to determine if there were any international advances in Machine Stress Grader (MSG) accuracy checking techniques and or procedures that could potentially be adopted/adapted to enhance or simplify PTC's MSG Accuracy Check method.

The literature review focused on locating and documenting international MSG practices with particular emphasis on controlling the grading accuracy of flat-wise bending type stress grading machines. The study tour focussed on viewing first hand current MSG practices in the US and Europe including visiting grading inspection agencies and obtaining regulatory documents and process control forms not available in the published literature.

For the sake of completeness the review required at least cursory examination of all contributory factors known to impact or have influence on the accuracy of the MSG process. Due to budgetary constraints, review of the existing PTC Accuracy Check method extended to desktop evaluation only.

In addition to specifically investigating MSG Accuracy Check methods this report documents the developmental history of MSG and MGP in Australia and provides a comprehensive overview of current MSG practices in Australia and the Western World.

1.0 Historical development of PTC's product certification system

Prior to the introduction of Machine Graded Pine (MGP) to the Australian market place in 1996, PTC, in conjunction with CSIRO, led the world in developing a suite of Quality Control (QC) methods for monitoring of MSG in a mill environment. Based on the results of in-mill testing this suite of QC methods was adopted by PTC in 1997 as the basis for its Quality Assurance (QA), auditing and product certification scheme. Although some minor operational adjustments have been made to these methods they have remained relatively unchanged since their adoption in 1997.

The practice of MSG continues to evolve. CSIRO is currently in the process of undertaking a comprehensive in-grade study to recalibrate MGP grade thresholds in line with changes in the average mechanical properties of Australian grown pine.

The sole purpose of the PTC Accuracy Check method is to verify the ability of mechanical stress grading machines to accurately measure timber stiffness. The method is based on use of calibration sticks to dynamically control the accuracy of the stress-grading machine. According to a report by the UK Building Research Establishment (BRE)[1] the use of calibration sticks in the UK to dynamically check machine grading is permissible but is not mandatory and therefore only used infrequently.

2.0 Key findings and conclusions

To date application of the Accuracy Check method has, as expected, raised a number of operational and technical issues including the amount of down time associated with preparation of calibration sticks and undertaking the required tests. Technical issues include the effect the temperature of the calibration sticks and/or the ambient temperature have on the Modulus of Elasticity (MoE_{flat}[2]) profile, hence the ability to compare two MoE_{flat} profiles of the same stick accurately on different days is reduced. A short list of key issues identified by both mill staff and PTC auditors is provided as part of the introduction to this report.

Along with examining factors influencing overall accuracy of MSG, this project has identified a number of differences between Australian and overseas MSG practices including

- Timber species being graded in the US and Europe generally have different and inherently less variable mechanical properties than those encountered in Australian grown pine species.
- No accuracy control methods equivalent to PTC's method is being applied elsewhere in the world.
- Various materials and designs for non-timber control planks (Calibration sticks) have been tested none are currently in operational service.
- European and US regulatory authorities have legislative control over compliance with machine-grading systems and standards whereas in Australia industry compliance with PTC's Quality Assurance system (QA) is voluntary.
- In the US and Europe the process of machine grading is controlled by either machine or output control. Machine control (the norm in Europe) relies on fixed machine settings as determined by the grading agency for all machines of a specific type. Output control (the norm in the US) relies on timber being regularly taken from the production line and tested to confirm timber meets required strength characteristics after the timber has actually been graded.
- Output control systems enable the actual stiffness and the 5-percentile strength trends to be monitored, however the lower sampling rate means incorrectly sorted margin pieces may take a while to be detected.
- PTC's Dynamic machine control Accuracy Check method enables corrective action to be taken as an integral part of controlling the accuracy of the process at the time the timber is actually graded and consequently much faster response to a problem with machine accuracy than output control systems.
- By regularly checking on machine performance, it is possible to detect when a machine is drifting out of control thus preventing the production of large volumes of timber that do not meet grade and require withholding from the market or re-grading.

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[1] Benham, C., C. Holland and V. Enjilly. 2003. Guide to machine strength grading of timber, BRE Centre for Timber Technology and Construction, Digest No. 476, BRE, Watford, Herts, UK.
[2] MoE determined flat-wise by a three point bending test.

The absence of any PTC equivalent Dynamic machine control Accuracy Check method made it impossible to undertake any direct comparisons between the current PTC Accuracy Check method and methods used overseas. Not withstanding the lack of direct comparison, the main conclusion from this review is that PTC's current MSG Accuracy Check method and its application is more comprehensive than any other MSG accuracy control method (s) currently used overseas. This finding leads to the conclusion that the present, PTC Accuracy Check method and its application could potentially be simplified.

3.0 Further investigation required.

Given the range and extent of issues identified and in order to verify if the current Accuracy Check method can be enhanced and or modified it is recommended that a comprehensive in-mill investigation be undertaken. Further investigation will need to encompass all aspects of the Accuracy Check method from its statistical basis through to operational aspects of its application.

Although the PTC Accuracy Check method appears to be more responsive to out of control situations the economics of this approach has never been fully evaluated in terms of operational benefit cost. The scope and extent of further investigation will need to be developed in consultation with both the PTC and the sawmillers utilising PTC's certification services and methodologies. Recommended additional investigations are expected to encompass but not be limited to:

- Quantifying the frequency, cause and effect of machine adjustments consequential to failed accuracy tests to determine specifically how and why such adjustments are made and how they effect the consistency and accuracy of grading.
- Quantifying the impacts of specific contributory factors such as variations in timber thickness and machine vibration have on grading accuracy.
- Determining what remedial actions could be taken to improve the consistency of machine settings. More frequent checks of machine settings could lead to a reduction in the frequency of calibration stick use.
- Examining the construction, storage and shelf life of calibration sticks
- Recording and analysing data on how often a calibration stick gives an unacceptable value. If this is relatively infrequent then the interval between using the sticks could potentially be extended.
- Examining the use and relevance of statistical machine control charts in checking machine accuracy.
- Re examining the underlying statistics on which the accuracy test is based,
- Quantifying the benefit/cost of various alternative combinations of machine and output control systems.

Pending further investigative work it is the recommendation of Forest Research that on no account should individual mills drop or change any of the PTC check methods in favour of those used overseas as these alternative procedures need to be fully evaluated and justified for the Australian situation.

1 INTRODUCTION

1.1 Background

Forest Research[3] was commissioned by the Forest and Wood Products Research and Development Corporation (FWPRDC) to undertake a literature review of Machine Stress Grading (MSG) Accuracy Check methods including a short international study tour to investigate MSG control systems used in the US and Europe. The primary aim of this review was to determine if there were any international advances in MSG accuracy checking techniques and or procedures that could potentially be adopted/adapted to enhance or simplify the Plantation Timber Certification (PTC) [4] existing MSG Accuracy Check method.

For the sake of completeness the review required at least cursory examination of all contributory factors known to impact or have influence on the accuracy of the MSG process. Most stress grading machines used in Australia are of the flat-wise bending type. Therefore control systems for these machines were the focus of this study. Flat-wise bending machines use constant deflection, constant force or a combination of force and deflection. The most common makes of machine stress graders currently operated in Australia are Metriguard CLT's and HCLT's. Other machine stress graders include Eldeco Darts and Plessey Computermatics.

For quality assurance and product certification purposes the majority of Australian MSG operations are regularly audited and assessed by PTC. The sole purpose of the PTC Accuracy Check method is to verify the ability of a grading machine to accurately measure timber stiffness by comparing the machines dynamic measurement of MoE_{flat} with the known static measured MoE_{flat} profiles of calibration sticks.

Although, since its adoption in 1997, PTC's Accuracy Check method has generally provided good service, to date its application has raised a number of operational and technical issues examples of which are as follows:

- The current method does not indicate where the "fail" result originates from the process.
- The temperature and moisture content of the sticks effects the MoE_{flat} profile; therefore the test methods ability to compare two MoE_{flat} profiles of the same stick on different days is reduced.
- The MSG may not have been in calibration when the original profile was stored.
- The calibration stick used in the test method may have lost structural integrity, i.e. low-point static MoE_{flat} > 5% difference from the original measurement.
- After any major changes to the infeed / outfeed of a machine stress grader all calibration stick MoE_{flat} profiles should be changed, but generally this is not followed up at the mill.

[3] New Zealand Forest Research Institute Limited trading as ***Forest Research***

[4] **Plantation Timber Certification**, PTC, is a wholly owned subsidiary of the Plantation Timber Association of Australia, and conducts third-party audited product certification activities for the Plantation Timber Association of Australia. PTC was established to inspect and report upon the quality certification practices and procedures of its Licensees, to ensure that finished products conform to current Australian and Industry Standards.

- A build up of resin on the rollers is likely to affect the accuracy of the test.
- Down time associated with the need to stop production to undertake accuracy tests. Calibration sticks require at least 2 hours to prepare. Often requires operators to undertake the task of preparing calibration sticks during weekends outside of their normal shifts.
- Loss of structural integrity of calibration sticks due to frequent use. In some case sticks are tested each hour, this frequency reduces lifespan of sticks, may only last 2 months, especially in the lower E-range.
- The test limits appear to be too large. There have been instances where broken calibration sticks have resulted in a “PASS”.
- The criteria has to accommodate the possibility of the first data point being missed, if not the MoE_{flat} profiles would be out of step by one data point.
- Eldeco Darts have difficulties measuring the first and last points.
- Pinpoint dynamic low-point with *Eldeco* software is difficult. Difficult to ascertain the start of the grading to within 100 mm making it difficult to test the calibration factor $0.95 < E_{stat}/E_{MSG} < 1.05$.
- The two way flip test procedure may not be necessary for CLT and HCLT machine stress graders, as they measure both sides of the board and yield the average E-measurement.
- Difference between static tester span and dynamic machine testing spans. Static tester span usually 914 mm (3’ 6”) is the same as the Eldeco Dart machine stress grader. The span for the CLT/HCLT machine stress grader is 1219 (4 ft) mm. Need to investigate affect of the dynamic MoE_{flat} measurement being taken over one span length and the static MoE_{flat} measurement over another span length.
- Calibration factor (between static and dynamic low-point) not really utilised.

Prior to reviewing the existing PTC method, it was considered prudent to first investigate overseas MSG control and quality assurance procedures in an attempt to identify if there were any international advances in MSG relevant to the Australian situation. A secondary consideration was to determine if there were any differences in approach or advances, could these be easily adopted and or adapting for application with MSG operations in Australia.

1.2 Methodology and approach

The methodology used was to perform a comprehensive worldwide literature review of machine stress grading and accuracy check methods. The literature review incorporated a desktop search through electronic database systems, a hardcopy search through library databases, and a search via world research organisations.

The literature review was used to identify important users of machine grading machines and the key contacts within the accrediting agencies. This information was used to plan a study trip to the USA and Europe. Two sawmills and one accrediting agency were visited in the USA, Ireland and Sweden and one accrediting agency and two machine stress grader manufacturers were visited in England.

The review concentrated on the types of machine stress graders currently operated in Australia, namely Metriguard CLT’s and HCLT’s, Eldeco Darts and Plessey Computermatics.

Forest Research was asked to include the following questions as part of the QC method comparison.

- Can the MSG accuracy test be improved to show where along the length of the board the machine is losing accuracy and what is the likely cause?
- Can the MSG accuracy test be modified to reduce machine downtime and hence reduce production losses?
- Can the MSG accuracy test be modified to lessen the effect on the MSG operators without compromising quality?

1.3 Literature review

The literature review incorporated a desktop search through electronic database systems, a hardcopy search through library databases, and a search via world research organisations. The review cited 242 references (Bibliography on page X). Of these 19 key references have been collated into a separate bound compendium. The extensive list of references cited in this review cover the full spectrum of MSG theory and practice. Not withstanding this the Authors have focussed on extracting and summarising published information of particular relevance to controlling the accuracy of the MSG process.

An Internet search[5] using the words *machine stress grading* produced 12,400 hits of which about 60 were relevant to MSG Accuracy. The Forest Products Society[6] web site contained an index of articles published in Wood Design Focus and machine-grading articles were cited. The Metriguard[7] web site also contained excellent references on machine grading of timber and veneers. An excellent article on quality production of MSR lumber and grade yield optimisation by Logan[8] is also available from the Metriguard web site. This article contains a detailed checklist for use with Metriguard machines. A literature search was also undertaken using TREECD[9] for the years 1939 to 2002.

1.4 International study tour

The International study tour focussed on viewing in-mill operational MSG practices in the US and Europe including visiting grading inspection agencies and obtaining regulatory documents and process control forms not available in the published literature. The study tour encompassed on-site visits to two mills and their associated inspection bureaus, in the USA, Ireland and Sweden along with visits to two machine manufacturer's facilities in England. The primary reason behind undertaking the tour was to verify if methods and procedures outlined in the published literature were actually being applied in practice.

The three questions relating to specifically to PTC Accuracy check method were not relevant to any overseas mills visited as they were using mainly output or static machine control. None of the overseas mills visited had experience with Dynamic machine control. As the mills were working to different standards, or more likely to prescribed instructions by the inspection agencies, the scope of their concerns with these issues may not be as wide as those involved with

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[5] www.yahoo.com
[6] www.forestproducts.org
[7] www.metriguard.com
[8] Logan, J.D. 1998. Quality Production of MSR Lumber and Grade Yield Optimisation, Metriguard.www.metriguard.com.
[9] TREECD. A Forest Industries database by Silver Platter International, N.V. 1999.

developing standards and testing different machine stress grading systems. The mills visited did not use any charts for control purposes nor did they use control planks. Notwithstanding the lack of constructive input on the specific questions outlined above the study tour helped clarify issues specific to overseas control systems from an operational perspective as opposed to the generally technical perspective documented in the literature.

1.5 Scope and extent of review

Although the focus of this review was on MSG Accuracy Check methods, the accuracy of the process could not be examined in isolation to the overall process of stress grading. To achieve this the review required at least a cursory examination to be made of all contributory factors known to or suspected of impacting on the accuracy of the process from basic theory to operational practice.

For the sake of completeness this report incorporates background overview covering elements of the process that are of general interest, such as the developmental history of stress grading as well as detailing specific aspects relating directly to the accuracy of the process, such as varying types of output control systems.

2 ACCURACY OF MACHINE PREDICTION (TIMBER STRENGTH/STIFFNESS)

2.1 Relevance

The basis of machine stress grading is an estimation of the strength properties based on the machine measuring one or several characteristics (indicating property), which are related to the engineering (strength and stiffness) properties of the timber. A machine's ability to accurately estimate strength is based on how well the measured characteristic is related to and hence can be used to predict the true strength of the timber and how well the machine can measure that characteristic.

2.2 Reviewed elements

The coefficient of correlation[10], r, is often used as a measure of how strong the relationship between the grading characteristic and the strength is. The measurement error of the machine can be represented by a coefficient of variation, ν.

Three numbers, coefficient of determination between the grading characteristic and the strength ($r^2_{strength}$) and stiffness ($r^2_{stiffness}$) and the measurement error (ν) describe the performance of machine stress graders:

1. The coefficient of determination, r^2, is used as a measure of how strong the relation between the grading characteristic and the strength and stiffness is. Figure 1 illustrates the value recovery versus coefficient of determination, r^2 for a given set of data. The relationship shown in Figure 1 will vary depending on timber prices and the quality of the timber graded.

2. The measurement error indicates how well the machine can measure the grading characteristic. The measurement error of the machine can be represented by the coefficient of variation ν.

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[10] Coefficient of correlation = r, coefficient of determination = r^2

Quality control procedures are designed to control the percentage wrongly accepted. The wrongly rejected is a value loss as illustrated in figure 1.

