Optimizing characteristic properties of visually graded soft- and hardwoods lamellas for the glulam production

Kovryga, Andriy; Stapel, Peter; Van De Kuilen, Jan Willem G

Publication date
2016

Document Version
Final published version

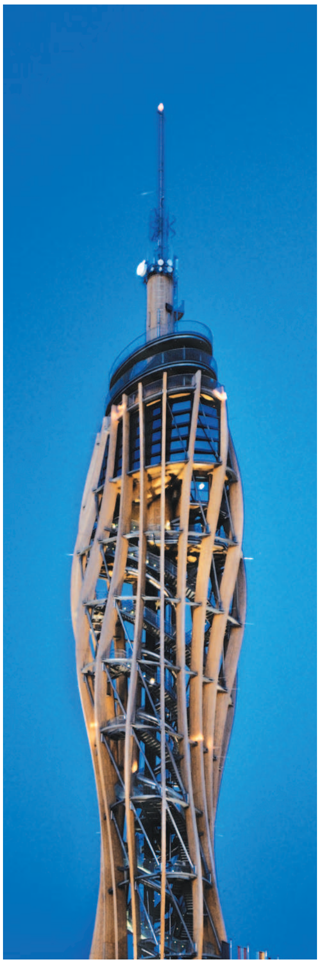
Published in
WCTE 2016 - World Conference on Timber Engineering

Citation (APA)
Kovryga, A., Stapel, P., & Van De Kuilen, J. W. G. (2016). Optimizing characteristic properties of visually graded soft- and hardwoods lamellas for the glulam production. In J. Eberhardsteiner, W. Winter, A. Fadai, & M. Pöll (Eds.), *WCTE 2016 - World Conference on Timber Engineering* (pp. 782-790). Vienna University of Technoclogy.

WCTE 2016

World Conference on Timber Engineering

August 22-25, 2016 | Vienna, Austria



e-book
Full Papers

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

Institute of Architectural Sciences
Department of Structural Design and Timber Engineering
Vienna University of Technology

INSTITUTE FOR MECHANICS OF MATERIALS AND STRUCTURES
imws

WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

WCTE 2016 e-book
containing all full papers submitted to the World Conference on Timber Engineering (WCTE 2016), August 22-25, 2016, Vienna, Austria

Editors:
Josef Eberhardsteiner, Wolfgang Winter, Alireza Fadai, Martina Pöll

TU Verlag
an der Technischen Universität Wien

Editor:
TU-MV Media Verlag GmbH
Wiedner Hauptstraße 8-10
A-1040 Wien
www.tuverlag.at
office@tuverlag.at

Bibliografische Information der Deutschen Bibliothek:

Die Deutsche Bibliothek verzeichnet diese Publikation in
der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet
über
http://dnb.d-nb.de abrufbar

www.tuverlag.at
ISBN 978-3-903024-35-9

WCTE 2016
World Conference on
Timber Engineering
August 22-25, 2016 | Vienna, Austria

OPTIMIZING CHARACTERISTIC PROPERTIES OF VISUALLY GRADED SOFT- AND HARDWOODS LAMELLAS FOR THE GLULAM PRODUCTION

Andriy Kovryga[1], Peter Stapel[2], Jan-Willem G van de Kuilen[3]

ABSTRACT: For the production of lamellas for GLT or CLT visually or machine strength graded timber is required. Visual grading allows only for a limited number of classes while reject rates tend to be high. The present paper shows the potential of an evolutionary algorithm NSGA-II optimizing the boundaries of multiple visual grading criteria in a reliable way. The optimization routine is applied to optimize the boundaries of the visual grading criteria given in DIN 4074-1 and DIN 4074-5. Destructive and non-destructive test data of 1515 specimens of Norway spruce (*Picea abies*) and 704 specimens of European beech (*Fagus sylvatia*) tested in tension were analysed. The optimization aims at: a) a maximization of the yield; 2) grade timber to the desired strength classes. Using this optimization routine for both beech and spruce higher yield figures compared to the grading according to DIN 4074 can be obtained while the desired characteristic strength are being reached.

