Quality control and improvement of structural timber

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Abstract

Modern applications of structural timber like *e.g.* in the field of multi-storey domiciles or large span structures require graded timber products with sufficient and in many cases high performing mechanical properties. This can only be reached by means of advanced methods for quality control within the production process of structural timber. In this paper, quality control and improvement of structural timber is subdivided into three constitutive sub-items: 1) process monitoring, 2) process calibration and 3) process optimization.

The paper at hand can be considered as a summary of the authors' investigations and contributions within COST action E53. Different approaches for quality control and improvement of structural timber by means of machine grading are described. An optimized combination of the three sub-items of process control may lead to an enhanced recovery of the timber material quality and to an improved benefit and reliability in the graded timber material.

1 Introduction

Modern grading machines facilitate the integration of the grading process into the industrialized production scheme with its high demand for production rate. Besides the speed the efficiency of the grading machines depends on the machine's capability to divide the gross supply of ungraded timber into sub-sets of graded timber that fulfil some predefined requirements.

Several types of grading machines can be found on the market, measuring different sets of particular indicative properties during the grading process, *e.g.* bending deflection, ultrasound velocity, natural frequency, x-ray absorption, *etc*.. However, independent from the type of the grading machine and the number of measured properties, grading machines generate one compound variable as an output, which is a function of all particular properties measurable by the machine as a prediction of the grade determining property (*e.g.* strength, stiffness or density). Disregarding the fact that this variable is an artifact composed from the machine measurements and the underlying function or algorithm the indicative variable is generally termed *indicating property* and this is the term also used in the remainder of the present paper. For every grading machine acceptance criteria are formulated in form of intervals for the corresponding 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 these machine settings.

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The present European practice for machine based grading of structural timber is specified in the European Standard EN 14081. According to this standard the control of machine settings relies on two procedures, the so-called *machine control (cost matrix) method* and the *output control (CUSUM) method*. These two methods are broadly considered to be either too complex or expensive.

Hence, investigations have been conducted by the participants of COST Action E53 for each of the sub-items of quality control. Some of the contributions of this paper’s authors are summarized in the subsequent chapters. Different aspects of quality control and optimization are combined to achieve a coherent and overall strategy for quality control of structural timber based on machine assessment of timber properties; applicable for both, revision of existing codes and standards as well as for company-internal product optimization.

In the following chapters the overall quality control procedure is subdivided into three main topics: *process monitoring, process calibration* and *process optimization.* Due to the limited length of this paper the particular approaches and methods are described just briefly. Hence, for better understanding and additional information references to the relevant publications are provided within every chapter.

2 Quality control and improvement of structural timber

Graded timber material can be utilized for structural purposes either directly as solid timber columns and beams or indirectly in the form of basic raw material for engineered timber products. In both cases, when timber products are utilized in high performance timber structures *i.e*. whenever the load bearing capacity or the stiffness determines the design, it is a requirement that the timber products are classified to ensure adequately performing mechanical properties. In modern production management, where speed, reliability and costs are prerequisites for competitiveness, machine grading is in reality the only viable option. As a consequence, advanced and modern methods for the calibration and running assessment of grading machines have to be developed and implemented into practice.

However, since wood is a natural grown building material deviations in timber quality may occur during the grading process over time. This has been observed within industrial environment [1] as well as within a pan-European scientific project [5]. Major fluctuations may be caused either by different sources of the raw material (growth areas, supplier) or by different cutting patterns and dimensions.

2.1 Process monitoring

In general, when considering the control of manufacturing processes, the problem is to maintain a production process in such a state that the output from the process conforms to given design requirements (*e.g.* characteristic values for strength, stiffness and density). During the operation phase the process will be subject to changes which cause the quality of the output to deteriorate. And also the quality of the input material quality of the process may already be subject to significant aberrations.

In this section a possible procedure for identification of systematic changes in the tested material quality directly based on the machine grading measurements, at the same time as these are obtained, is outlined. All investigations are based on observations of the indicating property only. No corresponding strength, stiffness and density values are used in this context. The aim is to gather as much information as possible just by observations of non-destructively measureable properties.

For this purpose a dataset of a large sized timber manufacturing enterprise is used containing monitoring data of graded Norway spruce (*Picea abies* Karst.) which has been documented over a time period close to one month. Indicating properties for tension strength (IPmor), tension modulus of elasticity (IPmoe) and density (IPdens) are assessed by the grading machine GoldenEye 706 [1] [3]. While the dimensions (43x85 mm), the sawing pattern (2 ex log) and the log diameters (13-15cm top end) are considered to remain constant over time, source countries of the timber and the corresponding suppliers change every now and then. Every value of the IPs can be assigned to a certain producer and country. The mentioned constant factors which normally lead to specific variability in the material properties offer now the unique chance to investigate solely the effect of varying source countries and the consequences on the observed material properties.