Figure 1

Relationship between Measured Indicating Property and Strength or Stiffness

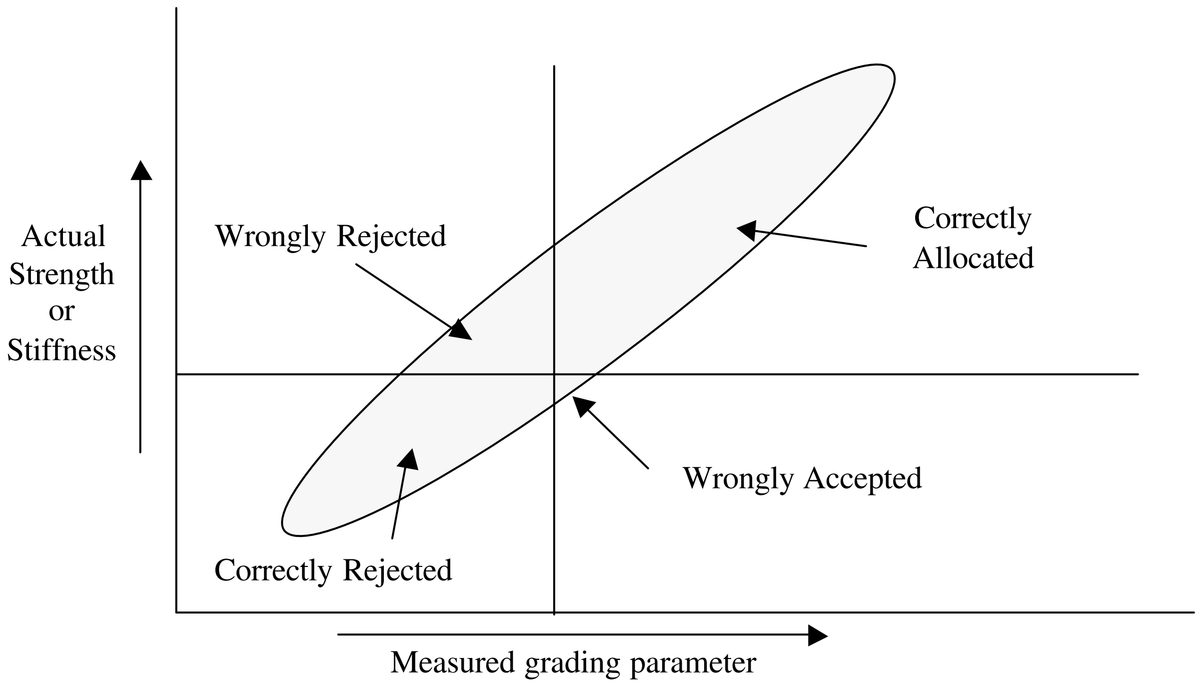


Figure 1 illustrates allocation of timber to one grade, but the same procedure can be used to allocate timber to more grades. The measured grading parameter determines the spread of the "cloud" and thus the percentage wrongly rejected.

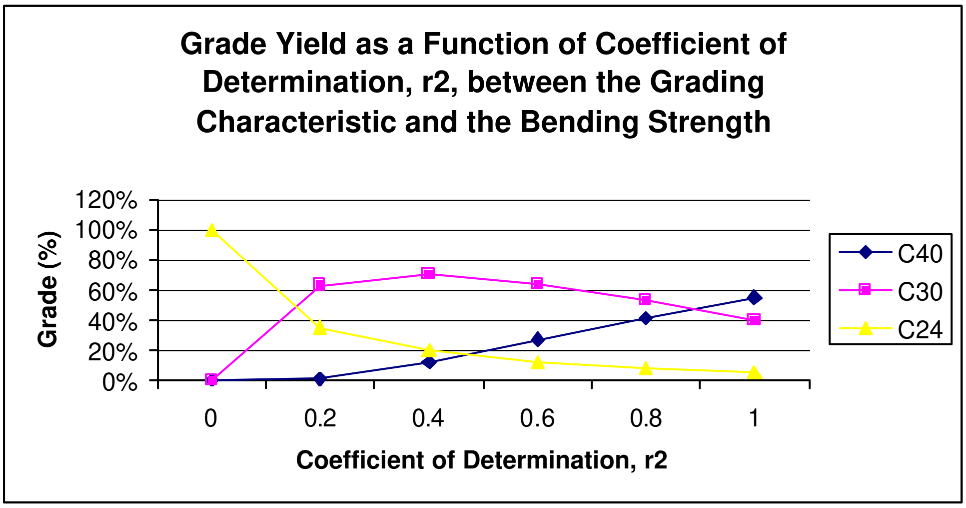
The relationship between the predictor and the engineering property of interest is analysed using statistical techniques. For some engineering properties, such as Modulus of Elasticity (MoE=stiffness), the average values are important while for others, such as Modulus of Rupture (MoR=strength), the 95% tolerance limit is of interest.

Figure 2 illustrates the grade yield as a function of coefficient of determination, r^2, between the grading characteristic and the bending strength. Coefficient of variation of the measurement error of the machine, $\nu = 0.1$.

Figure 2 is based on the work by Boström[11] and shows that the timber grade yield will be C40=55%, C30=40% and C24=5% if the coefficient of determination, $r^2 = 1$. If the $r^2 = 0.6$, a typical value for mechanical machine stress graders, the grade yields will be C40=25%, C30=65% and C24=10%.

[11] Boström, L., and C. Holmqvist. Sate-of-the-art on Machine Stress Grading, SP Swedish National Testing and Research Institute, Sweden. Table 1, p.4.

Figure 2



From Figure 3 an improvement in the r^2 of a machine stress grader from 0.6 to 0.8 is worth about $8/$m^3$ sawn timber graded (about 2% increase in value). For a good grading machine the coefficient of variation ν should be less than 10 percent.

Figure 3

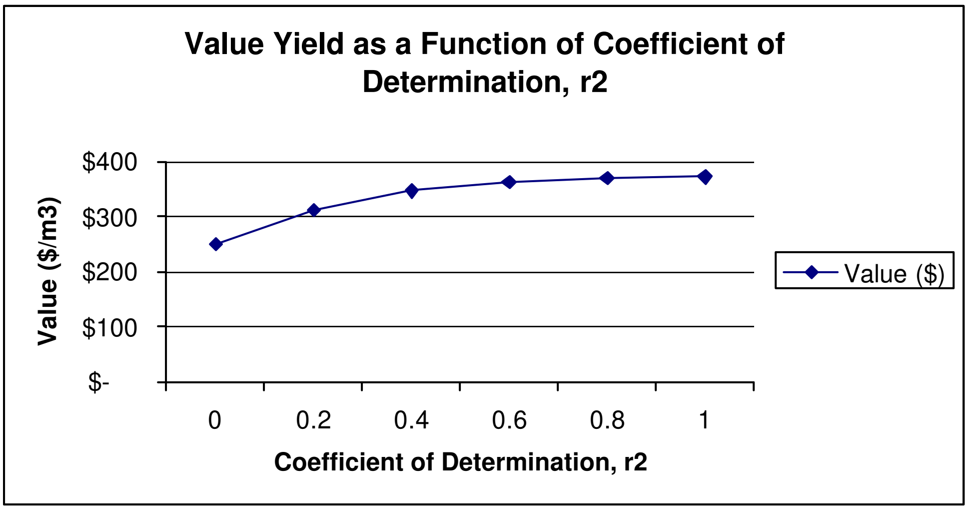


Table 1 shows how the indicating properties contribute to coefficient of determination. Knots alone are a poor indicator of timber strength while knots and modulus of elasticity combined can be a very good predictor.

Table 1

Coefficient of Determination between Indicating Property and Timber Strength.

Characteristic used to predict strength	Coefficient of determination r^2
Knots	0.15-0.30
Annual ring width	0.20-0.40
Density	0.15-0.40
Modulus of elasticity	0.50-0.70
Knots and annual ring width	0.35-0.50
Knots and density	0.35-0.60
Knots and modulus of elasticity	0.35-0.80

The type of measuring system and timber size can influence the correlation coefficient between the indicating property and the bending strength or stiffness for different machines[12].

Table 2 shows the coefficient of determination between the indicating property and bending strength and Table 3 shows the coefficient of determination between the indicating property and edgewise modulus of elasticity.

Table 2

Coefficient of Determination between the Indicating Property and Bending Strength

Machine Grader	45x120mm	45x195mm
Cook-Bolinder	0.51	0.73
Computermatic	0.41	0.62
Finnograder	0.34	0.55
Sylvatest[13]	0.20	0.50

Table 3

Coefficient of Determination between the Indicating Property and Modulus of Elasticity

Machine Grader	45x120mm	45x195mm
Cook-Bolinder	0.71	0.87
Computermatic	0.57	0.68

2.3 Summary of findings

Features such as production rate, maintenance, ease of operation and capital cost are important factors for mill owners to consider when adopting MSG. In terms of grading accuracy the machines capability is dependent on the strength of the correlation between the indicating property (IP) and the MoE (r^2_{MoE}) and MoR (r^2_{MoR}) and the coefficient of variation of the measurement error of the machine, ν. It is these elements that ultimately determine the ability of the MSG to accurately predict stiffness hence maximise value recovery from the feedstock. The r^2 and ν coefficients can be influenced by the feed speed of the grading machine, length and the cross section of the timber graded. Any accuracy checking method needs to take account of the predictive capabilities of a MSG to ensure test limits are set within those capable of being routinely achieved or exceeded by the machine under normal operating conditions.

3 STRESS GRADING METHODS.

3.1 Relevance

12 Boström, L. Machine Strength Grading Comparison of Four Different systems, SP Report 1994:49, p.39.

13 The correlation coefficients improve from 0.20 to 0.34 and 0.50 to 0.62 if the density is added to the ultrasonic wave speed equation $E_{sylva}=c^2.\rho$.

When structural timber is produced in the sawmill, some pieces can be eight or more times stronger or stiffer than others of the same dimensions. These differences are mainly due to the variability in wood cell structure and defects such as knots and sloping grain. It is this variability, which poses the greatest impediment to the efficient use of timber as a structural material. To overcome this variability timber needs to be sorted into grades based on strength and stiffness known as stress grades. Pieces, which qualify for the higher grades can be assigned higher working stresses. The type and application of varying grading methods can have significant impact on the accuracy of both the assignment process and the level of yields.

3.2 Review elements

There are two types of stress grading methods:

- **Visual stress grading** - Based on visual inspection of timber to ensure the timber meets the defect limits described in the relevant grading rules. Visual grading rules can also be applied to machine stress graded timber with visual overrides applied to the whole piece or to the ungraded ends only.

- **Machine stress grading** - Timber is passed through a machine, which measures one or more parameters non-destructively. Based on the measured parameters, known as indicating properties, strength and stiffness is predicted.

Both stress-grading methods are based on the use of predictors to estimate engineering properties. In visual grading the size and location of visual defects such as knots are used to predict strength. In machine grading stiffness or density is normally used as a predictor USA grading rules differentiate between Machine Stress Rated lumber (MSR), Machine Evaluated Lumber (MEL) and E-rated lumber. Machine stress rated lumber (MSR) is the normal machine graded product while MEL is a specialist product and E-rated lumber is a laminating grade. In Australia timber is marketed as Machine Graded Pine (MGP) with associated stiffness and strength parameters. MGP grades are unique to Australia and New Zealand.

An excellent overview of MSG is available from the USDA Forest Service as a General Technical Report FPL-GTR-7[14]. This report covers the history of stress grading (visual and machine), the theory and practice of machine grading, current machine grading operations and the assessment of production potential. The American sawmills use mainly output control for their machine stress graders.

A review undertaken by the UK Building Research Establishment[15] provides an excellent overview of stress grading methodology from a European perspective. British and European sawmills use mainly machine control for their machine stress graders.

3.3 Summary of findings

The application of different grading methods can have significant impact on the accuracy of both the assignment process and the level of yields. In conjunction with rigorous quality control MSG can give higher grading accuracy and yields compared to visual grading[16].

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[14] Galligan, W.L. and K.A. McDonald, 2000. Machine Grading of Lumber. Practical Concerns for Lumber Producers. Forest Products Laboratory, Madison, WI. 39p.

[15] Benham, C., C. Holland and V. Enjilly. 2003. Guide to machine strength grading of timber, BRE Centre for Timber Technology and Construction, Digest No. 476, BRE, Watford, Herts, UK.

4 BRIEF DEVELOPMENTAL HISTORY OF AUSTRALIAN STRESS GRADING

4.1 Relevance

It was considered important to document the developmental history behind the adoption of MSG in Australia to ensure that the rationale for MSG and in particular the importance of MGP was not overlooked in relation to the need to maintain ongoing accuracy of the process.

4.2 Review elements

The literature documents that the first steps were made towards establishing timber-grading standards for the Australian timber industry in 1939. At this time the Standards Association of Australia (SAA) set up a Timber Sectional Committee, which sought first to establish definitions for the wide variety of trade terms and standard trade names for specific timbers[17]. Shortly thereafter the Forests Department of Western Australia and CSIR jointly developed visual grading rules for jarrah to ensure that timber of acceptable and uniform quality could be supplied for any specified major end use[18].

By the late 1930's CSIR had developed a system to classify the more common Australian and imported timbers into four strength groups[19] on the basis of an extensive testing program. In addition C. J. J. Watson of the Queensland Forest Service had made a comprehensive study on North Queensland woods to classify them for building purposes according to their durability and strength[20]. The SAA committee developed its first standard grading rules for timber (for flooring) in 1939.

The knowledge gained on the mechanical properties of Australian woods also enabled new design data to be developed by CSIR and this was published in 1939 by Langlands and Thomas in a *Handbook of Structural Timber Design* which became a standard reference work[21]. During the Second World War it was found possible on the basis of CSIR's work to introduce a reduction in standard timber sizes for domestic housing to conserve resources[22].

The number of strength groups into which Australian timbers were classified was increased from four to seven in the 1960's, in part to enable the inclusion of plantation pines and overseas timbers. A stress grading system was also introduced which designated the grades with numerical 'F' values (equivalent to the typical basic working stress in bending for the grade in megapascals) instead of the descriptive terms used earlier[23].

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[16] Johansson, Carl-John, Grading Timber with Respect to Mechanical Properties, Timber Engineering, Table 3.11. Draft paper.
[17] http://www.austehc.unimelb.edu.au/tia/234.html
[18] Gregson, F. and Turnbull, R. F., 'The grading of Western Australian timbers', CSIR, Melbourne, Pamphlet No. 41, 1933.
[19] Langlands, I. and Thomas, A. J., 'Handbook of structural timber design', CSIR Division of Forest Products, Tech. Pap. No. 32, 1941.
[20] Watson, C. J. J., 'North Queensland building timbers and specifications for their use', Queensland Forest Service, Pamphlet No. 1, 1939.
[21] Langlands, I. and Thomas, A. J., 'Handbook of structural timber design', CSIR Division of Forest Products, Tech. Pap. No. 32, 1941.
[22] Thomas, A. J. and Langlands, I., 'Building-frames: timber and sizes', CSIR, Melbourne, Pamphlet No. 112, 1941.
[23] Kloot, N. H., The strength group and stress grade systems, *CSIRO Forest Products Newsletter*, No. 394: 1-5, 1973.

While stress grading could be undertaken on the basis of visual inspection and knowledge of the strength group to which the timber belonged, interest developed in mechanical grading because of its potentially better accuracy. This led in the mid-1960s to the development by the Wood Technology Division of the Forestry Commission of NSW, working together with Plessey Aust. Pty. Ltd., of the 'Computermatic'[24] machine stress grader which became widely used in Australia and overseas[25]. The machine measures the stiffness of a sample from its deflection under a standard load and thus required knowledge of the correlation between this measured parameter and strength. Two commercial grading machines, the “Continuous Lumber Tester (CLT)” by Metriguard and the “Stress-O-Matic” by Crow, were developed in the United States in the 1960’s.