KEYWORDS: Visual strength grading, DIN 4074, Characteristic Strength, Yield, Evolutionary algorithm, NSGA-II

1 INTRODUCTION

The characteristic strength of lamellas is important for GLT and CLT production and their mechanical properties. The producer utilizes strength graded lamellas specified for example in the European product standard EN 14080 or the European tensile strength class system EN 338.

For the production of lamellas strength graded timber is required. Strength grading can be done visually or by using a grading machine. In visual strength grading, only visual observable parameters are used whereas in machine strength grading invisible mechanical parameters can be used additionally.

Machine grading allows for an efficient production of lamellas as multiple strength classes and various strength class combinations can be selected by the producer for the specific grading machine used. Visual strength grading observes several shortcomings, as only a limited number of classes is available.

Another disadvantage is that the characteristic strength of the visually graded timber, as revealed in several studies [1,2,3], can differ significantly from the declared value. In the study of Johansson [1] a notably higher characteristic bending strength compared to the declared value for the highest grade was found for different national standards. Recently a number of grading rules from different countries were compared by Stapel and Van de Kuilen [2]. The study revealed that the allocations of the visual grades to the strength classes listed in EN 338 were not correct in several cases and precise declaration of the growth regions is required. Furthermore, the study has shown that the boundary parameters according to board grading rules given in DIN 4074-1 and DIN 4074-5 are not the optimal ones. Higher yields and easier grading can be achieved by grading the boards using the optimized rules, e.g. the adjusted joist grading rules for boards [3]. Beside the grading rules, grading standard and the origin performance of the visual grading depends on the cross – section [2,3].

Grading in higher strength classes and/or optimizing the grading boundaries for the yield improvement might provide sufficient competition advances for a producer by enhancing the raw material utilization. A method that would allow optimizing boundaries of multiple visual grading criteria in a reliable way was not studied yet.

In the present study the method using the multi-objective optimization for the grading rules adjustment dependent on the specific producer needs is presented. The objectives within the optimization are: 1) maximize the yield; 2) grade timber to the desired strength classes.

2 MATERIALS

For the current analysis Norway spruce (*Picea abies*) and European beech (*Fagus sylvatica*) specimens tested in tension are analysed. For the analysis 1515 spruce lamellas with dimensions ranging from 30x100 to

[1] Andriy Kovryga, TU München, kovryga@hfm.tum.de

[2] Peter Stapel, TU München, Germany

[3] Jan Willem van de Kuilen, TU München, Germany & TU Delft Fac. of Civil Eng., Netherlands

40x250 were selected. The beech sample accounted 704 specimens with cross sections between 25x100 and 40x170. The spruce specimens were tested in accordance with EN 408:2010 with a testing span of 9 times the height of the specimen, whereas for beech only 218 out of 704 were tested over 9h. For the remaining part the testing range was reduced to 200mm. For all the specimens the grade determining properties density, modulus of elasticity and tensile strength were measured. Additionally, the visual grading parameters in accordance with DIN 4074-1 have been recorded for each piece and are introduced in section 3. Knots above 5mm were measured.

Table 1 gives an overview of the specimens taken for the current analysis. The overall quality of spruce corresponds to the average quality reported for Central Europe. The low characteristic density of ungraded spruce is noticeable.

3 VISUAL GRADING

3.1 VISUAL GRADING CRITERIA

Visual strength grading is regulated in national grading standards and uses visible criteria to assign specimens to the visual grades. The optimization carried out in this study was applied on the German visual grading rules DIN 4074-1 [4]. Therefore, for the current specimens with cross-sections relevant for the glued laminated timber production the visual grading parameters required in grading rules for boards (‘‘Brett/Bohle’’) according to DIN 4074-1[4] were estimated. The visual grading parameters are:

DIN single knot (SK) the size of the single knot related to the width and calculated using equation:

$$SK = \frac{\sum a_i}{2 \cdot w} \quad (1)$$

where a_i is the size of the knot area *i* measured parallel to the edge of the board (Figure 1).

DIN knot cluster (KC) is considered for all knots appearing over a length of 150 mm. The Knot cluster is calculated as follows:

$$KC = \frac{\sum a_i}{2 \cdot w} \quad (2)$$

where w is the width and a_i is the spread of the knot over the width of the board appearing over 150 mm. Both grading criteria single knot and knot cluster are considered for the grading of boards and lamellas.