For the characterisation of the course of process and for the identification of input material quality shifts the total dataset is split into *k=160* consecutive sub-samples each of size *s=1000.* First, the parameters of an appropriate probability density function (PDF) are estimated by means of the Maximum Likelihood Method (MLM). Subsequently, mean values and 0.5-fractile values are assessed probabilistically for each sub-sample to quantify its quality. Due to the fact that the computed mean and 0.05-fractile values are assessed for the observed indicating properties they just serve as a quality criterion for the input material and should not be mixed up with the required characteristic values in the context of grading timber into a specific strength class *e.g.* according to EN 338.

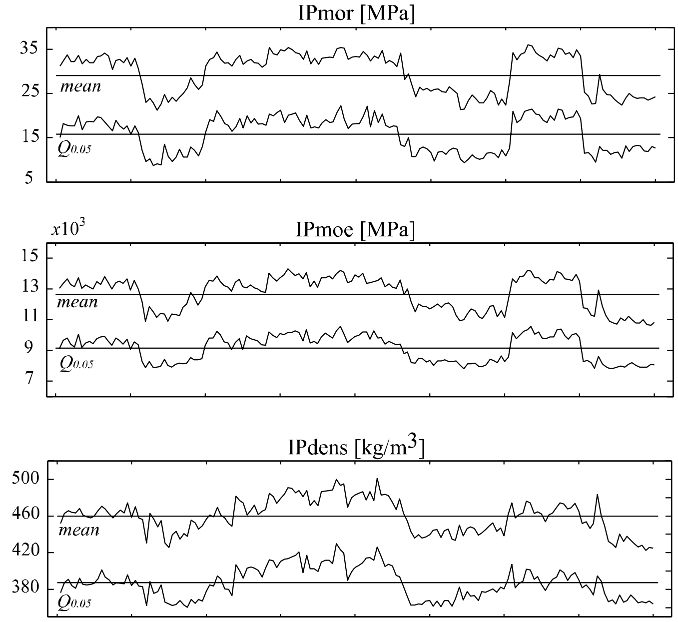

Figure 1: *Time series of characteristic mean and 0.05-fractile values of all k=160 sub-samples for IPmor, IPmoe and IPdens.*

Figure 1 shows the assessed mean and 0.05-fractile values for each sub-sample and every type of indicating property. The straight line in the middle of the figures illustrates the average value of all 160 sub-sample mean values. Equivalently, the lower straight line indicates the average value of all 160 sub-sample 0.05-fractiles. The jagged lines represent the mean and 0.05-fractiles of the three indicating properties for every particular sub-sample probability distribution. Definite shifts in the jagged lines of the indicating properties are observable. The most significant fluctuations can be found in the grading process starting at board numbers about 2,000, 22,000, 40,000, 122,000 and 142,000.

For the IPmor and IPdens the average of the 0.05-fractiles is taken as desired characteristic of timber material input quality. Lower Control Limits (LCL) and Upper Control Limits (UCL) can be defined based on these desired quality characteristics.
For MOE the average value of the sub-sample means is used as desired quality level. That means that the timber material as it is delivered to the manufacturing enterprise should in average exhibit these statistical characteristics.

Three methods for the identification of deviations in the quality of the input timber material are applied to the dataset.
The first one adapts the *CUSUM* control chart method which is given in the European Standard EN 14081, part 3 as one of two possibilities for the control of machine strength grading in Europe. In the context of the investigations of this paper this method is denoted as the *non-destructive CUSUM method*. Instead of really proof loading the timber specimens physically just the predicted grade determining properties are evaluated.
The second method, the *control limit method*, first defines desired values for the overall input timber material properties and based on these, upper and lower control limits are calculated to control the quality of the input timber material.
A third method quantifies differences in the regression coefficients where the relationships of the different IPs are compared to each other between the different source countries of the timber. The effect of growth areas is discussed based on this method. Additionally the regression coefficients of the three IPs assessed on data of remarkably varying input timber material quality are compared.

The results of the application of these three methods are presented in detail at the World Conference of Timber Engineering 2010 in [2].

The core element for the detection of quality shifts is the continuous real-time monitoring of the grading machine measured strength, stiffness and density indicating properties. Different approaches can be used to indicate quality deviations directly based on these non-destructive data measurements. On this way both of the following items can be avoided: 1) Expensive destructive testing procedures although the material quality and production process is “under control”. 2) Inefficient exploitation of the timber material potential since settings of the grading machine would be too conservative for extraordinarily good timber quality.