In the 1970s CSIRO pursued a simpler and more direct method of strength assessment which tests the ability of a sample to withstand a predetermined bending load similar to that which it will meet in use[26]. Machines based on this 'proof grading' principle have also been developed[27]. During the 70’s and 80’s research on new principles continued but very few new types of commercial machines were developed.

The situation changed with the start of the European standardisation work at the end of the 1980’s, which included a set of common strength classes for structural timber as well as standards for machine strength grading and grading machines[28]. Today several different machine types are available using different measuring principles, including radiation, cameras, vibration, and microwaves, to estimate the timber strength and stiffness.

4.3 Summary of findings

Australia has a long history of stress grading development spanning over 70 years. In many cases this development has been world leading and MSG continues to be the subject of ongoing refinement. The importance of accurate stress grading in retaining wood as a structural material cannot be underestimated and sawmillers will need to maintain quality standards to ensure structurally fit for purpose timber is accurately and consistently produced.

5 DEVELOPMENT OF MGP AND PTC'S ACCURACY CHECK PROCEDURES.

5.1 Relevance

As this review focussed solely on the PTC Accuracy Check method, documenting the background developmental history behind derivation of MGP grades and the current PTC Accuracy Check method was seen an important scene setting exercise to benchmark any proposed new development or refinements against.

[24] The production of the “Computermatic” was transferred to Measuring and Process Control in England. In the 1990’s Eldeco took over the maintenance of the Computermatic machines from Plessey and then later started producing their own stress grading machine called Eldeco Dart.

[25] Booth, H. and Anton, A., 'Method of grading timber and timber products', Aust. Pat. No. 285255, 1964.

[26] Leicester, R. H., 'Proof grading technique', Proc. Sympos. For., Prods, Res. International, Pretoria, S. Africa, Paper 311, 1985.

[27] Anon., 'Low cost proof grader', *Aust. For. Ind. J.*, 51/52: 31-32, 1986.

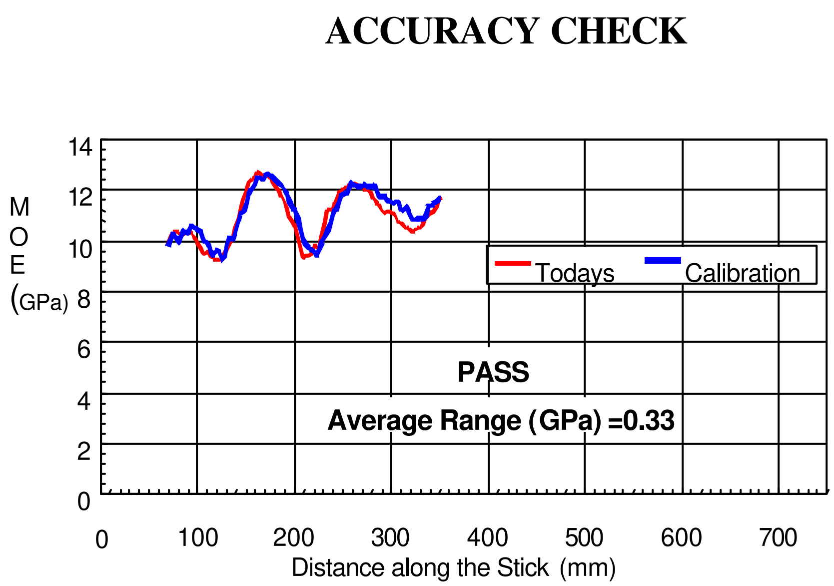
[28] Boström, L. and C. Holmqvist, State-of-the-art on machine grading, SP Swedish National Testing and Research Institute, Sweden

5.2 Review elements

Between 1991 - 1993 Pine Australia[29] and CSIRO undertook a comprehensive in-grade evaluation of Australian grown pine. The objective was to accurately quantify plantation grown pine timber structural design properties in the stress grade and in the size in which it is produced. The current MGP10, 12 and 15 grade design properties were determined from machine stress-graded F5, F8, and F11 Australian Pine evaluated during this in-grade study. Prior to the introduction of MGP to the Australian market place in 1996, PTC, in conjunction with CSIRO and the NSW State Forests, led the world in developing a suite of three Quality Control (QC) methods for monitoring of MSG in a mill environment.

The Accuracy Check Method, illustrated in Diagram 1, was designed to verify that a mechanical machine stress grader could grade accurately along the entire length of the board and across different grades.

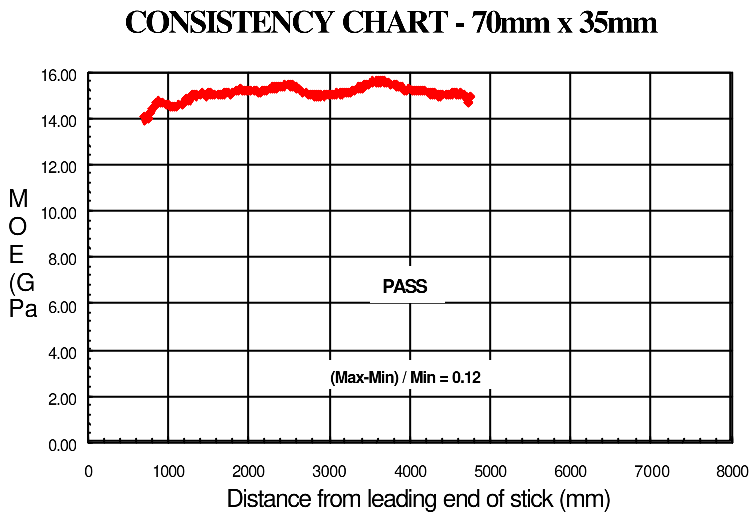
Diagram 1



The Consistency check method, illustrated in Diagram 2, was designed to detect if the MSG develops any bias during the shift.

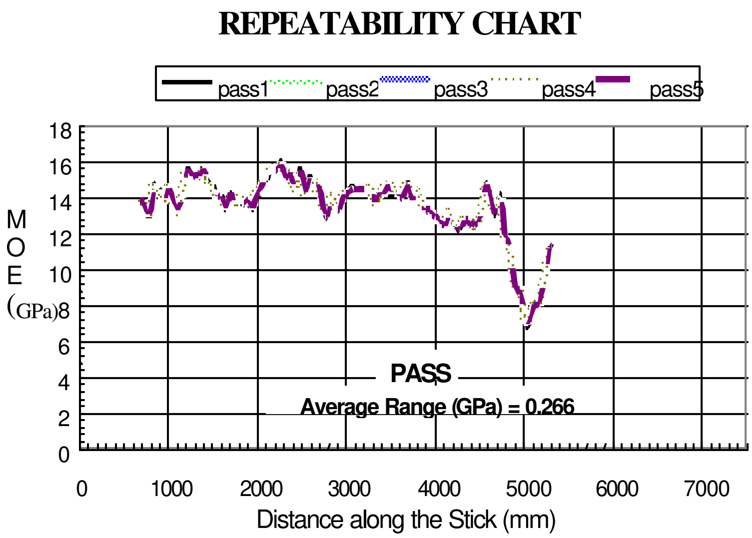
[29] Pine Australia has been superseded by the formation of The Plantation Timber Association of Australia.

Diagram 2



The Repeatability check method, illustrated in Diagram 3, was designed to detect the ability of the MSG to repeatedly measure the same board five times.

Diagram 3



5.3 Summary of findings

The suite of QC methods has to date been seen by the Australian industry as offering the potential to substantially improve overall control of the grading process. Based on the results of in-mill testing this methodology was adopted by PTC in 1997 as the basis for its Quality Assurance, auditing and product certification scheme. Although some minor operational adjustments have been made to these methods they have remained relatively unchanged since their adoption in 1997.

The practice of MSG continues to evolve. CSIRO is currently in the process of undertaking a comprehensive in-grade study to benchmark and quantify any shift in the mechanical properties of Australian grown pine due to changing resource characteristics caused for example by increased volumes of more juvenile wood arising from shorter rotations.

6 OVERVIEW OF PTC PRODUCT CERTIFICATION METHODOLOGIES

6.1 Relevance

Product certification is all about maintaining standards. To maintain standards quality can be built into the product or the producer can rely on mass inspection. The modern trend is to avoid dependence on mass inspection and rely more on improved process control.

In sawmilling two systems are used when machine stress grading sawn timber. The one system is based on output control (acceptance sampling) while the other is machine control (process control) system.

6.2 Review elements

6.2.1 PTC Machine Stress Grader Accuracy Check Procedure

The "Old" PTC F-Grade MSG Accuracy Check Method was an output control (acceptance sampling) system with prescribed product sampling and test procedures while the current PTC MSG Accuracy Check Method is basically a dynamic machine control (process control) system with heavy reliance on control planks to ensure dynamic control.

The Pine Australia Product Certification Manual, Appendix D, p.D11, Structural products MGP Grades, describes the following MSG accuracy check procedure:
D3.1 Scope
This procedure outlines the steps required to determine the accuracy of the mechanical stress-grader using the three calibration sticks for a nominal size of timber to be graded.
D3.2 Procedure

1. *A calibration stick is passed through the mechanical stress-grader (infeed mode 1) and the machine modulus is recorded continuously through this process. Data recorded (example QD D3) if there is no computer available.*
2. *Today's run is compared against the calibration run and the difference at each location is calculated and recorded (example QD D3) if there is no computer available.*
3. *The average of the differences at each location is calculated and recorded (example QD D3) if there is no computer available.*
4. *The above three steps should be repeated for each of at least 3 calibration sticks for the given nominal size the grading machine is set for.*
5. *Each calibration stick average difference should not be greater than 1 GPa. If one calibration stick fails then repeat the above four steps of this procedure. If again it fails replace the calibration stick. If all calibration sticks fail then check the machine settings, and calibration sticks according to procedure D1, and repeat the procedure.*

The Pine Australia Product Certification Manual, Section 3, p.16, Structural products MGP Grades, describes the following machine stress grader accuracy check:
Follow Procedure D3: Accuracy Check at a rate described in Table 3.8.2.1 using each of the three calibration sticks for that size. The testing rate is related to past quality performance and therefore the testing level should be recorded.
Definition of "Fail" for sampling purposes is when 2 or more sticks don't comply on 2 consecutive passes. If the machine fails the check, adjust the machine and repeat Procedure D3 until it passes.
Table 3.8.2.1 Accuracy test Frequency

Testing Level	*Frequency*	*Time at this level*
1. Initial start-up	*3 sticks EIGHT times per shift*	*First month of MGP production*
2. Tightened	*3 sticks EIGHT times per shift*	*5 consecutive shifts of no FAILS*
3. In-control	*3 sticks THREE times per shift,* ***plus*** *3 sticks ONCE at the end of each shift*	*Until FAIL is recorded. Then return to level 2.*

6.2.2 Control Planks versus Calibration Planks

Boström et.al.[30] make a distinction between control planks[31] and calibration planks[32]. It was inferred from the PTC manual that the calibration stick it refers to is the equivalent of the control plank referred to by Boström. The draft standard prEN 14081-2:2000 also uses the term control plank to describe an "object that simulates the characteristics of timber that are being sensed by the measuring devices in a grading machine, which, when passed through the machine, is able to check the calibration of the machine dynamically."

The proposed EN and ISO standards both provide for machine control using control planks and a major project (CONGRAD) is currently under way in Europe to design suitable control planks.

According prEN 14081-3:2000 p. 14, control planks may improve the grading accuracy and result in greater safety and higher grade yields. The European study by Boström included testing 20 different control planks made from timber (spruce), lignostone[33], obo[34], glass fibre epoxy[35], aluminium[36] (various combinations), polyamide and polyoxymethylen.

The European draft standard prEN 14081-3:2000. p. 15, use the control plank to determine the grade boundary by setting the grade boundary for the machine 5% above the calculated indicating property of the control plank. The test requirement can be met with one pass of a control plank. The PTC check method (Section 3, Structural products MGP grades, p. D11) calls for an accuracy test with three control planks and comparing the MoE_{plank} along the distance of the stick. Each calibration stick difference should not be greater than 1.0 GPa, which is equivalent to a 10% difference in a 10 GPa board (MoE_{plank}) compared to an allowed 5% in the indicating property to detect a grade change as described in prEN 14081-3:2000. The 1.0 GPa limit in this test refers to the average range of the differences at each grading point between two runs of the same stick.

[30] Boström, L., V. Enjily, G. Gaede, P.Gloss, C. Holland, C. Holmqvist, P. Joyet. 2000. Control of Timber Strength Grading Machines, SMT4-CT97-2207, SP Report 2000:11, Borås, Sweden.
[31] According to Boström et.al. "control planks are for routine quality control and they ensure the machine performs at all times the same as when newly manufactured, repeatability testing." P.82
[32] According to Boström et.al."Calibration planks ..can be considered diagnostic tools.. to dynamically asses both quantitatively and qualitatively the measuring systems used by the grading machine" p.82.
[33] Lignostone is a densified laminated wood.
[34] Obo is a compressed wood laminate with veneers thinner than lignostone.
[35] Extruded square tubes.
[36] Extruded square tubes.

6.2.3 "Old" F-Grade MSG Accuracy Check Method

The "Old" PTC F-Grade MSG Accuracy Check Method was basically an output control system with prescribed product sampling and test procedures. These procedures are best compared against the Southern Pine Inspection Bureau (SPIB) procedures, as it is very similar in approach with small differences in the daily sampling rates, but significant differences in the test procedures. The periodic monitoring procedure by a testing laboratory differs mainly in detail. The "Old" F-Grade accuracy check method used control planks prepared by the mills which were then sent to the grading agency, where the low point E was verified. The board was formally marked and sent back to the mill. The in-mill procedures involved running verified control planks through the MSG at the beginning and end of each shift to check whether the machine gave the same grade as determined by the grading agency. With the grade limits for 90x35mm F5 the grading range was 5.52 to 8.27GPa with a further –10% and +15% on these limits.

The SPIB has a prescribed sampling rate of 5 pieces every 4 hours. It requires a long span E test with positioning at random (the face with the paint on to face the operator) to determine $MoE_{joist\ long\ span\ average}$ followed by proof loading to determine the MoR_{joist}. The CUSUM technique is used to determine the course of action. The periodic monitoring by the SPIB includes monthly visits by inspectors. Quarterly inspections are done to evaluate conformance to established requirements under the quality control procedures. Periodic testing include measuring tension strength at a suitable laboratory for those mills without equipment to do tension tests. Samples of timber are also sent to an independent laboratory for strength and stiffness testing. The manual provided by SPIB does not specify the sampling intensity but the mills visited indicated a sample size of about 40 pieces every three months.

The PTC F-Grade MSG Accuracy Check Method used a simple "pass" or "fail" criteria on the basis of MoE_{min} and does not make use of CUSUM statistical control procedures. The MSG Accuracy Check Method has a normal prescribed sampling rate of 4 pieces in the first hour, 2 in the second hour and 1 per hour for the remainder of the shift. Two failures per week means the sampling level will have to be increased. The timber is only tested for stiffness (MoE) at the weakest point and failure only noted if the failure is repeated after rechecking the grade through the grading machine. The periodic monitoring is limited to a minimum sample of 100 boards, taken over any period during the year, but not over less than a fortnight.

6.2.4 Current PTC MSG Accuracy Check Method

The PTC MSG Accuracy Check Method is basically a dynamic machine control system with heavy reliance on control planks to ensure dynamic control. The PTC procedures are best compared against the draft ISO standards ISO CD 13912 and the draft European standards prEN 14081-1:2000, prEN 14081-2:2000, prEN 14081-3:2000 and prEN 14081-4:2000. The PTC standard uses timber for the control planks while the EN standard allows for both timber and manufactured control planks to cater for a wider range of sensing technologies. The use of control planks is not mandatory in prEN 14081-3:2000. The current PTC MSG Accuracy Check Method describes the method to select timber for use as a control plank.