Edge knot criterion (Schmalseitenast) – E needs to be taken into account additionally. This criterion considers the penetration depth of the Edge knot E. Figure 1 shows how E is determined. However, for boards used for glulam lamellas production the criterion is not required as a grading criterion.

E is calculated using the following equation:

$$E = \frac{e}{w} \quad (3)$$

If more than one knot appears on the side, using the equation 4:

$$E = \frac{\sum_{i=1}^{n} e_i}{w} \quad (4)$$

The presence of the *pith* is considered for the analysis and represented as present (1) and not present (0).

The low value of the visual grading criteria stands for either rare occurrence or small size of the strength reducing knots and therefore higher strength values. Conversely, high values of the visual grading criteria intend lower strength values.

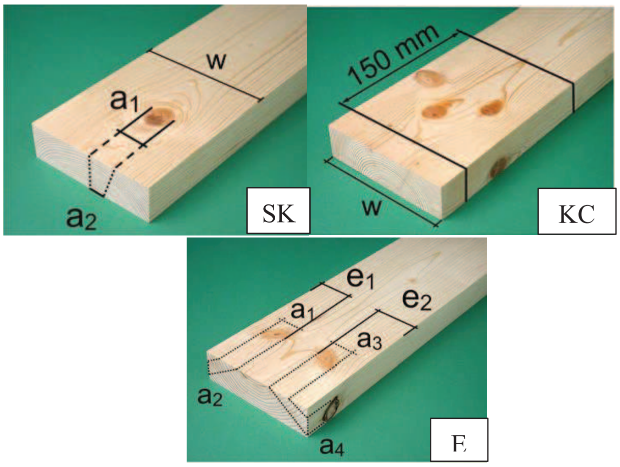


Figure 1: *Measuring rules for knots according to grading rules for boards according to DIN 4074 – 1. (Adapted from [3,5])*

Table 1: *Descriptive statistics of the materials used in the current study*

Species	N	Statistics	SK [-]	KC [-]	E [-]	ρ_{12} [kg/m³]	$E_{0,12}$ [N/mm²]	$f_{t,150}$ [N/mm²]
Spruce	1515	μ	0.183	0.362	0.424	445	11546	30.1
		CV [%]	43.9	44.5	78.2	12.0	23.0	43.0
		$Q_{0.05}$	0.106	0.124	0.000	366	7576	13.6
Beech	704	μ	0.121	0.140	0.036	722	13413	64.9
		CV [%]	102.7	100.9	323.5	5.7	22.8	50.2
		$Q_{0.05}$	0	0	0	658	7725.0	22.6

3.2 GRADING PROCESS

During the visual grading the timber piece should match the boundaries of the visual grades in order to be assigned to a grade. The visual grades listed in DIN 4074-1 for softwoods are S13, S10 and S7. The grade S13 shows the highest requirements on the mentioned visible parameters, whereas S7 maintains the lowest ones. For hardwoods the corresponding visual grades are listed in DIN 4074-5 [6] and are: LS13, LS10 and LS7.

To optimize the visual grading performance, the entire visual grading is considered as a function that assigns boards based on certain boundary values of the grading parameters to the corresponding visual grade.

Consider $v_{b,m}$ = $(v_{b,1} \ldots v_{b,m})$ as a vector of grading parameters m of a board b. The board b is assigned to the visual grade G if the following conditions are true:

1. Each value of the grading parameter in a vector $v_{b,m}$ should not exceed the upper boundary of the class ($x_{up,m}^{(G)}$)

$$v_{b,m} \leq x_{up,m}^{G}, m = (1 \ldots m) \quad (5)$$

2. At least one $v_{b,m}$ exceeds the upper boundary of the next higher class $G+1$

$$\exists v_{b,m}, m = (1 \ldots m): \; v_{b,m} > x_{up,m}^{G+1} \quad (6)$$

For the highest grade S13 the $x_{up,m}^{(G+1)}$ = 0.

3.3 STRENGTH CLASSES

In Europe national grading standards should not assign any characteristic property values to the visual grades. EN 1912 lists for each combination of specimen, grading standard, visual grade and origin the corresponding strength grade.

The strength classes and their respective characteristic properties are listed in EN 338. The major characteristic properties are: 5th percentile of tensile/bending strength, the mean static modulus of elasticity, and the 5th percentile of the density. Depending on the product application the bending or the tension properties are of interest.

