Approach for an efficient Control of Grading Machine Settings

Markus K. Sandomeer[1], Jochen Köhler[2]

[1]ETH Zurich, Swiss Federal Institute of Technology, Zurich, Switzerland, sandomeer@ibk.baug.ethz.ch

[2] ETH Zurich, Swiss Federal Institute of Technology, Zurich, Switzerland, jochen.koehler@ibk.baug.ethz.ch

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ABSTRACT

Machine grading systems operate according to similar principles; one or more strength related properties of the timber to be graded are measured non-destructively by the machine and based on these measurements a population of un-graded timber is subdivided into sub-populations of graded timber material. The grading acceptance criteria are formulated in form of boundary values for the indicating property that have to be matched to qualify a piece of timber to a certain grade. These boundaries are termed grading machine settings. The performance, i.e. the statistical characteristics of the output of grading machines strongly depends on these settings, and in general very much attention is kept on how to control them.

Currently applied procedures to control the grading machine settings are either machine controlled or output controlled, however, both procedures do not facilitate the efficient use of information which is gained prior and during the operation phase of the grading facility.

This presentation will highlight the existing methods for the control of grading machine settings according to the European standard EN 14081. Moreover an alternative approach for the control of grading machine settings will be presented. This approach is based on Bayesian regression analysis and allows a probabilistic modeling of timber material properties. It can be seen as a combination of the machine control and output control approach. The alternative approach facilitates the consistent consideration of new information gained during the whole grading process and will be summarized in a coherent and implementable format. Possible benefits of its application in practice are discussed.

1 Background

Timber is by nature a very inhomogeneous building material. The mechanical and physical properties of sawn timber vary on a large scale as a product of e.g. wood species and provenience. Regardless of species and origin, timber properties diverge not only from tree to tree but also within a tree, over the cross section and along the stem axis.

A pre-requisite for the use of timber in load-bearing constructions is that the relevant mechanical and physical properties (strength, stiffness and density) are known and can be controlled to remain within desirable limits. In comparison to other man-made structural materials, such as steel and concrete, this cannot be achieved by changing the composition of the raw materials or by shifting some of the environmental conditions. In order to use timber efficiently as a reliable structural material the only way of obtaining controlled timber properties within required limits is by means of strength grading procedures, either machine grading or visual grading.

Currently, there are many developments in the application of high-speed non-contacting scanning systems which may offer the possibility of reduced grading costs, well-organized quality control and more efficient utilization of structural timber. These highly innovative technical devices offer a great amount of various information gathered during the grading process which is to date not incorporated efficiently in the existing methods concerning the control of grading machine settings.

In this paper existing procedures for the control of grading machine settings according to the European Standard EN14081 are discussed. Currently established methods can be either *machine controlled* or *output controlled*, however, both procedures do not facilitate the efficient use of information which is gathered during the operational phase of the grading facility.

Therefore, an alternative approach for the control of grading machine settings is introduced which can be seen as a combination of the machine and output control procedure. It facilitates the consistent consideration of new information gained prior and during the grading process. The approach is summarized in a coherent and implementable format and possible benefits of its application in practice are discussed.

2 Machine Grading of Structural Timber

Grading machines operate according to similar principles; one or more indicating properties of the timber to be graded are measured by the machine and based on these measurements a sample of ungraded timber is subdivided into subsamples of graded timber. However, the capability of indirect measurements for predicting the strength can never be perfect and therefore, uncertainties are always incorporated which have to be considered in the underlying grading model.

If more than one indicating property is measured by a certain type of grading machine, a combined indicating property is identified, e.g. by regression analysis. In general grading acceptance criteria are formulated for the indicating property in form of boundary values which have to be matched to qualify a piece of timber to a certain grade. These boundaries are also termed grading machine settings. The performance, i.e. the statistical characteristics of the output of grading machines strongly depends on the settings, and in general very much attention is kept on how to control them. In Figure 1 observations on the indicating property and the property of interest are illustrated. Boundary values of the indicating property (ip1 and ip2) subdivide the sample into sub-samples assigned to grade 1, grade 2 and reject.