6.2.5 Comparison with draft ISO standard

The draft ISO standard ISO CD 13912 has a specific repeatability test A.6.2 (i), a calibration test A.6.2 (ii) and a consistency test A.6.2 (iii), to detect problems of machines losing accuracy along the length of the board, but does not use control planks for these tests.

6.2.5.1 ISO CD 13912 A.6.2 (i) Machine Repeatability

At the start of each shift, one or more pieces of timber should be passed through the MSG 5 times, with the same leading edge and face directions used each time. For a conventional MSG machine, the range of the machine readings, measured at each data point on the timber and averaged along the length of the whole piece of timber, should not exceed 10% of the threshold grading modulus.

6.2.5.2 ISO CD 13912 A.6.2 (ii) Machine Calibration

For calibration purposes 5 pieces of timber shall be selected to cover the range of timber to be graded. The timber shall be selected to be reasonably straight and with well-defined strength reducing defects.

First each piece of timber is sent through the machine four times, each time with a different leading edge and face configuration. The criterion for acceptance is that the range of machine readings, measured at each data point, shall not exceed 20% of the threshold grading modulus for a stress grade under consideration.

Next the four scanner readings are averaged, and this averaged set of values is compared with an independent calibration at a few critical points. The calibration is made by comparison with a static measurement of the modulus of elasticity on flat at locations near the points of minimum grading moduli. The criterion for acceptance is that the minimum values obtained by the machine and the static test should not differ by more than 2% of the static value. This calibration procedure should be done every three months.

The calibration sticks should be passed through the machine at the commencement of every shift. The criterion for acceptance of an in-service calibration run is that the measured difference between the two sets of data at each point, averaged over the whole piece of timber, shall not differ by more than 15% of the minimum modulus of the stick.

6.2.5.3 ISO CD 13912 A.6.2 (iii) Machine Consistency

The procedure for undertaking a consistency check is to store the data obtained for 500 pieces of timber during a normal production run. The data from these 500 pieces are then averaged for each location at a specified distance from the leading end. The acceptance criterion is that the value obtained by averaging the ensemble averages for all locations shall have a range of not more than 20% of the average value.

The ISO procedure is similar to the PTC consistency check method, except PTC uses information from 100 sticks. The PTC MSG Accuracy Check Method may also have problems when used with machines such as the Tecmach where the air bags can allow the board to ride over the load sensor without applying the full load.

6.3 Summary of findings

Output controlled versus machine controlled[37]. Machine control was developed in the late 1960's due to the large number of sizes, species and grades used in Europe. Machine control relies on the machines being strictly assessed and controlled. The machine settings remain constant for all machines of the same type. Output control is suitable where the machines have repeated production runs of at least one shift. In output control timber is continuously taken from the production line and proof loaded. In Europe almost all timber-grading companies are using machine control, while in North America output control is used[38].

Research into dynamic machine control using manufactured control planks is being undertaken in Europe but this type of machine control is of little interest to USA mills and associated accrediting agencies..

The PTC system is a machine control system and reliant on regular dynamic tests, which includes the use of control planks, to verify that the machine remains under control. These types of machine control test procedures were originally developed for machines such as the Plessey Computermatic and the Eldeco Dart. Test procedures can be machine dependent as some machines, such as the Techmach (a two pass machine), have self-testing features.

Most of the larger sawmills in Australia use US manufactured Metriguard machines that were originally designed for output control, not machine control.

7 STRESS GRADING MACHINES

7.1 Relevance

Machine graders are used to sort timber into grade classes using a measurable predictor. Statistical Quality Assurance techniques are used to ensure that the graded timber will have the correct engineering properties associated with the grade. Mechanical stress grading machines rely on set up, calibration, sampling, testing and quality control systems to ensure the process is under control.

7.2 Review elements

7.2.1 General overview

Manufacturers such as Metriguard and Eldeco[39] manufacture testing equipment for use with machine stress graders. These test machines are use to periodically measure the stiffness and the strength of the timber produced.

The data recorded by a machine grader is processed so as to produce a sorting criterion used as a basis for defining a grade of timber. Böstrom and Holmqvist[40] have reviewed state-of-the-art

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[37] Holmqvist, C., G. Gaede, P. Joyet, L. Boström. 1999. Control and Calibration of Timber Strength Grading Machines. RILEM Symposium on Timber Engineering, Stockholm, Sweden, P.533-542.
[38] Boström, L. and C. Holmqvist, State-of-the-art on Machine Stress grading, RILEM Symposium on Timber Engineering, Stockholm, Sweden, P.513-522.
[39] www.eldeco.com
[40] Boström, L., and C. Holmqvist. Sate-of-the-art on Machine Stress Grading, SP Swedish National Testing and Research Institute, Sweden.

machine graders but their review does not include any hard data on the effect of different grading techniques on machine performance.

Machines are used to produce Machine Stress Rated (MSR) timber (or to E-rate timber) for laminating. Although the E-rated grades are obtained mechanically with many of the same devices used for machine stress grading, they are not "stress" grades because they do not require destructive tests for qualification of strength properties, only non-destructive tests to verify MoE[41]. Machine stress graded lumber is a traded commodity while E-rated grades are produced to meet the specific needs of laminators.

7.2.2 Types of machines

Some grading machines measure and sort lumber based on deflection over a short span, others measure over a short span but integrate the results over the entire length of the piece, other devices make one measurement over the entire length of the piece. As a consequence, both the manner in which the data are obtained and the manner in which they are analysed and reported by the device influence the relationship between the machine data, the specification, and the grade yield[42].

A variety of machines are available for mechanically grading timber. Some are production "in line" machines which can be fed directly from the dry mill planer. Other machines are "off line" operating at 3 to 10 boards per minute. This study is only concerned with "in line" machines.

The following types of new or second-hand[43] timber grading machines are available:

- Electromechanical measuring as a plank (MoE_{plank})
  - Continuous Lumber Tester CLT (Metriguard, USA)
  - Stress-O-Matic (Crow, USA)
  - Dart (Eldeco, Australia)
  - ESG (Ersson, Sweden)
  - Micromatic (MPC, England)
  - Computermatic (MPC, England)
  - Cook Bolinder (Techmac, England)
  - EuroGrecoMat
  - Raute Timgrader
- Electromechanical measuring as a joist ($LMoE_{joist}$)
  - E-Grader (New Zealand)
- Frequency response (MoE_{plank})
  - Transverse Vibration E (Metriguard, USA)
  - Dynagrade (Dynalyse, Sweden)
  - Dimter Grademaster
- Stress wave transmission time (LMoE)
  - Sylvatest
- X-Ray density profile (MoE_{plank})
  - X-Ray Lumber Gauge (Newnes)
  - Golden EYE (Microtec)

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[41] MoE = Modulus of Elasticity. Prefix L denotes long span test. A subscript p is added to indicate measured as a plank or j if measured as a joist.
[42] Galligan, W.L., and K.A. McDonald. 2000. Machine Grading of Lumber Practical Concerns for Lumber Producers, USDA Forest Service FPL-GTR-7. P.5
[43] Some machines listed may no longer be manufactured.

- Camera techniques, including tracheid effect
  - Dimter Grademaster
  - Ersson/Soliton
- Near-Infrared Reflection Spectroscopy (NIR)
  - No industrial systems
- Microwave (LMoE)
  - SpeedGrader (still experimental) (CSIRO, Australia)
  - Finograder (no longer on the market)

Machine stress graders can be used on their own, or be combined (e.g. Golden EYE X-Ray and laser tracheid or electromechanical Dart and microwave SpeedGrader), or be supplemented by visual grading. Often visual overrides are applied for part or all of the length of the timber to supplement the information obtained by the machine. Most standards for machine stress grading make provision for visual grading overrides but rely on output control to achieve the desired mechanical properties.

Over 95% all machine stress graders are based on the principle of flat-wise bending. Internationally the following machine stress graders are currently in commercial use[44]:

MACHINE MANUFACTURER	NUMBER OF MACHINES
Computermatic/Micromatic	153[45]
Cook Bolinder/Tecmach	66
CLT & HCLT	100+[46]
Dynagrade	30
Newnes XLG	25
Raute Timgrader (Mainly Finland)	19
Dart (Australia/New Zealand/Canada)	22[47] (*13 Australia, 4 NZ, 5 Canada)
Ersson ESG 240	8
EuroGrecomat (Mainly Germany)	6
"E" Grader (New Zealand/Australia)	5 (4 NZ, 1 Australia)
GradeMaster 403	5

Maintenance of the machine graders is of great importance and manufacturer recommendations must be followed at all times. Refer to Logan[48] for a general checklist.

7.2.3 New Machine Grading Systems

Boström compared four different MSG systems[49]. Because of the complexity of the interaction between these variables early machines such as the Finnograder, which used microwaves and gamma rays to grade timber, performed poorly predicting bending strength (r^2=0.34-0.55)

[44] Based on Johansson, Carl-John, Grading Timber with Respect to Mechanical Properties, Timber Engineering, Draft paper.
[45] Data supplied by Carol Calf. MPC.
[46] From Metriguard website. Manufacturer was contacted by no reply received.
[47] Manufacturer provided figures (*12 installed in Australia 1 on order).
[48] Logan, J.D. 1998. Quality Production of MSR Lumber and Grade Yield Optimisation, metriguard.www.metriguard.com.
[49] Boström, L. 1994: Machine Strength Grading, Comparison of Four Different Systems. Swedish National Testing and Research Institute, SP Report 1994:49.

compared to mechanical bending machines (r^2=0.51-0.73 for Cook-Bolinder[50] and r^2=0.41-0.62 for Computermatic).

New machine grading systems are currently being developed and are based on combining different sensing systems. For example CSIRO has developed a microwave system to be used in conjunction with the Eldeco Dart bending machine. A laser tracheid defect detection system has been added to the Ersson bending machine. Microtec[51] has developed an X-Ray and laser tracheid grade scanning system. Systems using sensors such as laser tracheid, X-Ray and microwave may be able to extract even more value from the available resource. According to a study by CSIRO[52] adding a microwave-sensing unit to a mechanical machine stress grader can increase recovery[53] by about 10 percentage points.

A number of systems to detect defects such as knots are available from suppliers such as Barr-Mullin, CAE-Newnes, Lucidyne, Luxscan, Innovative Vision and Microtec. The output from these machines can be used on their own, or combined with the signal from other machines, for grading purposes. These machines are normally not used for grading structural timber, as knot detection on its own does not provide a good measure of strength and stiffness.

Pre-sorting of logs into stiffness classes using resonant frequency or stress wave timing techniques can also help to improve grade yields. All these approaches are aimed at improving grade yields at high grading speeds.

7.2.4 Commercial Control Systems

Most machine stress graders have some form of data analysis and reporting system. Because of the limitations of the manufacturer supplied systems third-party control systems have been developed. For example Straightedge[54] has a product called Tadpole, a machine stress grading control system, and is marketing the system in Australia, New Zealand and the USA. Forintek[55] Canada has developed a MSR toolkit and datalogger, which is only available to their members. A similar system is being developed in Sweden but no details were available.

7.2.5 Factors That Can Effect Grading Machine Performance

Mechanical machine stress graders are relatively simple bending machines, however getting accurate results at speed can be a problem. The following are some of the problems identified in the literature reviewed:

- **Beam depth**. According to Perstorper[56] bending machines such as the Cook Bolinder underestimate the edgewise bending strength and stiffness of large dimension timber
- **Constant Force versus Constant Deflection**. According to Samson[57] feed speeds range from 50 to 150m/min for constant force machines to 250 to 400m/min for constant deflection

[50] Now sold as Tecmach.
[51] www.microtec.org.
[52] New Electronic Timber Grading - by Microwave, Press Release 8 June 2001; Ref: 2001/142 #19, 2001. CSIRO Built Environment, CSIRO. www.dbce.csiro.au
[53] 5-percentile strength.
[54] www.**straightedge**solutions.com
[55] Mill Product News, July/August 2002 p.25. www.forintek.ca/public/Eng/E5-Pub_Software/7.software.html
[56] Perstorper, M., 1994. Dynamic modal tests of timber evaluation according to the Euler and Timoshenko theories. Ninth International Symposium on Nondestructive Testing of Wood.

machines. Sampson found that, for constant deflection stress-grading machines, speeds up to 315m/min has no effect on the average E measured by the machine, but effects E values measured at individual locations on the timber. The error due to speed arises from the load mechanism, which is set into vibration on feeding the timber. This noise in the load signal can be filtered using a low-pass filter.

- **Feedspeed**. In a comparison study of four different machine strength grading systems[58] the test speeds for the Cook-Bolinder[59] and Computermatic[60] were limited to 50m/min "in order to minimise the dynamic effects due to vibrations and swinging of the timber". The frequency of noise generated by the feed mechanism varies with machine speed[61].
- **Kinks**. Kinks can cause errors and Logan[62] describes how the CLT eliminates problems due to kinks.
- **Length of free end of the specimen outside the machine span**. Pope reported that low frequency signals, around 5-10 Hz, were generated by overhang and the frequency increased rapidly as the overhang decreased.
- **Machine control versus output control**. According to Smith[63] Machine Controlled Stress Grading was developed to provide quality control in situations where many different species, grades and sizes are graded. It is also suitable where the resource is constantly changing due to silviculture or changes in harvesting location. Smith concluded that machine control can be adequate and there was "*no need for North American producers of machine stress graded lumber to retain an output controlled system of quality control*."
- **Rate of loading on the strength of wood**[64]. In universal testing machines the timber is loaded at a fairly slow rate but if the loading rate is increased the measured strength can be increased by up to 20%. This may be due to the "reaction time" for wood to respond to stress.
- **Signal filtering**. Signal filters can be used to improve the signal quality but according to Pope[65] the cut off frequency must be carefully determined taking into account the feed speed and defect resolution required.
- **Surface roughness**. Surface roughness due to sawcuts or uneven profiles[66] can generate high frequency noise, which can be removed by filtering.

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[57] Samson, M. and B. Huot, 1989. Machine Stress-rating nonuniform Lumber at High Speed. In Proceedings 7th International Nondestructive Testing of Wood Symposium, Washington State University. 1989.
[58] Boström, L. 1994: Machine Strength Grading, Comparison of Four Different Systems. Swedish National Testing and Research Institute, SP Report 1994:49.
[59] Normal grading speed 60-100m/min
[60] Normal grading speed 60-100m/min
[61] Pope, D.J. and F.W. Matthews, 1999. The application of signal filters to timber stress grading machine output, Journal of the Institute of Wood Science, 15(1). p.7.
[62] Logan, J.D. 1978. 4th Nondestructive testing of wood symposium, Washington State University. P.285-303.
[63] Smith, I. 1989. A Direct Derivation of Machine Settings in Machine Controlled Stress Grading of Softwood Lumber. In Proceedings 7th International Nondestructive Testing of Wood Symposium, Washington State University. 1989.
[64] Markwart, L.J. and J.A. Liska, 1955. The influence of rate of loading on the strength of wood and wood-based materials.p.3-18. In Symposium on Speed of Testing of Non-Metalic Materials, ASTM No 185.
[65] Pope, D.J. and F.W. Matthews, 1999. The application of signal filters to timber stress grading machine output, Journal of the Institute of Wood Science, 15(1). pp.6-13.
[66] Pope, D.J. and F.W. Matthews, 1999. The application of signal filters to timber stress grading machine output, Journal of the Institute of Wood Science, 15(1). pp.6-13.