One major benefit of the introduced approach is that a reaction to the currently observed input material quality is just needed if significant shifts in the predicted characteristics are indicated by the control methods. Thus, both can be optimized: the benefit in the context of higher yields and more accurate classification as well as the reliability of the timber material characteristics as required for further processing by the customer or by the codes and standards.
The results of the investigations show that shifts in the input quality may be detected by applying control chart methods to the observed data. CUSUM values are assessed by non-destructive "proof loading" and recorded in the control charts. As an alternative approach the general average characteristic values of the timber input material can be assessed based on probabilistic methods. These may serve as a benchmark for the definition of so-called desired values. Accepting a certain range around these desired values (upper and lower control limit) quality of the input material can easily be controlled in real-time. Regression analysis can be conducted to show the influence of different source countries on the regression coefficients between the assessable indicating properties. This method gives more evidence to the detection of quality shifts.

2.2 Process calibration

Regression analysis is the central element for the assessment of the interrelationship between the IP of the grading machine and the relevant timber material properties assessed in laboratory and tried to be predicted by the grading machine. The result of the regression analysis can be described by a probabilistic regression model. Current machine grading methods in the European Standard EN14081 assume that the coefficients of the regression model remain constant over time not taking into account the fact that quality of the input timber material may fluctuate.

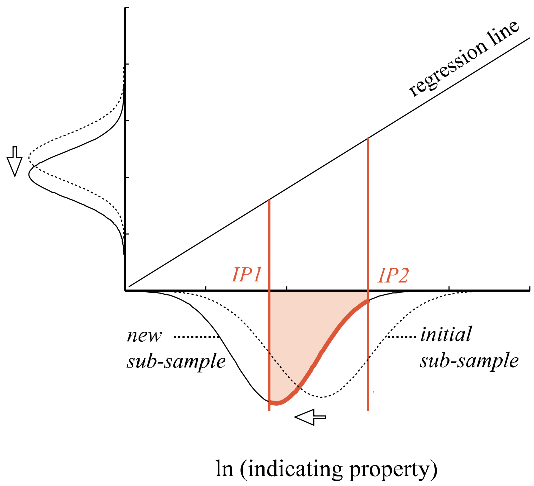

Figure 2: *Observations of the IP in the interval between IP 1 and IP 2 are assigned to the predictive probability density function of the grade determining property.*

Investigations within different projects have shown that re-calibration of the regression model in case of detection of significant quality shifts may enhance yield and reliability of the graded timber material. Based on re-calibrated coefficients of the regression model the settings of the grading device can be adjusted and output quality and yield may be enhanced. A detailed description of the mathematical process of regression analysis transferred to the problem of grading structural timber can be found in [4] and [6].

Figure 2 shows that observations of the IP in the interval between IP1 and IP2 (settings of the grading device) are assigned to the predictive PDF of the grade determining property (*e.g.* tension strength). The predictive PDF would be shifted downwards, if the multitude of the observations were made in the lower range of the interval. This shift is indicated by the arrows in Figure 2.

Data of Norway spruce specimens originating from $n = 1162$ simultaneous observations of the IP of the grading machine *GoldenEye 706* [3] and the timber tension strength are used in this study. The specimens that have been tested originated from different growth areas within Europe. The entire dataset is utilized for the representation of the average timber material quality. This sample is denoted as *initial sample*.

Figure 3 illustrates the regression model for the initial sample together with the corresponding data. The left part of the illustration shows the linear relationship when the indicating property and the grade determining property are transformed logarithmically. In Figure 3, right, re-transformed into normal scale, the relationship appears non-linear.

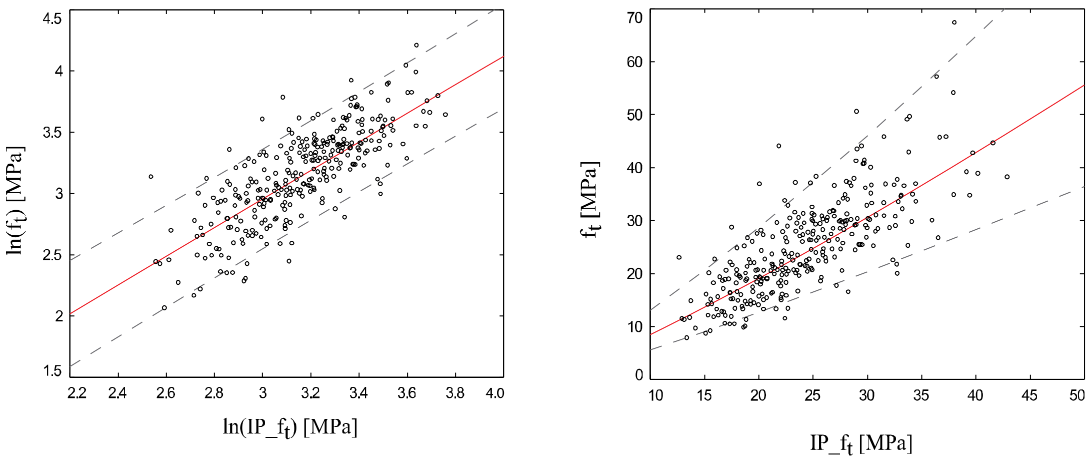

Figure 3: *Illustration of the established regression model based on observations of the IP of the tension strength and the tension strength.*

Sub-samples with apparently higher and lower input material quality are graded subsequently and the initial regression model is re-calibrated based on the additional observations of the sub-samples. Results can be found in detail in [6].