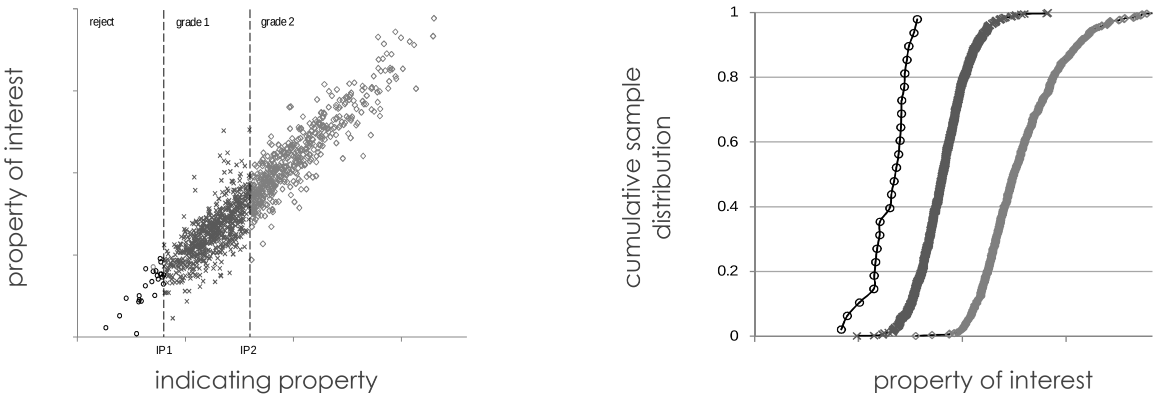

Figure 1: *<u>left:</u> Observations on the indicating property and the property of interest. The grading machine settings (ip1 and ip2) subdivide a sample into subsamples assigned to 'grade 1', 'grade 2' and 'reject'. <u>right:</u> Cumulative sample distribution of the property of interest of the graded subsamples.*

Timber used for structural purposes is assigned to a specific strength class system (e.g. EN 338) which constitutes the classification of timber samples based on requirements on their characteristic values of the relevant material properties of interest. In EN 338 the required characteristic values for the strength and density of the graded material are defined as the 5^{th}-percentile values of the underlying sample distribution. The characteristic modulus of elasticity (MOE) is specified by its mean value.

For the assignment of a timber sample to a certain grade by means of machine strength grading, these mentioned characteristic values of the three relevant material properties (strength, stiffness and density) have to be achieved. For this purpose machine grading becomes an important element of quality control operations in the production line of structural timber elements.

3 Discussion of different Schemes for the Control of Grading Machine Settings

When considering the control of grading machine settings it is in general distinguished between two main procedures, the machine controlled system and output controlled system. Focusing the European Standard EN14081 the machine controlled system is represented by the so-called "cost matrix method" (EN14081, part 2). A commonly applied method for output control systems is the "cumulative sum" method (CUSUM) given in part 3 of the mentioned standard. An alternative approach will be introduced which can be seen as a combination of the machine and output controlled systems.

3.1 Machine controlled System

The control of grading machine settings based on the *machine controlled* system was developed in Europe almost 40 years ago and different methods have been used. A new approach was introduced by Rouger (1996, 1997) in which the performance of the machine is compared with that of a 'perfect' machine capable of grading each specimen to its optimum grade. In the comparison of the *assigned grade* and the *optimum grade* a cost analysis is used where weighting factors are applied to pieces that are wrongly upgraded or downgraded. This method for machine control found its way into the actual European standard EN 14081, part 2 and is denoted as the *"cost matrix method"*. Today, all grading machines in Europe producing timber for the European market are operating with machine control systems *(Boström et al., 2000)*. Elaborate descriptions of the single steps of the machine control procedure have been carried out earlier and can be found e.g. in EN 14081, part 2, Rouger (1997), Bengtsson & Fonselius (2003), Köhler (2006) and Köhler & Steiger (2006).