- **Twist**. Twist can cause errors in machine stress grading. Samson investigated the effect of twist[67] and concluded "*bending type grading machines tend to overestimate the MoE of timber containing twist*". At the allowable twist limit[68] the overestimation of MoE was 10%.
- **Vibration.** Samson[69] investigated the effect of vibration and speed on the accuracy of constant deflection grading machines. The vibrations set up in the timber induce noise on the load signal, but filtering the load signal can eliminate this noise. The Metriguard[70] high-speed machine stress graders have two bending zones and the second bending zone includes a vibration sensor to compensate for measuring errors due to vibrations. The work by Nayroles[71] showed that the dominant vibration mode and frequency vary with specimen position within the machine.
- **Warp (bow)**. Warp can amount to 50% increase or decrease in strength applied (typical range 0-20%). To overcome the problems with bow the Cook Bolinder machine requires two passes, the Plessey Computermatic has a warp-measuring arm and the Metriguard machines bend timber in both directions.

7.2.5.1 Effect of Wood Properties

The mechanical properties of wood are related to species, moisture content, defects such as knots and associated slope of grain, grain angle, compression-wood and micro-fibril angle.
Timber species being graded in the US and Europe generally have different and inherently less variable mechanical properties than those encountered in Australian grown pine species.

Because the strength and stiffness of timber is influenced by hard to measure variables such as micro-fibril angle, machines that measure the stiffness of the timber have remained the mainstay of the industry. The mechanical properties of radiata pine compared to Northern Hemisphere species was reviewed by Kininmonth[72].

7.3 Summary of findings

The type of machine used, its associated quality control system, and the variability in the mechanical properties of the timber being graded all have a direct influence on the quality and quantity of grade yields. The capabilities of each machine in terms of its ability to accurately predict stiffness needs to be taken into account when defining limits for accuracy checking.

Although many different sensing systems have been developed the basic bending machines remain the preferred industry workhorses. The main reason for the lack of success by

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[67] Samson, M., I. Bindzi and M. Fafard, 1993. Errors caused by twist in machine stress rating of lumber, in 9th International Symposium on Nondestructive Testing of Wood, Madison. P.151-156.
[68] Angle of twist 3.5 degrees per metre. Samson, M., I. Bindzi and M. Fafard, 1993. Errors caused by twist in machine stress rating of lumber, in 9th International Symposium on Nondestructive Testing of Wood, Madison. P.153.
[69] Samson, M. and B. Huot, 1989. Machine Stress-rating non-uniform Lumber at High Speed. In Proceedings 7th International Nondestructive Testing of Wood Symposium, Washington State University. 1989.
[70] Metriguard produces two models (CLT and HCLT) and grading speeds can be in excess of 450m/min.
[71] Nayroles, B. !997. A dynamic analysis of a bending test used in the lumber industry. European Journal Mechanical. A/Solids 16 (4). pp 619-644.
[72] Kininmonth, J. A. and L. J. Whitehouse, 1991. The Properties and Uses of New Zealand Radiata Pine, Ministry of Forestry, Rotorua.

technologies such as X-Ray or microwaves is their high cost relative to simple bending machines and the inability of these types of technologies to adequately deal with the complex structure of wood in relation to stiffness.

8 RELIABILITY OF TIMBER STRUCTURES

8.1 Relevance

The demand for MSG timber is driven by the need to improve the reliability of timber structures. This reliability is based on timber being accurately graded as fit for end use purpose. The Accuracy Check method is designed to both ensure that the mill is accurately producing timber that consistently meets the required standard as well as assuring the buying public that the timber consistently meets the specified standard. This section was included to reiterate the importance of accurate machine stress grading in retaining the ongoing reputation of MGP as a structurally reliability fit for purpose product in the market place.

8.2 Review elements

Safety factors in building codes are traditionally based on long-term experience using partial safety factors. An alternative is the use of statistical evaluation based on probabilistic reliability theory. The Joint Committee on Structural Safety[73] is currently developing an international model code for probability-based assessment and design of structures.

According to the theory of limit state design structures and structural elements shall be designed, constructed and maintained in such a way that they are suited for their use during the design working life and in an economic way[74]. In particular they shall, with appropriate levels of reliability, fulfil the following requirements:

- Remain fit for the use for which they are required (serviceability limit state requirement)
- Withstand extreme actions (ultimate limit state requirement)
- Shall not be damaged by accidental events (robustness requirement)

Timber structures are designed using limit states design values which, in most cases, are based on a mean return period of 50 years. Material strength is represented by a characteristic value defined as the 5% fractile value. The structural stiffness parameters are represented by a mean value.

Methods to determine the 5% fractile value has been researched by Rantu-Maunus[75] and other and they compared tail fitting models using the following distribution functions:

- Lognormal distribution
- Two-parameter Weibull
- Three-parameter Weibull

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[73] Vrouwenvelder, 2001, in: Ranta-Maunus, A., M. Fonselius, J. Kurkela and T. Toratti. 2001. Reliability Analysis of TimberStructures. VTT Technical research Centre of Finland, Meddelanden. Research Notes 2109.p.101.
[74] Joint Committee on Structural Safety, Probabilistic Model Code, Part 1 Basis of Design. JCCC-OSTL/DIA/VROU-10-11-2000 12th draft.
[75] Ranta-Maunus, A., M. Fonselius, J. Kurkela and T. Toratti. 2001. Reliability Analysis of TimberStructures. VTT Technical research Centre of Finland, Meddelanden. Research Notes 2109.p.101.

Standardised methods for the correlation of characteristic 5% fractile values[76] are described ISO 12491[77] (a material-independent standard in which general principles for the application of statistical methods to be used in quality control are given), Eurocode 1 (Section 5, part 1), Eurocode 5, EN TC 124.bb[78], EN 384[79], ASTM D2915[80]. Refer to Rantu-Maunus p.65-69 for a discussion and case studies. The relevant Australian standard is AS 1170.

The coefficient of variation (V) for bending strength of wood range from about 0.20 to 0.40 compared to 0.05 for steel and this affects the safety factors used. V is determined by the grading method used and is higher for visual grading than for machine grading. V also depends on the type of machine grader used.

The report by Sørensen and Hoffmeyer[81] describes the statistical analysis performed to determine material strength parameters as part of a European investigation into the reliability of timber structures. The paper describes the statistical distributions used (Normal distribution, 2-parameter Weibull and 3-parameter Weibull); parameter estimation using the Maximum Likelihood Method (MLM) and the Least Squares Technique (LST); reliability aspects to determine the characteristic values using partial safety factors. The report concluded that it is reasonable to introduce different partial safety factors for bending, tension and compression strength.

The timber standards and grading policies are based on meeting the needs of the building codes, and these codes are being harmonised through various standards committees.

8.3 Summary of findings

Building codes in relation to structural use of timber are based on the engineering properties of timber. Designers, engineers and certifiers depend on the timber they use having the correct engineering properties for specific end uses. The material strength of timber is represented by a characteristic value defined as the 5% fractile value. The structural stiffness parameters are represented by a mean value. Mechanical machine graders measure only stiffness and derive the strength values from a correlation between stiffness and strength. Periodic product strength and stiffness testing is required to verify the ability of a machine to accurately measure timber stiffness.

9 INFLUENCE OF STANDARDS AND GRADING POLICIES

9.1 Relevance

This section reviews the relevant machine stress grading standards, including draft ISO and EN standards. This section was included as standards and grading policy reflect the current and future thinking of Australasian and International MSG policy makers.

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[76] A confidence level of 75% are used for the 5% fractile value.
[77] ISO 12491:1997. Statistical methods for quality control of building materials and components.
[78] EN TC 124.bb 2000. Structural timber-Test Methods- Calculation of characteristic 5-percentile value. Working draft December 2000.
[79] EN 384:1995. Structural timber-determination of characteristic values of mechanical properties of wood based materials.
[80] ASTM D2915:1994. Standard practice for evaluating allowable properties for grades of structural lumber.
[81] Sørensen, J.D. and P. Hoffmeyer, Statistical Analysis of Data for Timber Strengths, Aalborg University and Technical University of Denmark.

9.2 Review elements

9.2.1 New Standards

The most recent standard is the draft ISO standard (ISO/TC 165N232 rev 2000-05-19), to be accepted, before the end of 2003[82]. The original ISO standard was based on EN 348, EN 408 and EN 1193. The proposed new ISO standard gave consideration to ASTM D198, D1990 and D4761 and other North American standards and practices, and also to the Australia/New Zealand Standard AS/NZS 4063.

The proposed new ISO standard has been specifically expanded so that the requirements are applicable to all timber stress-graded by any method. The draft ISO standard (ISO CD 13912) has been expanded to cover grading of all species of timber and grading by any type of grading machine. The standards are concerned with the outcomes, and the monitoring of the process to ensure performance standards are maintained.

The creation of a common European market has resulted in standardised design rules for timber structures. The new Eurocode 5 calls for structural timber to be strength graded. A set of common strength classes has been introduced through EN338. Standard EN519 deals with the requirements for machine strength graded timber and grading machines.

In the proposed new ISO standard[83] (ISO CD 13912) quality control related to the grading operation is undertaken by placing checks on the following four components:

1. Resource input. Timber species log source, silviculture and cutting pattern.
2. Machine operation[84]. In addition to ensuring that the machine has been set up as specified by the machine manufacturer, the repeatability, calibration and consistency shall be checked.
3. Visual override. Relates to edge knots, shakes and through splits. Unscanned end lengths may be visually graded. This is important to include ungraded ends and to exclude strength limiting defects such as large knots.
4. Quality of the output grades. Initial, periodic and daily procedures are prescribed in the proposed ISO standard and are similar to those prescribed in AS/NZS 4063:1992 and AS/NZS 4490:1997. The recommended AQ procedures differ in detail and CUSUM constants and rules have been revised in ISO CD 13912.

The study tour revealed that the following standards appear to be driving the future of International machine stress grading:

1. USA PS 20-99 American Softwood Lumber Standard[85]. This standard provides for the setting up of the American Lumber Standards Committee (ALSC), which reports to the National Bureau of Standards. Implementation is through agencies such as Southern Pine Inspection Bureau (SPIB). Each agency publishes grading rules such as Standard Grading

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[82] Dave Barrett, personal communication indicated that it was scheduled for 2002, but is now most likely to be tabled at the next meeting of the ISO committee scheduled for September 2003.
[83] This is a draft standard, and as such has yet to be agreed to by the participating members.
[84] ISO CD 13912 #A.6.2 .
[85] U.S. Department of Commerce, National Institute of Standards and Technology, Voluntary Product Standard PS 20-99.

Rules for Southern Pine Lumber 1994 with supplements. The American Lumber Standards Committee published a Machine Graded Lumber Policy in November 1998. This document describes the agency requirements for mill quality control. The agencies shall require facilities that machine grade lumber to conduct daily quality control of machine graded output. As a minimum, the quality control shall include the following components:

- Offline measurement of MoE.
- Offline strength testing by proof testing.
- Verification of daily test results.
- Procedures for regrading of lumber identified as non-conforming.
- Periodic tests to check lumber output. Semi-annual tests are adequate where CUSUM quality control is used. For machine stress rated lumber, lumber must be tested for both MoE and MoR on edge or MoE and UTS.

2. CANADA. ISO CD 13910. *STRUCTURAL TIMBER-- SAMPLING, TESTING, AND EVALUATION OF THE CHARACTERISTIC VALUES OF STRENGTH-GRADED TIMBER*, (Draft 19-5-2000), and ISO CD 13912 STRUCTURAL TIMBER-GRADING-*REQUIREMENTS FOR MACHINE GRADED TIMBER*, (Draft 19-5-2000),

3. ENGLAND BS EN 338:1995 Structural Timber Strength Classes and BS EN 519:1995 Structural Timber-Grading-Requirements for machine strength graded timber and grading machines. Other relevant standards are BS EN 336:1995, BS EN 338:1995, BS 5268-Part 2:1986 and ISO 9003:1994. The UK Timber Grading Committee operates through the Timber trade Federation and they have appointed a Technical Committee to:

   - Advise as to the acceptability of new machine applications.
   - Confirm or advise as to the acceptability of new machine settings.
   - Confirm or advise on the acceptability of control plank designs.

4. EUROPE[86] prEN 14081-1 Timber Structures-Strength graded structural timber. Part 1 General Requirements, prEN 14081-2 Part 2 Machine Grading-Additional requirements for initial type setting, prEN 14081-2 Part 3 Machine Grading-Additional requirements for factory production control, prEN 14081-2 Part 4 Machine Grading-Grading machine settings for machine controlled systems. In England these standards will replace BS EN 519:1995 Structural Timber-Grading-Requirements for machine strength graded timber and grading machines.

5. AUSTRALIA/NEW ZEALAND AS/NZS 4063:1992 Timber-Stress Graded-In-grade strength and stiffness evaluation, AS/NZS 4490:1997 Timber-Stress Graded-Procedures for monitoring structural properties, AS/NZS 1748:1997 Timber-Stress Graded-Product requirements for mechanically stress graded timber. Australia and New Zealand will most likely adopt the ISO system. All these draft standards are currently under review. AS/NZS 1748:1997 discusses quality control but its clauses are not mandatory.

6. AUSTRALIA PTC Product Certification Manual Section 3 Structural products MGP grades, Section 4 Structural products F-Grades.

[86] Europe includes Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.

The ISO CD and prEN are draft standards and due for ratification within the next 12 months. The UK Timber Grading Committee Guidelines for Approved Certification Bodies provides a comprehensive list of British Standards.

9.2.2 ISO Standards

Two draft ISO standards (ISO CD 13912[87] and ISO CD 13910[88]) describing the requirements for machine-graded timber is currently available.

ISO CD 13910 was based on the European Standards EN 384, EN 408 and EN 1193. Consideration was also given to ASTM D198, D1990 and D 4761 and AS/NZS 4063.

In ISO CD 13912 quality control related to the grading operation is undertaken by placing checks on the following four components:

- Resource input.
- Machine operation.
- Visual override.
- Quality of the output grades.

In theory it should be possible to control quality by either: control of the resource input and the machine operation, or by checks on the quality of the output grades. Because of the variability and complexity of timber it is recommended in the standard that all four sections of a grading operation be subjected to checks and controls.

The standard is very detailed with instructions for:

- Initial Evaluation,
- Periodic Evaluations, and
- Daily Evaluations.

ISO CD 13912, Annex A.1, describes the use of the CUSUM procedure for daily evaluations.

9.2.3 AS/NZS Standards

In AS/NZS 4490:1997[89]and AS/NZS 4063:1992[90] quality control related to the grading operation is undertaken by placing checks on the following three components:

- Resource input.
- Machine operation.
- Quality of the output grades.

Appendix A of AS/NZS 4490:1997 describes a monitoring procedure by measurement of modulus of elasticity.
The sample size is given by:

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[87] ISO CD 13912. STRUCTURAL TIMBER-GRADING-*REQUIREMENTS FOR MACHINE GRADED TIMBER*, Draft No 5 (rev 2000-05-19)
[88] ISO CD 13910. STRUCTURAL TIMBER-SAMPLING, TESTING, AND EVALUATION OF THE CHARACTERISTIC VALUES OF STRENGTH GRADED TIMBER, Draft (rev 2000-05-19)
[89] AS/NZS 4490:1997 Timber-Stress-graded-Procedures for monitoring structural properties
[90] AS/NZS 4063:1992 Timber-Stress-graded-In-grade strength and stiffness evaluation

$N=400v^2$
Where: v is the coefficient of variation of the modulus of elasticity.
The recommended sampling rate is a minimum of 1 in 10,000 or a recommended 1 in 1,000 if tighter control is required.