Table 2: *Requirements on the characteristic properties for the tensile strength classes [7]*

Strength class	ρ_k [kg/m³]	$E_{t,0,mean}$ [N/mm²]	$f_{t,0,k}$ [N/mm²]
T14	350	11000	14
T14.5	350	11000	14.5
T15	360	11500	15
T16	370	11500	16
T18	380	12000	18
T21	390	13000	21
T22	390	13000	22
T24	400	13500	24
T26	410	14000	26
T28	420	15000	28

For glulam lamellas due to the increased demand on glulam products the tension classes were recently harmonized and introduced to FprEN 338:2015. Currently, the tensile strength classes are limited to softwoods only and called T classes. For hardwoods no separate tensile strength classes are listed in FprEN 338:2015. However, visual grades for hardwoods can be assigned to T classes as well, as it is done in the current study. Table 2 gives an overview of the T classes and corresponding major characteristic properties.

4 MULTI-OBJECTIVE OPTIMIZATION

4.1 General on multi-objective optimization

Real life decisions contain several, mostly conflicting, objectives that prevent a simultaneous optimization. As a result, not a single solution but rather a set of optimal solutions, so called Pareto-optimal solutions, is a target of multi-objective optimization. The Pareto-optimal solution is not-dominated by any other solution in the objective feature space, meaning that this solution is not worse than other solutions in all objectives and is at least better in one [9]. The principle of non-dominance is illustrated in Figure 2. Whereas the solution B is a non-dominant solution, the solution A is dominated by B. Based on the obtained set of solutions, also called Pareto front, a designer can make a trade-off on a limited number of solutions, rather than considering the full range of possible solutions. Such solutions would allow for sawmillers to maximize yield in certain classes or optimize the strength profile, or both in a multi-objective space.

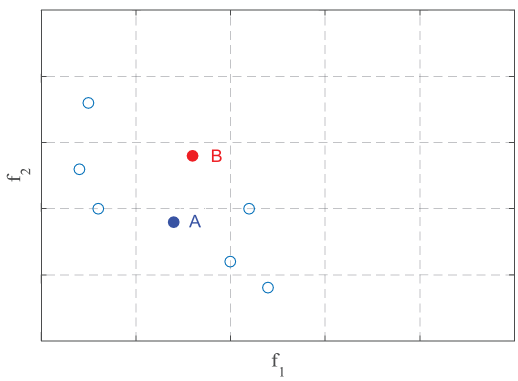


Figure 2*:Non-dominance principle with A dominated by B*

4.2 NSGA-II Algorithm

To find a set of potential solutions in the current study the Fast Non-Dominated Sorting Genetic Algorithm, called NSGA-II, introduced by Deb et al. [8] was used. The NSGA-II is a widely used powerful optimization algorithm [9]. For all genetic algorithms, the underlying principle is similar - the extinction of weak and unfit species by the natural selection [9]. Based on their fitness, stronger individuals have a greater chance to pass in the next generation. In our case an individual is a solution - combination of yield and characteristic strength/ and tensile strength class obtained by grading with a certain visual bounds. As the algorithm operates, fitter solutions survive from generation to generation [9].

The NSGA-II has several key features such as elitism – meaning that the best solutions are retained during the life-time of the algorithm or fast non-dominant sorting algorithm [8].

Basically, the algorithm runs through the followings steps:

1. Initial population. The initial population is created randomly out of the possible range for the decision variable.

2. Non-dominant population sorting. The best individuals are selected for the next generation based on their fitness, whereas the lower valued are rejected and new generated solutions take their place. Therefore, the NSGA-II uses fast non – dominant sorting algorithm to sort individuals in several non - dominant levels/fronts. The individuals in the first front are non-dominant at all, whereas the individual in the following front are dominated by the solution in the first front.