2.3 Process optimization

This section shows how an optimal (in terms of monetary benefit) set of timber grades can be identified by solving an optimisation problem. The objective function of the optimization problem is defined based on the outcomes of a probabilistic grading strategy. The identified timber grades can be described by means of the probabilistic characteristics of the relevant material properties (bending strength and MOE as well as density). The constraints to the optimization problem, in terms of the requirements for timber strength classes according to EN 338 are put directly into the objective function. In order to be able to solve the optimization problem, the cost of the control and the benefit of fulfilling the required characteristic values belonging to different grades have to be specified first.

In general it can be demonstrated how an optimal set of grading acceptance criteria for a specific grading procedure can be found by applying a predefined optimization function. A number of different grades according to EN 338 are selected as possible grades and a reject domain is defined for timber, which does not have to fulfil any requirements. Results are shown together with example values for the monetary benefit and the requirements in terms of material properties in the corresponding publication [7].

In practice the benefit associated with timber of a particular grade would depend on several factors such as the size of the individual timber member, the total amount of available timber for a given grade, the production capacity of a given sawmill, the available grading machines and not least the market price for timber of the different strength classes. The implementation of the proposed approach in practice would have to incorporate these and other factors into the formulation of the benefit function.

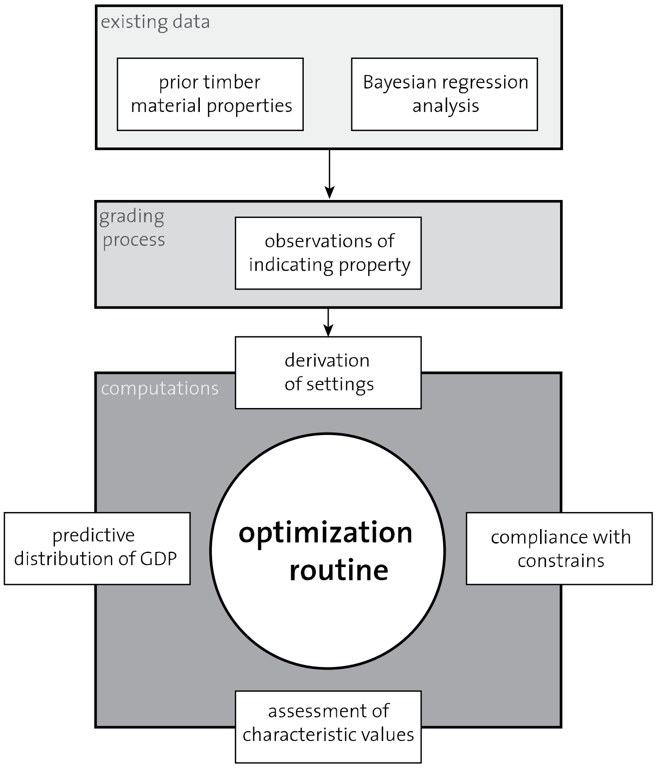

Figure 4: *Cost and reliability optimized machine grading based on probabilistic modelling concept.*

As illustrated in Figure 4 the introduced cost optimized concept for grading structural timber comprises several steps. A detailed description together with the results of an experimental application of this method can be found in [7].

The selection of a grading procedure can be made in relation to cost benefit considerations. Based on the proposed statistical modelling of timber properties as a function of the type and efficiency of the grading procedures, a cost optimization routine may be formulated for the identification of optimal grading. Therefore, the cost of the control and the benefit of fulfilling the requirements set for the material characteristics belonging to different grades have to be given.

3 Summary & Outlook

Different investigations have shown that there may be serious periodical variations in the input quality of the timber material which is used for industrial manufacturing of structural timber products. The core element for the detection of such quality shifts is the continuous real-time monitoring of the grading machine measured strength, stiffness and density indicating properties.
Based on this, a consistent and efficient strategy for control and improvement of structural timber material quality should involve three basic control elements: process monitoring, process calibration and process optimization.
It is shown that an optimized combination of these three elements may lead to improved benefit and reliability in the graded timber material.

The objective for future investigations is seen in the application of the proposed approaches under practical and industrial environment. Furthermore, ways of reaction with regard to adjustment of grading machine settings have to be defined and the consequences for the reliability of the output material properties have to be assessed.

4 Acknowledgment

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