The acceptance criterion is:
$E_{mean, data} > 0.94\ E_{mean, target}$
Where: $E_{mean, target}$ denotes the target mean value of modulus of elasticity.

Appendix B of AS/NZS 4490:1997 describes a monitoring procedure by measurement of modulus of elasticity.
The sample size is given by:
$N= 1,000v^2$
Where: v is the coefficient of variation of bending strength.
The recommended sampling rate is a minimum of 1 in 10,000 or a recommended 1 in 1,000 if tighter control is required.

The acceptance criterion is:
$B_{0.05, data} > 0.91\ B_{0.05, target}$
Where: $B_{0.05, data}$ denotes the target value of the five-percentile bending strength initially determined for the population.

A cumulative frequency procedure for fitting the data to determine the five-percentile value is given in Appendix B.

Appendix C of AS/NZS 4490:1997 describes a monitoring procedure by measurement of tension strength. Appendix D of AS/NZS 4490:1997 describes a monitoring procedure by a proof testing machine.

9.2.4 Overseas approaches to periodic evaluation - calibration and consistency checks

ISO CD 13912 §A.6.2(i) calls for the machine grader to be calibrated every three months.

- Calibration by selecting 5 pieces of timber selected to cover the range of timber to be graded. Each piece shall be passed through four times, each time with a different leading edge and face configuration. The criterion for acceptance is that the range of machine readings, measured at each data point on the timber and averaged along the whole piece of timber, shall not exceed 20% of the threshold grading modulus for stress grade under consideration. Next the four scanner readings are averaged, and this averaged set of values compared with an independent calibration at a few critical points. The criterion of acceptance is that the minimum values obtained by the machine and by the static test should not differ by more than 2% of the static value.

- Consistency checks involve storing the data from 500 pieces of timber during a normal production run. The data from the 500 pieces are averaged at each location. The acceptance criterion is that the value obtained by averaging the ensemble averages for all locations shall have a range of not more than 20% of the average value.

- At a sampling rate of 1 in 10,000 (1in 1,000 for tight control) timber is to be tested to measure bending strength and modulus of elasticity.

None of the grading inspection agencies visited currently required a calibration or consistency test as prescribed in the draft ISO standard. The Overseas mills visited generally did not see a need for these tests particularly expressing concern that the test would not work in some areas, eg. timber from logs with severe butt swell.

Mills using output control undertook periodic evaluation by sampled 5 pieces every 4 hours. This is close to a sampling rate of 1 in 2,000 for mills with high speed grading machines. Because of the low percentage of pieces being accepted (under 5% of production) at the two mills visited the actual sampling rate of accepted timber is closer to 1 in 200.

9.2.5 Daily Procedures - continuos monitoring and repeatability

The details of the continuous monitoring programs are not prescribed in any of the standards. AS/NZS 4490:1997 reads “Continuous monitoring is a program carried out on a daily, shift or batch basis. As the actual procedures depend on the production system in use, this Standard cannot provide specific requirements for continuous monitoring”. The machine manufacturers and the Inspection Agencies normally determine the details of the required daily procedures.

The proposed draft standard ISO CD 13912 §A.6.2(i) Calls for:

- Repeatability test at the beginning of each shift where one or more pieces of timber is passed through 5 times with the same leading edge. For conventional grading machines, the range of machine readings, measured at each data point on the timber and averaged along the whole piece of timber, should not exceed 10% of the threshold grading modulus.

- The control planks described in the previous section are passed through the machine once per shift. The criterion of acceptance is that the measured difference between the two sets of data at each point, averaged over the whole piece of timber, should not differ by more than 15% of the minimum modulus of the stick.

- A CUSUM procedure using a sample size of 5 pieces per shift is described with a worked example in an informative Annex A.1.

9.3 Summary of findings

The draft ISO standard (ISO CD 13912) has been expanded to cover grading of all species of timber and grading by any type of grading machine. Standards are tending to put more focus on the quality of the outcomes including monitoring of the process to ensure performance standards are maintained.

Any enhancement and or redevelopment of PTC's Accuracy Check methods will need to take account of potential changes in standards particularly if the draft ISO standard is ratified for use in Australia. Although the majority of Australia's MSG product is currently sold on the internal domestic market any move to export of structural sawn timber will need to encompass compliance with overseas standards. As such any accuracy checking procedures need to be flexible enough to adapt to the potential different requirements of export markets.

10 OVERVIEW OF OVERSEAS MSG CONTROL SYSTEMS

10.1 Relevance

The literature review revealed that MSG control systems similar to PTC's Dynamic machine control are not generally used outside of Australia. It was therefore considered relevant to review overseas control procedures to ascertain why Dynamic machine control was not favoured as well as outline the differences between PTC's control methodology and the different control systems being used overseas.

10.2 Review elements

Two control systems, known as "machine control" and "output control" are used for machine stress grading. Machine control is described as process control and output control is described as acceptance sampling in statistical quality control textbooks.

According to the literature reviewed output control is normally used in the USA and machine control in Europe. In the view of the authors this distinction between machine control and output control is not as clear-cut as often assumed. In the USA the set-up of the machines are strictly controlled by the inspection agency and the users have limited scope for adjustment (a maximum of 3% upward adjustment) before the system parameters must be re-evaluated. The Southern Pine Inspection Bureau (SPIB) requires output to be sampled every 4 hours and tested for stiffness by measuring the modulus of elasticity (MoE) and proof loaded to determine the strength by measuring the modulus of rupture (MoR). In Europe the machines are set up as specified and the machine settings are fixed for all machines of a type. From time to time timber from the market is sampled and tested to monitor the output quality.

A European project team working with the SP Swedish National Testing and Research Institute did a detailed review of control systems for machine stress graders[91]. The report reviewed machine control and output control systems.

10.2.1 Review of Machine Control

In machine-controlled systems the machines are evaluated and suitable settings determined for each timber type, grade and dimensions graded. The system relies on machines being strictly assessed and controlled, using machine settings which remain constant for all machines of the same type. Derivation of the machine settings plays a very central role in this system. According to Johansson[92] at least three different procedures have been used in Europe and Rouger[93] proposed a new approach.

Traditional machine stress graders relied on bending the timber and measuring the force (constant deflection machine) or measuring the deflection (constant force machine) to determine the stiffness at regular intervals along the length of the timber. New machines using different techniques and multiple sensors are now becoming commercially available and require some system of dynamic control to ensure the machine remains in control.

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[91] Boström, L., V. Enjily, G. Gaede, P.Gloss, C. Holland, C. Holmqvist, P. Joyet. 2000. Control of Timber Strength Grading Machines, SMT4-CT97-2207, SP Report 2000:11, Borås, Sweden.
[92] Johansson, Carl-John, Grading Timber with Respect to Mechanical Properties, Timber Engineering, Draft paper.
[93] Rouger, F. 1997. A new statistical method for the establishment of machine settings, Proceedings of the Timber Engineering Conference, Rotorua, New Zealand.

There are two ways to achieve machine control, Static control and Dynamic control.

In static control each input is measured independently to show the input is correct and within accepted tolerances. The accuracy of the output may also be displayed. The static control does not reveal any of the dynamic interactions caused by factors such as vibration.

To achieve dynamic control, control planks have been proposed. The function of the control plank is to reveal unsafe conditions of the machine. Ideally one pass of the control plank should be sufficient to decide whether the machine is in-control. In some cases more than one control plank may be required to cover a spectrum of input/output ranges.

In both cases visual overrides are normally applied to defects in the un-graded ends of the timber or along the whole length of the boards if high strength is required.

The USA mills generally do not report any problems with the output control system but the two mills visited recover less than 5% of their production as machine graded lumber. They also apply strict visual grading rules to the full length of each piece, which effectively halves the machine grade yield from about 10% to less than 5% of production. Both mills visited produced only one machine stress grade, although one of the mills tried to produce two grades but found it too difficult to apply the visual grading rules to two machine stress grades. In Europe the mills recover a high and low machine stress grade (typically TR26 and C16) and try and recover 80% or more as machine graded lumber with the visual downgrading mainly due to distortion. In Europe mills often produce two or more machine stress grades[94].

The European grading rules include machine settings for pairs of grades that can be produced simultaneously.

The study tour confirmed that when producing high performance machine stress grades, as done by the USA mills visited, the critical characteristic is that the inherent strength and the mean modulus of elasticity of the timber being graded is often well above the required standards. The result of the CUSUM for strength (MoR) is sensitive to knots, which is essentially controlled by the visual overrides. If the product produced is a lower grade, such as C16, as produced by the mills visited in Ireland and Sweden, the critical characteristic will be stiffness (MoE) and the strength will not cause any grading problems.

If several grades are graded simultaneously the modulus of elasticity may be the critical property for the lower grade and the strength the critical property for the higher grade. In Sweden mills often produce TR26 (a high quality timber grade for roof trusses) and C16 a framing (carcassing) grade.

Currently none of the agencies visited require a repeatability test. Metriguard produced a Metriguard Repeatability Programme[95] in which 32 pieces are passed through the machine twice while recording Low-point E and average E but this is not a daily test as the data must be sent to Metriguard for analysis.

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[94] These observations were backed by information provided by the mills visited but because of the small number of mills visited the observations may not be representative of what happens in the industry in general.

[95] Logan, J.D. 1991. Introduction: Repeatability Measurements in the CLT Continuous Lumber Tester, Metriguard Inc. Pullman, WA, USA.

10.2.2 Use of Control Planks

Control planks are only being used in Australia, New Zealand and Germany (for high grades only). None of the mills visited in the USA, Ireland, England or Sweden[96] used control planks. Use of control planks is however specified in Annex B of the draft prEN 14081-3 standard. The provisions in the draft EN machine stress grade standards are important because it reflects the current views of the expert panels responsible for the standards. These expert panels are aware of the benefits of control planks but are also concerned with issues such as obtaining an acceptable service life from control planks and containing costs.

10.2.3 Review of Output Control

Output control is used in countries such as USA, Canada, Australia, New Zealand and Japan and relies on a statistical process[97], which includes strength and stiffness information from daily sampling tests. The output control system balances customer's risk against producers risk.
In output controlled systems the graded timber is regularly sampled and the sampled timber tested to determine the modulus of elasticity (MoE) and proof-loaded. Two control charts are used, an attribute CUSUM chart for the modulus of rupture (MoR) and a variable CUSUM chart for the modulus of elasticity (MoE). The Southern Pine Inspection Bureau requires a sample of 5 pieces to be randomly chosen every four hours and proof loaded to a value proportional to the allowable stress. EN 519 requires 10 specimens from each strength class to be sampled per working shift and tested in edgewise bending and proof loaded. These procedures allow the MoE to be measured (variables[98]) and the strength is monitored through the occurrence of failures (attributes[99]).

An issue with output controlled machine stress grading is the time it takes before an out of control situation is detected. This is of particular concern where strength (modulus of rupture) is the critical property and attributes charts are used (pass-fail the proof load). For species and grade combinations where the stiffness (modulus of elasticity) is the critical property the variables chart is used and this generally gives a much faster response than the attributes chart.

At the mills visited using output control it took about 30 to 60 minutes per shift to sample and test 5 pieces of timber every 4 hours. None of the mills visited had any recent out of control experiences.

10.2.4 Use of Control Charts

The CUSUM technique is associated with output control systems as used in the USA. It appears that the CUSUM approach described in ISO CD 13912 is quite different from the procedure used in the USA. In ISO CD 13912 the CUSUM control constants K, Y and Z are based on the sample size (n=5, 10 or 20) and coefficient of variation (V) ranging from 0.05 to 0.5. The SPIB CUSUM constants, X,Y,Z are based on the grade E in psi.

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[96] The Dynagrade uses two control planks with a known frequency for calibration purposes.
[97] Systems such as Tadpole™ by Straightedge have been installed in sawmills in Australia and New Zealand and marketed in the USA. The authors do not know how many companies actually use the statistical techniques available to them. The SPIB procedures include CUSUM calculations.
[98] A single measurable quality characteristic, such as a dimension, weight or volume is called a variable.
[99] "Conforming" or "non-conforming" quality characteristics are called attributes.

Under certain circumstances the CUSUM technique used for output control can be too slow to show an out-of-control situation and a procedure using control planks may be preferred. Investigations have shown that the CUSUM technique is very sensitive to the distribution of strength and stiffness distributions. The CUSUM technique can work well for some species with a change in timber quality being detected within two shifts.

The SPIB calls for all production machines to be calibrated at the beginning of each production shift and after 4 hours of machine operation. This also involves daily calibration of the quality assurance proof loader. The mills visited in the USA estimated that machine calibration, including cleaning and inspection took about 15-30 minutes every 4 hours. Sampling, measuring moisture content, loading timber into the test machine, testing 5 pieces for MoE and proof loading was timed at about 4 to 6 minutes per piece or 20 to 30 minutes for every 4 hours of production. For large dimension timber two persons were required to handle the timber. Entering data and calculating the CUSUM values took about 10 minutes per occasion. Total time required to do machine calibration and output control was about 2 hours per shift. If the process goes out of control and intensive sampling is required it can become a full time job for one or two persons.

Because of the diversity of machine stress grading techniques it is highly likely that output control will be generally accepted for all high volume grades and dimensions and the CUSUM technique will be the preferred method of statistical control of stiffness and strength.

10.2.5 Non-conforming product

The SPIB provides a detailed flow chart where all production is represented by an out of control situation is held pending confirmation tests.

Neither of the two mills using output control had any experience with out of control caused by the machine stress graders. The visual grading requirements meant control was usually lost due to human error applying the visual grading rules. The SPIB distorted grain rules for knots away from the edge appear to be difficult to apply under commercial conditions and the one mill said it tried to produce two MSG grades simultaneously but found that the visual graders found it difficult to apply visual overrides to two MSG grades.

10.2.6 Corrective action

The SPIB rules allow the mill to increase the machine setting by up to 3% during an out-of-control situation, but if more than 3% adjustment is required production of that grade must stop until it can be re-qualified.

10.3 Summary of findings

Quality control related to the grading operation is undertaken by placing checks on the following four components; resource input, machine operation, visual override and quality of the output grades. In theory it should be possible to control quality by either: control of the resource input and the machine operation (machine control), or by checks on the quality of the output grades (output control). Because of the variability and complexity of timber all four components of a grading operation should be subjected to checks and controls.

Output control systems generally give a higher-grade yield than machine control systems. To some extent this outcome is expected due to the fact that their use and design is based on controlling output from generally localised resource with relatively homogenous engineering properties.

None of the overseas mills visited used control planks for dynamic machine control. Their control procedures were geared to meet the needs of their markets and they often had strict visual overrides associated with the machine grading operation. Dynamic machine control, using control planks, is not used because it is not in general use overseas as these techniques are still under development and development of a single calibration stick specification is difficult given the wide range of machine types in use.

11 CURRENT OVERSEAS RESEARCH

11.1 Relevance

Although Australian MSG R&D has resulted in some world leading developments the Literature review uncovered a number of overseas R&D projects of direct relevance to MSG in general and the accuracy of the process in particular. MSG R&D is ongoing in a number of countries and although Australia has had a long history of R&D in the area of MSG, it would be short sighted to overlook overseas R&D based on "not invented here" therefore not relevant.

11.2 Review elements

The most significant current research project is a European project called CONGRAD[100] (Control and Calibration of Timber Grading Machines). According to Boström and Holmqvist[101] the objectives of the CONGRAD project are to develop methods and calibration tools for different machine types and to further develop statistical procedures for output control.

The CONGRAD project includes investigations into the

- use of control planks. The intention is to suggest design principles for long life (500+ cycles) control planks and
- performance of CUSUM control charts for attributes and variables and the procedure described in the standard EN519, where both attributes and variables CUSUM charts are used.