In a machine controlled system all machines of the same type are said to be identical and any combination of grading machine settings is applicable to all machines of that type and application range. Therefore, the grade determining machine settings have to be derived by initial type testing which requires an assessment for each machine type based on a very extensive experimental study. In order to establish reliable settings for the different grades, sizes, species and origins often several thousand pieces of timber are passed through the machine and thereafter tested to failure. With this substantial assessment the grading machine settings are derived prior to the operation phase of the machine and optimized to a representative ungraded timber sample which might be typical for the daily use of the grading machine. Therefore the sampling and approving phases of the initial derivation of grading machine settings claim the most efforts (*Figure 2*). Settings derived once, are recorded in EN14081, part 4 and fixed for every machine of the same type and application range.

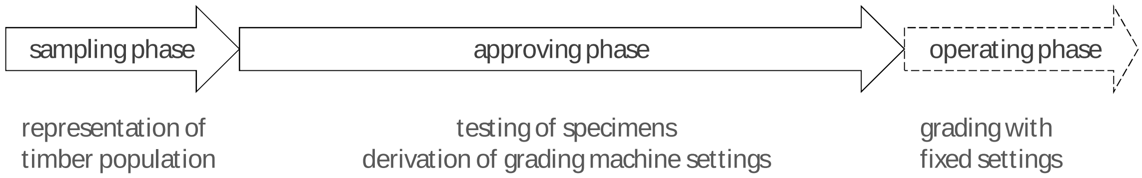

Figure 2: *Different phases of the machine controlled grading procedure.*

All grading machines together with their grade determining settings for the indicating properties are enlisted in the European standard EN 14081, part 4, subject to the condition that they are approved in accordance with the requirements given in the same standard. This list is updated approximately every half a year, each time shortly after the Technical Committee CEN/TC124 has adjudicated upon the approval of new grading machines or new application ranges of existing grading machines.

3.2 Output controlled System *(CUSUM method)*

Considering the control procedures of the *CUSUM* (cumulative sum) method given in EN14081, part 3 a limited number of specimens of each grade and dimension has to be selected a certain number of times per working shift. The selected specimens have to be proof-loaded to check that the quality of the timber is within desirable limits. If the timber survives the proof loading, it is deemed to have acceptable strength properties. Successive values of a variable are compared with a defined target or reference value, and the cumulative sum of deviations from this value is recorded in tabulation and plotted on charts. If the accumulation reaches or exceeds a pre-determined decision interval, this is taken to indicate that a change has occurred in the mean level of the variable and the process is said to run *out of control*. The *CUSUM* approach assumes that the process is initially *in control*. This can be ensured by some initial qualification or certification test which has to be passed prior to the establishment of the continuous control program.

CUSUM operates with two separate types of charts, an *attributes chart* and a *variables chart*. In the attributes chart the number of pieces that fails when proof loaded is recorded, while in the variables chart the actual values of the modulus of elasticity are used and their mean value is calculated for the assessment of the cumulative sum. *Figure 3* shows an example of a graphical combination of an attributes and variables chart. It can be observed, that the process runs out of control after testing four test samples by means of proof loading.

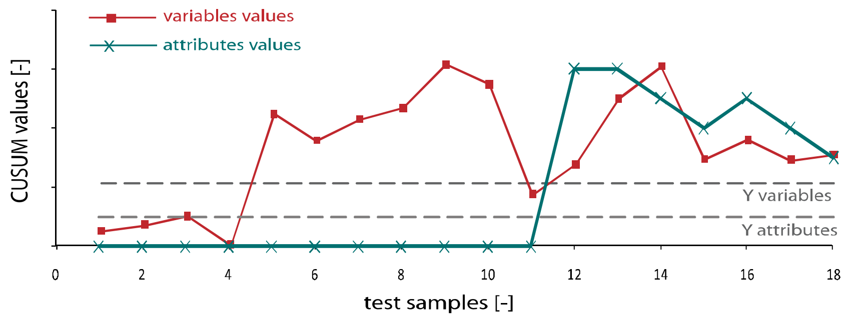

Figure 3: *Example of CUSUM values in a combined variables and attributes chart of the output control procedure. It is observable that the values exceed the Y-boundary value for the first time after proof loading four test samples and therefore the process is said to be out of control (Sandomeer & Köhler, 2007).*

If the process runs out of control a different set of charts has to be applied until the process returns to in control. When the process switches to out of control, in general, some check of the stress grading process must be performed. If the process does not return to in control after a defined series of test samples the production has to be stopped and investigation of the process and corrective action may be undertaken before several nonconforming units are manufactured.