3. Crowding distance is used to assure the uniform spread of solutions (diversity) in the next population. The individuals from the non-dominant front that pass in the next generation are selected. The crowding distance is the distance between two neighbour solutions $z_k(x_{[n+1,k]})$ of the same non-dominant front along each objective [8]. It is calculated for each objective separately using the equation [9]:

$$cd_k(x_{[n,k]}) = \frac{z_k(x_{[n+1,k]}) - z_k(x_{[n-1,k]})}{z_k^{max} - z_k^{min}} \qquad (7)$$

4. New population. Creating a new population is an important step within the algorithm. New population R_t in generation t is a combined population of the population P_t as a part of the population P_{t-1} selected for the next generation based on non-dominance sorting (step 2) and crowding distance (step 3) and an offspring (children) population Q_t produced using the procedures *selection*, *crossover* and *mutation*. To create the offspring population for a new generation at first some individuals are selected using the crowding tournament selection operator (non-dominant rank r and the local crowding distance). Afterwards the crossover and mutation are applied to produce the new generation. During the crossover a new solution inherent to the characteristics is produced, whereas a mutation provides changes in the initial values of some genes by a chance and produces gene values different than those of parents.

The NSGA-II is designed for the minimization problems. To maximizes the objective functions using NSGA-II the maximization problem was turned into the minimization problem. Therefore, the objective function is multiplied with -1 during the runtime of the algorithm.

4.3 OPTIMIZATION PROCEDURE

The aim of the current multi-objective optimization is to find the combination of boundaries for the grading criteria that maximizes the yield to the visual grades and their characteristic properties. For this purpose, an objective function used by the NSGA-II to find the possible solutions is defined in following.

To find combinations of boundaries with desired yield to S13 and S10 for softwoods and LS13 and LS10 for hardwoods, as well as intended characteristic properties, the visual grading (section 3) is expressed as a function of the grading parameters ($x_{up,m}$) and not of the individual board specimens:

$$f_{yield} = f(x_{up,m}^{s13}, x_{up,m}^{s10}) \qquad (8)$$

$$f_{strength} = f(x_{up,m}^{s13}, x_{up,m}^{s10}) \qquad (9)$$

For each inserted boundary combination ($x_{up,z}$) the specimens in a sample are assigned to the visual grades and, thus, yield and the 5th percentile of characteristic strength and the other characteristic properties are calculated. By matching the characteristic values listed in tensile strength class system (Table 2) the corresponding strength class is returned.

The optimization was applied for the grading to S13-S10 and S10+. The combination S13-S10 was preferred to S13-S10-S7, as in previous investigations S10 and S7 have shown similar characteristic values [3]. Furthermore, the current market share of S7 timber in Central Europe is minor, compared to S10. For optimizing the yield and characteristic properties the desired objectives were optimized simultaneously in a single simulation run. Particularly, for grading to S13 and S10 all possible combinations were built prior to the grading and used as an input to the objective function.

To model the decision making process the results of the visual strength grading in accordance to the DIN 4074 are considered as a reference. To compare the optimization results with the reference, several combinations leading to the same strength class out of the entire set of optimal solutions are presented and discussed in following. Additionally, to highlight the various possible solutions some boundary combinations leading to higher strength classes are included.

5 RESULTS

5.1 BI-DIMENSIONAL OPTIMIZATION

The genetic algorithm allows to find a set of Pareto-optimal solutions. The most intuitive interpretation delivers visualization in two dimensional space, where the aim is to optimize only two objectives, like the yield and the characteristic strength of one single class, like S10+ or the highest grade S13 in visual grade combination S13-S10. The optimization of characteristic strength and yield to S13 using the NSGA-II for Norway spruce is illustrated in Figure 3. Each point on the highlighted Pareto-front represents a potential solution ranging from the highest yield to the S13 to the left and ending up with the highest characteristic strength to the right. It should be noted that the algorithm searches for the optimal solution in the objective space without considering the decision variables.

For the assignment to the tensile strength class the grade determining properties mean modulus of elasticity and

5th percentile of density are considered in addition to the 5th percentile of tensile strength. In this case the assignment to the strength class is optimized, resulting in the discrete values for the strength classes. The optimization of this assignment is visualized in Figure 4 with classes over the x axis.

If the optimization of the characteristic strength is compared to the strength class optimization, clear differences are observable. Whereas up to 15% of the specimens show the tensile strength values that match the requirements of T26 on the characteristic tensile strength (26 N/mm²), no visual boundaries to assign the species to this class could be found. This and the maximum possible strength class T24 clearly suggests that the other properties are grade limiting and obviously no higher strength classes than T24 matching all characteristic values can be achieved.