Picardo[102] investigated the effect of feed speed on machine grading. Timber was passed through a Cook-Bolinder at 50 and 100 m/min. The values at the higher speed were closer to the static values than at the slower speed, but the study sample was not large enough to establish that the correlation with strength properties were better at the higher speed.

[100] Holmqvist, C., G. Gaede, P. Joyet, L. Boström. 1999. Control and Calibration of Timber Strength Grading Machines. RILEM Symposium on Timber Engineering, Stockholm, Sweden, P.533-542.
[101] Boström, L. and C. Holmqvist, State-of-the-art on Machine Strength Grading, SP Swedish National Testing and Research Institute, Sweden.
[102] Picardo, Valez, Consumer Products, Timber and Furniture Dept.
Enterprise Ireland,Glasnevin, Dublin 9, IRELAND. Unpublished report. FORBAIRT project number 96101.

Holmqvist[103] reviewed the control and calibration of Timber strength grading machines. The report deals with the requirements for control planks so that machines can be dynamically calibrated and controlled, and the suitability of the Shewhart control chart, the cumulative sum (CUSUM) and exponentially weighted moving average (EWMA) chart.

The different control charts used for output control are the Shewhart control chart, the cumulative sum (CUSUM) and exponentially weighted moving average (EWMA) chart. The CUSUM procedures have proven to be more effective than the Shewhart control chart at detecting small shifts in the process. Holmqvist concluded that the CUSUM procedure in the EN 519 standard for output control does not appear to be suitable for detecting whether a process, initially in control, has gone out of control because the average run length was too sensitive. It was also found that when the MoE distribution of graded timber is close to those defined in the EN 338 standard, the CUSUM chart for variables is quickly out of control when a shift in mean MoE occurs.

Forintek[104] is planning a study to compare different types of machine stress graders but the work plan does not mention the effect of feed speed on machine performance. The New Zealand Forest Research Institute[105] is currently undertaking a study to compare six different machine stress graders and this study will look at the effect of timber quality, size, length and feed speed on grading accuracy.

11.3 Summary of findings

Research into requirements for control planks, to enable machines to be dynamically calibrated and controlled, is ongoing in Europe and new standards will most likely incorporate the use of control planks. It is, however, a controversial area and the research is to date has proved inconclusive.

The suitability of the Shewhart control chart, the cumulative sum (CUSUM) and exponentially weighted moving average (EWMA) chart have also been researched and these techniques have proved useful in overseas situations where engineering properties are generally less variable than those encountered in Australian grown pine. Use of these techniques, if applied correctly can be valuable. Adaptation and use of some aspects of control chart based statistical control should be evaluated and considered in the Australian situation.

12 USE OF STATISTICAL PROCESS CONTROL CHARTS

12.1 Relevance

The suitability of the Shewhart control chart, the cumulative sum (CUSUM) and exponentially weighted moving average (EWMA) chart have been extensively researched and these techniques can be valuable for process control, if used correctly. Complaints from operational users often result from the MSG process going out of control due to a shift in a parameter associated with the resource. Instead of investigating what the charts are telling the user the technique is often blamed. This section deals with statistical analysis associated with controlling the overall MSG

[103] Holmqvist, C., G. Gaede, P. Joyet, L. Boström. 1999. Control and Calibration of Timber Strength Grading Machines. RILEM Symposium on Timber Engineering, Stockholm, Sweden, P.533-542.
[104] Yvon Corneau yvon.corneau@qc.forintek.ca. Project is scheduled to start August 2002.
[105] New Zealand Forest Research Institute Ltd, trading as ***Forest Research***, is in the process of getting sponsors to fund a study into the performance of different machine stress graders.

process. Statistical analysis is used to ensure that stress graded timber has the correct engineering properties associated with an individual grade.

12.2 Review elements

The literature deals with three distinct areas where statistical analysis is used in relation to MSG.

- Initial evaluation and statistical analysis of data for timber strength.
- Reliability of timber structures.
- Control and calibration of timber strength grading machines.

Standard textbooks on statistics cover the use of control charts for attributes and for variables. Control charts for variables are used where a single measurable quality characteristic, such as modulus of elasticity, is used. Control charts for attributes are used on the outcome of a "pass" (conform) or "fail" (non-conforming) test. This is normally used where a sample of timber is proof loaded and a number of pieces will "fail" the proof load.

Because the Shewhart[106] control charts uses only the information about the last plotted point, and ignores the information given by the entire sequence of points, these control charts are relatively insensitive to small shifts in the process. The alternatives to the Shewhart control chart are the cumulative-sum (CUSUM) control chart and the exponentially weighted moving-average (EWMA) control chart. The Shewhart control chart for sample averages is suitable if the magnitude of the shift is 1.5σ or larger, while the CUSUM can be used with small shifts. This makes the CUSUM very sensitive to a change in sample population when grading timber. CUSUM control charts can also be used to obtain a particular run length.

Procedures for the control and calibration of timber strength grading machines are covered in detail in the Draft ISO CD 13912 STRUCTURAL TIMBER - GRADING - *REQUIREMENTS FOR MACHINE-GRADED TIMBER* Draft No 5 (rev 2000-05-09). This draft standard contains a detailed example of control charts using the CUSUM technique.

By comparing the response rate to out-of-control situations the CUSUM technique and the constants used must be suitable for the timber population it is to be used with. Some of the in-house procedures for certification and quality control are based on the work by Warren[107] while others use CUSUM procedures with CUSUM constants for each E grade class, while the draft ISO standard[108] has one set of constants for all grade classes.

A 20-page detailed paper by Warren describes the use of attribute charts for conditions where production is continuous and the sampling destructive. Warren quotes the Beatie procedure as "relatively easy to implement on the production line and uses a graphical presentation which is always advantageous."

According to Warren the basics of the control process, for any MSR grade, is for 5 or 10 pieces to be randomly selected on a daily or shift basis and proof loaded to 2.1 times the allowable stress. "This proof loading will enable a measurement of stiffness, E, to be obtained for each piece; but a measurement of strength, R, only for those pieces which fail the proof load. Thus for

[106] Montgomery, D.C. 1991. Introduction to Statistical Quality Control, Wiley. p.279.
[107] Warren, W.G. 1978. Recent Developments in Statistical Control Procedures for MSR. Proceedings of the 4th Nondestructive Testing of Wood Symposium, Washington State University.
[108] ISO/CD 13912 Draft No 5 2000 Structural timber -- Grading -- Requirements for machine-graded timber

strength we have “Pass” or “Fail” measurements only. Accordingly, we may develop a variables chart for E, but only an attributes chart for “R”.”

The CUSUM design described by Warren is based on the sample size and three parameters. For the variables CUSUM plans, the recommended parameters are based on a coefficient of variation (CoV) of 11%. According to Warren it was found that, “at the acceptable quality level (AQL), the average length of time in the within-control region changes dramatically with the coefficient of variation”. The average run length in the accept region (within control) is 130 shifts for a CoV = 11%, 20,000 shifts for a CoV of 7% and 32 shifts for a CoV =15%.

The Authors complied a spreadsheet to examine the sensitivity of the CUSUM control procedures recommended in BS 519:1995 and draft standard ISO/TC 165N232 Annex 1. The CUSUM procedure for bending strength in the draft standard ISO/TC 165N232 got back into control faster than under BS 519:1995.

The Authors concluded that the resource could have a large impact on the CUSUM constants used. BS 519:1995 and draft standard ISO/TC 165N232 illustrate CUSUM control for Modulus of Elasticity (MoE) and for Bending Strength (MoR). Some of the systems used by inspection agencies also include CUSUM control for minimum E.

The use of the CUSUM procedure is prescribed in the USA. The standards published by the US standards authority lists the engineering properties for the approved structural grade classes. Some standards are vague with the US Department of Commerce Voluntary Product Standard PS20-99 reading: ‘*6.3.2.2. Grading-mechanical-The grading of structural lumber by mechanical means is recognised as an acceptable method of grading. When graded by mechanical means all such grading equipment and methods shall be subject to approval and certification of the board.”* The American Lumber Standards Committee[109] (ALSC) has produced a policy document called “*Machine graded lumber policy*”. This document sets out the criteria for approval of machines used for machine grading of lumber, agency accreditation and qualification procedures. The sample MSR grade must meet the following minimum criteria:

- *Average edge modulus of elasticity (MoE) equal to or greater than the assigned average E.*
- *95% of the pieces have edge MoE greater than 82% of the assigned average E.*
- *95% of pieces have a modulus of rupture (MoR) greater than 2.1 times the assigned F_b.*

The agency requirements for mill quality control are also specified and clause E states:
“The agency shall require that mills or facilities which grade machine graded lumber conduct daily quality control of the machine graded output. As a minimum, the quality control procedures shall include the following components:

1. *Offline measurement of MoE.*
2. *Offline strength testing to verify assigned F_b and/or F_t. Testing may be conducted by proof testing using appropriate proof loading equipment. Proof loading equipment is defined as equipment capable of imposing a stress on the specimen of at least 2.1 times the assigned property value*
3. *Verification of daily test results to the quality control requirements established by the agency.*

[109] www.alsc.org.

4. *Procedures for re-grading of lumber identified by the quality control procedures as non-conforming with the grade specifications.*
5. *All agencies shall conduct physical tests of at least one grade, one size and one species to check lumber output criteria. Semi-annual tests are deemed adequate where CUSUM quality control is used. For machine stress rated lumber, lumber is tested for both MoE and MoR on edge or MoE and UTS."*

The policy document also allows for the monitoring of agencies. The monitoring agencies produce the product specifications and procedures for certification and quality control. These documents are usually confidential[110] and only available to participating mills. Statistical quality control procedures appear to be based on the work by Warren[111].

12.3 Summary of findings

The use of statistical control charts is described in the standards reviewed, however overseas on-site visits confirmed that mills only produce and refer to statistical charts if they have a problem that needs detailed investigation to be rectified. Statistical control charts are not used extensively for continuos monitoring. Although the CUSUM procedure has it shortcomings it is still the preferred statistical control method by overseas agencies such as the SPIB.

The Shewhart control chart, the cumulative sum (CUSUM) and exponentially weighted moving average (EWMA) charts are used for process control. The CUSUM technique attracts the most criticism because it can be a messenger with the unpopular message: "Your process is out of control" or "you have failed". The Southern Pine Inspection Bureau stated that "The CUSUM technique is not perfect but it has served them well".

Although the CUSUM statistical quality control procedures are based on the work by Warren the actual parameters used are based on studies by others. These V-Mask parameters are resource machine and mill specific needing to be based on the most economical average run lengths calculated for each mill.

13 ADDITIONAL INSIGHTS FROM THE STUDY TOUR

The study tour provided a number of additional insights from the perspective of MSG operators and grading agencies. These insights are summarised under key headings as follows.

- **Feed speeds.** For mills using machine control, production was constrained by the maximum feed speeds being legislatively set by the accrediting agency. The accrediting agency had set feed speeds to take account of the effect of machines losing accuracy for whatever reason. Mills using machine control tended to run their machine stress grader at low speed to increase the grade yield, as higher speeds tended to increase the percentage downgraded.

- **Data recording.** Mills using output control although generally using machines that could record data for analysis were not generally familiar with how to do it and did not think it was relevant to test individual boards to check for inaccuracies of the machines dynamic

[110] The Western Wood Products Association declined to provide the authors with a copy of their publication Machine Stress-Rated Western Lumber.
[111] Warren, W.G. 1978. Recent Developments in Statistical Quality Control Procedures for MSR. Proceedings of the 4th Nondestructive Testing of Wood Symposium, Washington State University.

measurement along boards. There were a number of instances where mills used older machine stress graders, which could not record data for analysis.

- **Standards.** The draft ISO standard ISO CD 13912 has a specific repeatability test A.6.2 (i), a calibration test A.6.2 (ii), and a consistency test A.6.2 (iii), to detect this problem of machines losing accuracy along the length of the board.

- **Need for tests.** The two machine manufacturers visited advised that they have to date not had any demand to incorporate a test system as described in the draft ISO or EN standards into their reporting systems.

- **Vibration.** The likely cause of machines losing accuracy along the length of the board has been investigated by a number of authors and is mainly due to vibration and the problem may increase with feed speed. This problem has been reduced in the Metriguard machine by using a vibration sensor in the second stage of the bending module and in the Eldeco Dart[112] by moving the bow-measuring arm to the outfeed side of the machine. The Tecmach uses air bags to minimise vibration and two separate bending units to de-couple any deflection from one module to the next.

- **Set up and Calibration test times**: All companies undertook set up and calibration tests and these took about 30-60 minutes per occasion. These tests were generally undertaken during normal production breaks. Total time required for machine calibration and output control was about 2 hours per shift undertaken off-line. For mills under output control the sampling and stiffness and strength testing took about 60 minutes per shift. It is unlikely that these times can be substantially reduced, even if data logging is automated.

- **Ouput control time**: For mills under output control the most time consuming part of verifying the accuracy of MSG is the regular sampling and measuring of stiffness (MoE) and strength (MoR) by proof loading. The PTC quality manual recommended that 5 pieces per grade per shift be proof load tested offline. The SPIB requirement is for 5 pieces to be sampled for stiffness and strength testing every 4 hours.

The current PTC MSG Accuracy Check Method is a machine control system using control planks to achieve dynamic control. For many overseas operations this method was generally seen as having limitations because it is based on the characteristics of the general timber population, rather than the characteristics of the specific timber population currently being produced. For overseas operations this invariably results in a lower grade yield. Machine control is considered more suited in instances where a large number of grades and sizes are being produced.

In overseas operations using output control, use of control planks to set up a machine was considered useful but not essential. The repeatability, calibration and consistency tests in the draft ISO standard ISO CD 13912 do not require the use of control planks and consequently are likely to be less time consuming to apply. Output control as used in the US was seen as providing sufficient data for diagnostic control purposes particularly as the engineering properties of timber being stress graded was inherently less variable than Australian grown pine.

[112] www.eldeco.com

14 CONCLUSIONS

Along with examining factors influencing overall accuracy of MSG, this project has identified a number of differences between Australian and overseas MSG practices including

- Timber species being graded in the US and Europe generally have different and inherently less variable mechanical properties than those encountered in Australian grown pine species.
- No accuracy control methods equivalent to PTC's method is being operationally applied elsewhere in the world.
- Various materials and designs for non-timber control planks (Calibration sticks) have been tested none are currently in operational service.
- European and US regulatory authorities have legislative control over compliance with machine-grading systems and standards whereas in Australia industry compliance with PTC's Quality Assurance system (QA) is voluntary.
- In the US and Europe the process of machine grading is controlled by either machine or output control. Machine control (the norm in Europe) relies on fixed machine settings as determined by the grading agency for all machines of a specific type. Output control (the norm in the US) relies on timber being regularly taken from the production line and tested to confirm timber meets required strength characteristics after the timber has actually been graded.
- Output control systems enable the actual stiffness and the 5-percentile strength trends to be monitored, however the lower sampling rate means incorrectly sorted margin pieces may take a while to be detected.
- PTC's Dynamic machine control Accuracy Check method enables corrective action to be taken as an integral part of controlling the accuracy of the process at the time the timber is actually graded and consequently much faster response to a problem with machine accuracy than output control systems.
- By regularly checking on machine performance, it is possible to detect when a machine is drifting out of control thus preventing the production of large volumes of timber that do not meet grade and require withholding from the market or re-grading.

The absence of any Accuracy Check methods equivalent to the PTC method made it impossible to undertake any direct comparisons between the current PTC Accuracy Check method and methods used overseas. Various materials and stick designs for fabricated control planks (calibration sticks) have been tested in Europe and reported on in the literature. None of the mills visited in the USA, Ireland, England and Sweden used control planks for the control of bending type machine stress graders.