3.3 Alternative Approach – Combination of Machine and Output controlled Systems

An alternative method for the control of grading machine settings was already proposed in Köhler (2003) and Faber et al. (2004). This method facilitates the consideration of uncertainties throughout the modeling of the grading process and probabilistic models of the material properties of graded timber material can be derived. Furthermore the proposed model framework enables the (statistically) efficient utilization of information gathered during the approval phase as well as during the running phase of the grading machine; that is, the statistical characteristics of graded timber material properties can be expressed and communicated by means of probability distribution functions, up to date in regard to the currently available information. However, the method appeared rather theoretical for practical application. Furthermore it is not clear how the statistical information about the graded timber material properties should be communicated, since the derived probability distributions are not part of a standard distribution family.

The basis of the presented method is a statistical representation of the relation of the material properties of interest (poi) and the measurements of the grading machine (indicating property = ip) by simple linear regression analysis as shown in the left illustration of *Figure 4*. The uncertainty of the estimation can be consistently considered by the fact that the prediction of the material property of interest is a normal distributed random variable. All parameters given in the equation (*Figure 4 left*) are random variables representing the statistical uncertainties. Therefore all uncertainties are incorporated into the grading model. Based on the relationship between the property of interest and the indicating property e.g. two boundary values for the indicating property may be assessed to subdivide the whole sample into different grades (*Figure 4 middle*). Beneath the x-axis the probability density function of the indicating property is illustrated. With a given boundary value for the indicating property and the given equation of the regression analysis, a conditional probability function for the property of interest can be calculated without considering the particular sample values anymore (*Figure 4 right*).

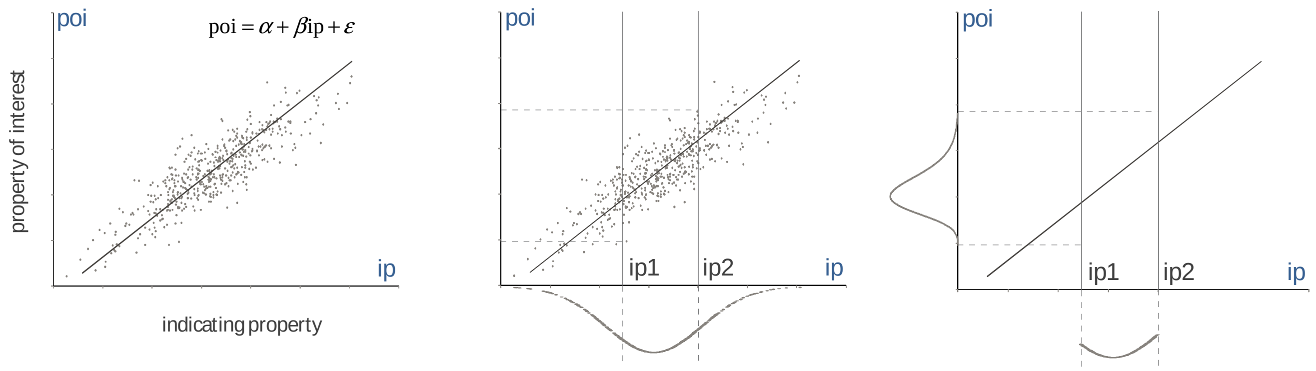

Figure 4: *left: Regression analysis to indicate the relationship between the property of interest (poi) e.g. tension strength and the indicating property (ip) measured by the grading machine.middle: Boundary values (ip1 and ip2) to subdivide the sample into different subsamples (grades). Calculation of the probability density function of the indicating property.right: Based on the regression analysis and the probability density function of the indicating property the conditional probability function of the property of interest can be assessed.*