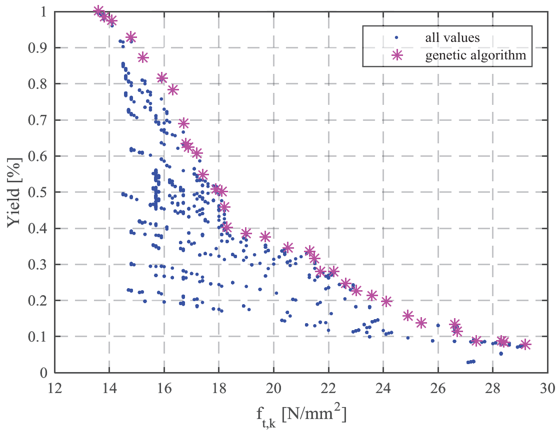


***Figure 3**: Solution space for objective functions yield and characteristic strength with pareto-front highlighted, for Norway spruce*

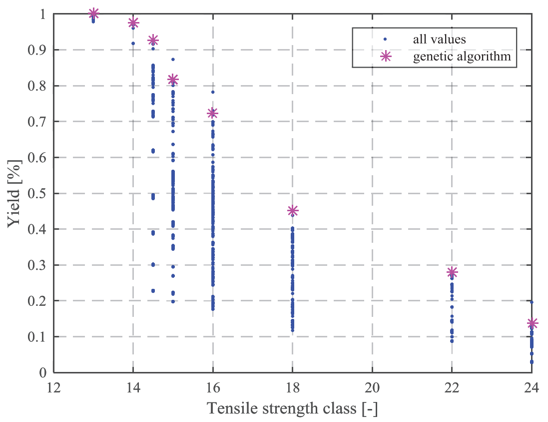


***Figure 4**: Solution space for objective functions yield and characteristic strength class with pareto-front highlighted, for Norway spruce*

5.2 MULTIDIMENSIONAL OBSERVATION

Usually, the multi-objective optimization comprises objective space exceeding two or even three dimensions. Whereas in our case the two dimensional observation was used for grading to "S10+", grading to S13-S10 included four dimensions – strength classes and the yield to both S13 and S10 separately. To visualize and analyse the results both a tabular summary and a spider-web chart (Figure 5) can be used. This chart shows five polygons representing the optimization solution and each apex of a polygon represents one criterion. The grading after DIN 4074 standard is used as a reference. The Figure 5a shows the yield to S13 and S10 for the different boundary solutions, if the S13 is assigned to T18 and S10 is assigned to T15. The yield to S13 and S10 if graded in accordance with DIN 4074 is enclosed by other optimal solutions. As can be seen for some solutions the yield to S13, for other in S10 is higher. For the solution "C" yields to both S13 and S10 are higher.

Using the algorithm different grade combinations can be achieved. The Figure 5b shows different possibilities to assign the S13 and S10 to the strength classes, if the yield is retained on the level of the total yield to S13 and S10 in accordance with DIN 4074. Whereas the total yield remains almost on the same level the assignment of S13 to T22 is possible ("E"). It is worse to note that the presented selection is only a part of the solutions returned by the algorithm. For some of the not presented solutions higher yield and/or higher strength classes compared to the reference could be achieved.