Not withstanding the lack of direct comparison, a secondary conclusion from this review is that PTC's current MSG Accuracy Check method and its application appears to be far more comprehensive than any MSG quality control methods currently used overseas.

This finding leads to the conclusion that the present PTC Accuracy Check method and its application could potentially be simplified. To formulate and adopt the best most cost effective Accuracy Check method for use within the Australian softwood processing industry additional investigative needs to be undertaken based on taking actual data from the Australian resource and applying the various test procedures to it. Of particular interest is a comparison of the PTC, ISO, EN and SPIB test procedures and the outcomes in terms of maximising the grade yield while maintaining grade compliance and minimising the disruption to production.

15 RECOMMENDATIONS

This project has highlighted a number of areas where further investigation could potentially lead to improvements and or efficiency gains in MSG grading practices generally in Australia and to the PTC Accuracy Check method in particular.

It is recommended that in-mill studies be undertaken at four or five Australian Mill sites, which are currently using either machine control and or output control. Relevant information should be collected to enable the cost-benefit of different control systems to be quantified including calculation of average run lengths (ARL).

The use of control charts such as Shewhart, cumulative sum (CUSUM) and exponentially weighted moving average (EWMA) can be valuable, if used correctly and it is further recommended that Mills make use of these types of charts when tight control is required.

The scope and extent of further investigation will need to be developed in consultation with both the PTC and the sawmillers utilising PTC's certification services and methodologies.

Recommended additional investigations are expected to encompass but not be limited to:

- Quantifying the frequency, cause and effect of machine adjustments consequential to failed accuracy tests to determine specifically how and why such adjustments are made and how they affect the consistency and accuracy of grading.
- Quantifying the impacts of specific contributory factors such as variations in timber thickness and machine vibration have on grading accuracy.
- Determining what remedial actions could be taken to improve the consistency of machine settings. More frequent checks of machine settings could lead to a reduction in the frequency of calibration stick use.
- Examining the construction storage and shelf life of calibration sticks
- Recording and analysing data on how often a calibration stick gives an unacceptable value. If this is relatively infrequent then the interval between using the sticks could potentially be extended.
- Examining the use and relevance of statistical machine control charts in checking machine accuracy.
- Re examining the underlying statistics on which the accuracy test is based,
- Quantifying the benefit/cost of various alternative combinations of machine and output control systems.

Pending further investigative work it is the recommendation of Forest Research that on no account should individual mills drop or change any of the PTC check methods in favour of those used overseas as these alternative procedures need to be fully evaluated and justified for the Australian situation.

16 FUTURE WORK

Further investigation will need to encompass all aspects of the Accuracy Check method from its statistical basis through to operational aspects of its application. Although the PTC Accuracy Check method appears to be more responsive to out of control situations the economics of this approach has never been fully evaluated in terms of operational benefit cost. The scope and extent of further investigation will need to be developed in consultation with both the PTC and the sawmillers utilising PTC's certification services and methodologies.

In order to determine whether PTC's dynamic machine control Accuracy Check method, using calibration sticks, can be simplified and or improved it is recommended that these trials focus on CLT & HCLT machines encompassing aspects as follows:

1 **Machine adjustments:** Collection of records to quantify the frequency of adjustment of stop bolts, including the direction of adjustment, degree of adjustment tightness (Indications are that his varies by operator) and impacts any variations in timber thickness have on these adjustments. In theory if the timber is always supplied at the correct thickness but in practice timber thickness does vary by ±0.5mm. If no wear or movement occurs in the stop bolts then no adjustment should be necessary. Records would need to be analysed in conjunction with the output control quality assurance (QA) data (MoE_{plank}, MoE_{joist} & MoR_{joist}) and would be expected to cover a number of very specific machine operational aspects such as

- To what degree does adjusting the stop bolts affect the consistency and accuracy of grading?
- Does continuous adjustment of stop bolts in one direction indicate that wear is occurring or that they are rotating during use? If so can this wear be eliminated or can the bolts be made more secure so they do not rotate in use?
- When the planer knifes are jointed or otherwise adjusted are the stop bolt adjustment checked to match the new dimensions?

2 **Frequency of calibration stick use:** Recording and collating data on how often a calibration stick gives an unacceptable value. If this is fairly infrequent then the interval between using calibration sticks could potentially be extended. When an unacceptable value is obtained what steps are done to remedy the situation? For instance does it normally require a stop bolt adjustment or a re-calibration with the long and short bars, if so what is nature of adjustment? (Direction and degree of adjustment).

Collation and interrogation of these types of records will enable the differentiation between random variation and intermittent variation to be quantified. There needs to be a balance between maintaining effective and efficient control and over controlling the process. Over control, due to too frequent calibration could potentially lead to increased variation.

3 **Effect of piece size:** Investigating the effect of piece size has on frequency of machine calibration, eg. do large sections require more frequent adjustment of stop bolts.

4 **Increased understanding of machine performance:** Understanding more about the reasons for and types of adjustments being made to CLT & HCLT machines could lead to improved interpretation of the information gained from use of calibration sticks.

5 **Adjustment to grade thresholds:** Investigating the possibility of adjusting grade thresholds to ensure maximum grade recovery whilst maintaining grade properties. Any such adjustment to grade thresholds needs to be undertaken in conjunction with the QA data for all the grades as one threshold affects two grades. This should be considered if the grade properties are being consistently over or under achieved.

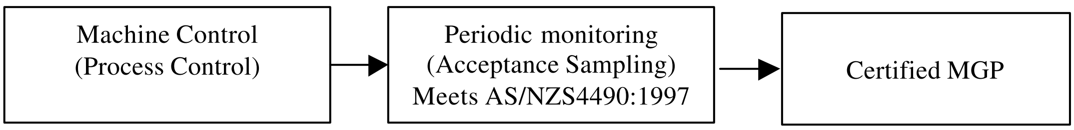
6 **Investigate factors impacting on machine consistency:** Undertaking in-mill trials to evaluate the effect of grading machine consistency and accuracy would enable the impact of out of control situations on final product properties to be better understood.

7. **Incorporating aspects of overseas control systems:** Investigating the potential to simplify PTC's Accuracy Check method through incorporating components of the Southern Pine Inspection Bureau output control procedures and the draft ISO and EN standards.

8 **Cost benefit analysis:** Ideally the benefits and costs of the following four levels of machine stress grader control need to be quantified:

- Static machine control (based on manufacturer specifications as used in Europe and deemed sufficient for control).
- Dynamic machine control (as per PTC machine accuracy check method).
- Output control only (as per SPIB).
- Dynamic machine control combined with output control (combined PTC and SPIB methods).

Currently Australian sawmillers producing MGP ensure the grading process is under control by undertaking both machine control and period monitoring (see illustration below).



Mills participating in PTC's MGP Product Certification program are audited using PTC's Dynamic machine control process control methods. In addition to this, compliance with the AS/NZS 4490:1997 standard requires all Mills to routinely undertake acceptance sampling to confirm MSG timber produced meets the periodic monitoring requirements for each grade.

By making a few assumptions it is possible to roughly quantify the benefits and costs of the different systems. Table 1 shows the basic data required to quantify the costs assuming operator only time at \$30/hour, machine production time at \$500/hour and a production level of 100m^3 per shift.

Table 1 - Proposed model to calculate the cost-benefit of different methods of control

Method of Control	Set up, non-production Operator minutes per shift	Machine control. Machine minutes per shift	Output control. Operator minutes per shift	Cost of control system. $/shift	Graded product yield %	Value of Production $/m3	Revenue $/shift	Increased Benefit $/shift
Static machine control	30	0	0	$ 25	65%	$ 330.00	$ 33,000	$ -
Dynamic machine control	30	30	0	$ 275	68%	$ 336.00	$ 33,600	$ 325
Output control only	30	0	60	$ 55	70%	$ 340.00	$ 34,000	$ 945
Output control with dynamic machine control	30	30	60	$ 305	71%	$ 342.00	$ 34,200	$ 895

Table 1 excludes value losses due to timber breaking when measuring MoR. These tests are prescribed in AS/NZS4490:1997 and should be done periodically at a sampling rate of 1:1000 to 1:10,000. At a production rate of 20 pieces per minute this means measuring MoE and testing for MoR must be done at least weekly if not daily.

All the variables shown in Table 1 are resource and site specific. Cost-benefit will vary depending on each mills actual operational costs and production levels. Actual physical quantification of the resource inputs, production rates and accuracy of the individual methods will need to be quantified and incorporated in order to determine the most cost efficient method of MSG control.

Undertaken off-line, output control is used to monitor machine performance as well as acceptance test production. For these reasons it will most likely have a more favourable benefit-cost than a machine control only system. Conversely the PTC machine control Accuracy Check method will respond much faster than output control systems to a problem with machine accuracy therefore the system is more likely to prevent the production of large volumes of incorrectly graded timber that may require withholding from the market or re-grading.

Any cost-benefit analysis needs to take into account the ultimate objective of each system, which is to ensure the process is accurate and always in control.

The cost of getting this wrong is large volumes of timber being incorrectly graded. The cost of having to withhold from or releasing to the market incorrectly graded timber, can far outweigh any reduction in costs associated with the time required to verify the accuracy of the process, dynamically as the timber is actually graded.

17 TERMINOLOGY AND ABBREVIATIONS

- ALSC: American Lumber Standards Committee.
- AQL: Acceptable Quality Level.
- ARL: Average Run Length. The ARL is used to make decisions about sample size and sampling frequency. The ARL can be used to calculate the run time before a false alarm will be triggered.
- C16: A European framing (carcassing) grade.
- Characteristic Value: The percentile of a statistical distribution, estimated with a specified degree of accuracy. The characteristic values used are either the mean value of the sample, or an estimate of the 5-percentile value.
- CLT: Continuous Lumber Tester by Metriguard.
- CONGRAD: European research project - Control and Calibration of Timber Grading Machines
- Control charts for attributes: If the quality characteristics cannot be represented numerically items either conform (non-defective) or non-conform (defective). Quality characteristics of this type are called attributes. Refer to Montgomery[113] for more details on control charts for attributes.
- Control charts for variables: Many quality characteristics can be expressed in terms of numerical measurements. A single measurable quality characteristic is called a variable. Refer to Montgomery[114] for more details on control charts for attributes.
- CUSUM control charts. The cumulative-sum control charts are used in preference to the Shewhart chart where small shifts are of interest. Refer to Montgomery[115] for more details on control charts for attributes.
- CUSUM: Cumulative-sum Control Chart.
- EWMA: Exponentially Weighted Moving Average.
- FWPRDC: Forest and Wood Products Research and Development Corporation.
- HCLT: High Speed Continuous Lumber Tester by Metriguard
- ISO: International Standards Organisation.
- Limit State Design versus basic working (allowable) stress: In basic working stress design, the adequacy of the structure is checked by calculating the elastic stresses in it due to the maximum expected loads, and comparing them with allowable stresses[116]. The allowable stress is equal to the failure stress of the material divided by a safety factor. Because of the limitations of the allowable stress method limit states design was introduced. The characteristic values for timber is thus used by some codes in preference to basic working stress.
- LST: Least Squares Technique.

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[113] Montgomery, D.C. 1991. Introduction to Statistical Quality Control, Wiley. p.147.
[114] Montgomery, D.C. 1991. Introduction to Statistical Quality Control, Wiley. p.201.
[115] Montgomery, D.C. 1991. Introduction to Statistical Quality Control, Wiley. p.279.
[116] Allen, D.E. CBD-221 192. Limit States Design, Canadian Building Digest, National research Council, Canada.

- MSG: Machine Stress Grading - The basis of MSG is that the machine-measured parameter (stiffness as a plank for typical machine stress graders) is closely related to stiffness as a joist and bending-, compression- and tensile-strength.
- Measured parameter or indicating property. Machine graders measure one or more parameters and use this data to calculate an indicating property, which is then used to predict strength or stiffness.
- MEL: machine evaluated lumber.
- MGP: The MGP grading system was developed and introduced in Australia because the "F" grade system undervalued Australian pine[117]. According to Walford[118] the essential difference is that the MGP system is performance based (output controlled) with a quality control system to check that the claimed properties are maintained while the "F-grade" system is prescriptive and the timber is produced to a defined set of machine settings or visual grading rules.
- MLM: Maximum Likelihood Method.
- MoE: Modulus of Elasticity. A measure of the stiffness of timber. Can refer to stiffness as a plank or a joist and can be measured over a short or a long span.
- MoE_{flat}: Modulus of Elasticity determined by static testing machine with three point bending measurement.
- MoE_{joist}: Modulus of Elasticity as a joist (determined by measurement of timber on edge).
- MoE_{plank}: Modulus of Elasticity as a plank (determined by measurement of timber on face)
- MoE_{stat} : Modulus of Elasticity measured by means of a static tester
- MoR: Modulus of Rupture. A measure of the strength of timber. Can refer to strength in tension, compression or bending.
- MSG: Machine Stress Grading.
- MSR: Machine Stress Rated lumber.
- Output control: In output control timber is continuously taken from the production line and proof loaded. Output control is suitable where the machines have repeated production runs of at least one shift. In Europe almost all timber grading companies are using machine control, while in North America output control is used
- Machine control[119]: Machine control relies on the machines being strictly assessed and controlled. The machine settings remain constant for all machines of the same type.
- Proof grading: Proof grading allocates a stress grade to a piece of timber if it sustains a specific proof bending stress. In other words it did not fail when proof loaded. The proof stress is generally 2.2 to 2.4 times the actual design stress[120].
- PTC: Plantation Timber Certification[121].

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[117] An Easy Guide to MGP Pine, Pine Australia. www.pineaust.asn.au
[118] Walford, B. 1999. The Engineering Qualities of New Zealand Pine, Pacific Timber Engineering Conference, Rotorua, New Zealand. Forest Research Bulletin 212. P.6.
[119] Holmqvist, C., G. Gaede, P. Joyet, L. Boström. 1999. Control and Calibration of Timber Strength Grading Machines. RILEM Symposium on Timber Engineering, Stockholm, Sweden, P.533-542.
[120] Refers to allowable working stress system, not limit states design method. Timber Research Unit, Department of Architecture, University of Tasmania. www.oak.arch.utas.edu.au
[121] PTC is a wholly owned subsidiary of the Plantation Timber Association of Australia.

- Shewhart control charts: Refer to Montgomery[122] for more details on the Shewhart statistical process control chart.
- SPIB: Southern Pine Inspection Bureau.
- Stiffness of structural timber[123]. The characteristic value of the Modulus of Elasticity (stiffness) of sawn timber is based on the minimum of E_{mean} or $E_{0.05}$ multiplied by a suitable confidence factor. The coefficient of variation of E, V_E affects the confidence factor.
- Strength of structural timber[124]. Engineered structures are designed using characteristic tension-, compression- and bending-strength values for the timber specified. These values are based on extensive in-grade testing of full-size timber. The bending strength is a complex problem as it depends on a number of factors including the ratio of tension to compression strength, non-linear ductile behaviour and size-dependent brittle fracture in the tension zone[125]. The characteristic strength values are based on the fifth-percentile value of the strength ($R_{0.05}$) multiplied by a suitable confidence factor. The coefficient of variation of R, V_R affects the confidence factor.
- Stress grading. Timber may be visually or machine (normally mechanically but other methods such as stress wave, microwave or x-ray may also be used) sorted (grouped) into "stress grades". This means timber with similar properties are grouped together to meet the requirements of specific end uses.
- TR26: A European high quality timber grade for roof trusses.
- TREECD: A database on CD by Silver Platter International.
- USDA: United States Department of Agriculture.
- ν: coefficient of variation.
- Visual stress grading: When timber is graded visually by applying grading rules prescribing defect size and location limits the resulting grades can be allocated to structural groups with associated engineering properties.

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