The assessed conditional probability density function allows calculating a predictive cumulative distribution function of the material property of interest. In *Figure 5* the cumulative distribution of the observed sample compared with the predictive cumulative distribution function is illustrated. The 5^{th}-percentile value of the tension strength predicted by the probabilistic model might appear quite conservatively however, it should be noted that the model prediction represents the predictive value of the 5^{th} -percentile value containing all uncertainties due to model assumptions and due to lack of data. Furthermore, variations in the timber material supply can cause considerable fluctuations and uncertainties regarding the characteristic values estimated just on the basis of sample statistics. The alternative approach based on Bayesian framework is capable to incorporate these uncertainties and to facilitate the integration of new knowledge which might be obtained during the running phase of the grading machine consistently.

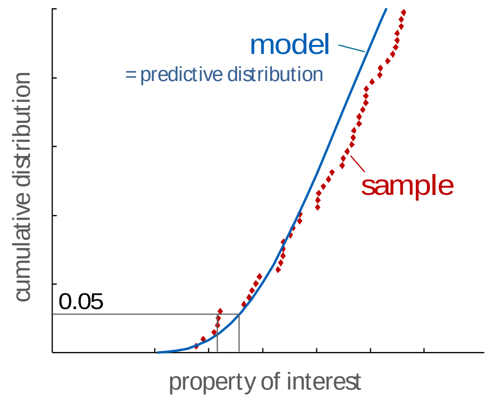

Figure 5: *Comparison of the cumulative distribution of the sample data and the probabilistic model. A shift in the 5^{th}-percentile value is observable (Sandomeer & Köhler, 2007).*

Based on continuous observations of the indicating property without any additional costs the model allows to formulate some decision criteria to indicate situations where variations in the input material of the grading process are expected. If such a situation is indicated additional output control tests (e.g. proof loading) should be initiated subsequently. Furthermore, the introduced method offers the possibility to incorporate new information into the grading model continuously by updating the Bayesian regression analysis and the resulting predictive distribution function of the material property of interest.

DISCUSSION & CONCLUSIONS

The goal of the present paper is to give an overview of the existing procedures for the control of grading machine settings given in the European Standard EN14081. The capability of the methods to incorporate statistical uncertainties as well as model related uncertainties into the grading process is of special interest. Furthermore, an alternative approach for the control of grading machine settings is introduced which is capable to incorporate the different uncertainties into its probabilistic grading model – an important pre-requisite for structural timber as a modern building material.

The machine controlled system given in EN14081, part 2 incorporates uncertainties into the grading model only implicitly, i.e. by sampling different subsamples of different origins and by comparing assigned grades with optimum grades. However, as long as the characteristic values of the derived strength classes are assessed by means of sample statistics considering solely the underlying set of data it is not possible to represent all uncertainties in a consistent matter.

The performance of the output control system by means of *CUSUM* control charts is observed to be capable to detect aberrations in the quality of the material supply. Though very much attention is kept on how to sample the test specimens randomly in order to manage the underlying statistical uncertainties, the method is still based on sample statistics and therefore only capable to qualify shifts of quality of the timber supply but not to quantify them.

The probabilistic approach shows to be a consistent combination of both methods described above. It is based on Bayesian framework and therefore capable to incorporate all uncertainties into the grading process and to facilitate the integration of new knowledge which might be obtained during the running phase of the grading machine consistently. This backflow of information can be seen as a crucial advantage in comparison to the established methods of the machine and output control systems.

Furthermore, the introduced approach offers the chance to assess shifts in the material quality by controlling the values of the indicating properties for the material properties of interest continuously. Note, that this information is always available without additional costs. Assessed aberrations of quality may be counteracted by means of updating the regression parameters of the probabilistic grading model. In consequence of updating the regression model it is a straightforward task to assign adjusted grading machine settings without additional substantial test procedures.

The suggested probabilistic approach not only forms a very strong tool for the statistical quantification of the material characteristics of timber but furthermore provides a consistent basis for quantifying the efficiency of different quality control and grading procedures.

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