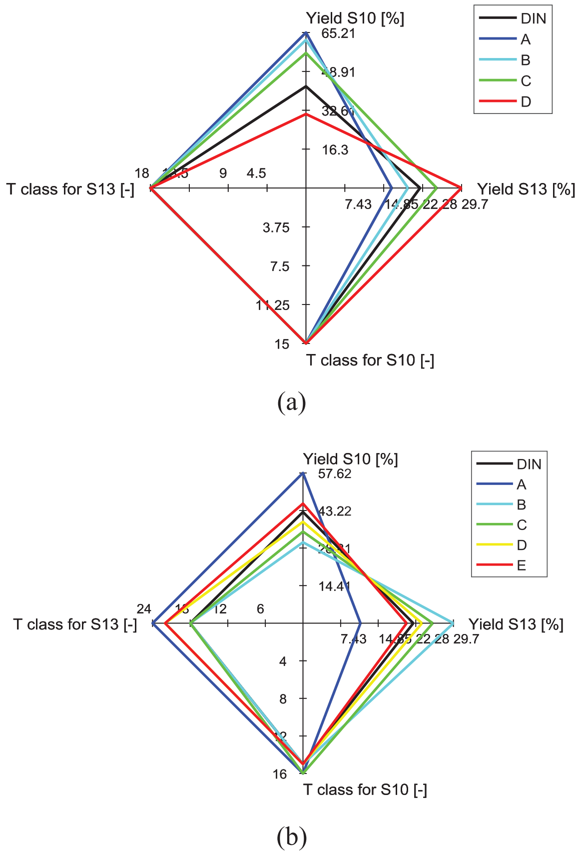


***Figure 5:** Spider web plot with optimization solutions for optimization of yield and strength to S13 and S10 for Norway spruce selected by: (a) Grade combination T18-T15, (b) same total yield to S13 and S10 compared to DIN 4074 (DIN)*

5.3 OPTIMIZING THE VISUAL GRADING BOUNDARIES FOR NORWAY SPRUCE

5.3.1 Grading to S13-S10

Out of the entire pool of potential "optimal" solutions only solutions with tensile strength grade comparable to the reference – DIN 4074 - are presented in following. The grading of the entire data set using the boundaries given in DIN 4074 leads to the following assignment: S13 – T18 and S10 assigned to T15.

The characteristic properties and the matched strength classes according to prEN 338:2015 are presented in Table 4. The solution "A" – "C" differ in yield to T18-T15, whereas "D" shows the highest possible grade for the same strength. Generally, for S13 assigned to T18 the characteristic density is the grade limiting property. Whereas for the lamellas graded after DIN 4074 the characteristic strength value (23.6 N/mm²) is above the requirements on the T22, the density meets only the requirements of T18 only (380 kg/m³). The selected optimization results "A" to "C" show characteristic strength value below the reference, even for the option with the highest property values. This suggests that the reference is not covered by the optimum and yields to the visual grades are lower than the ones returned by the algorithm.

Therefore, using the pareto-optimal solutions the highest total yield to S13 and S10 compared to the reference grading can be achieved. Option "D" shows for the same yield as the reference (~64 %) the highest possible assignment between visual grade and strength grade (S13 – T22).

The yield to the strength classes is shown in Figure 6. The solutions "A" and "B" show the highest total yield to both S13 and S10, whereas the option "C" shows the highest yield to S13 only if assigning S13 to T18.

In addition to the strength classes and the yields, the observation of the grading parameters is essential and shown in Table 3. For S13 the optimized alternatives show that the pith, if grading to T18-T15, is not needed as grading criterion. Whereas by simple adjustment of the criteria KC and E – solution "D" the characteristic values of T22 can be achieved.

Table 3: Boundary values of the grading criteria for Norway spruce graded with selected boundary combinations

Grade	Solution	SK	KC	E	Pith
S13	DIN	0.2	0.333	0.333	0
	A	0.2	0.4	0.2	1
	B	0.4	0.4	0.2	1
	C	0.2	0.3	0.6	1
	D	0.2	0.3	0.4	0
S10	DIN	0.333	0.5	0.666	1
	A	1	0.5	1	1
	B	1	0.5	1	1
	C	0.3	0.4	1	1
	D	1	0.4	1	1

The assignment of S10 to T15 leads for each combination except "C" to the simplified grading where both criteria - edge knot or/and single knot - are excluded from grading and the KC is considered as a single, major criteria.

It should be noted that the boundaries were optimized for the desired strength class combination – T18-T15. The optimization to the other combinations T22-T14 or T24-T14.5 are possible as well.

Table 4: Characteristic properties and Strength classes obtained with different boundary combinations for Norway spruce

Grade	Solution	N	ρ_k [kg/m³]	$E_{0,mean}$ [N/mm²]	$f_{t,k}$ [N/mm²]	T class
S13	DIN	330	380	13750	23.4	T18
	A	295	380	13600	21.7	T18
	B	378	380	13200	18.5	T18
	C	450	380	13400	20.6	T18
	D	324	390	13900	23.6	T22
S10	DIN	646	370	11500	15.4	T15
	A	941	370	11500	15.2	T15
	B	858	360	11500	15.3	T15
	C	470	370	11600	15.0	T15
	D	621	360	11700	15.5	T15

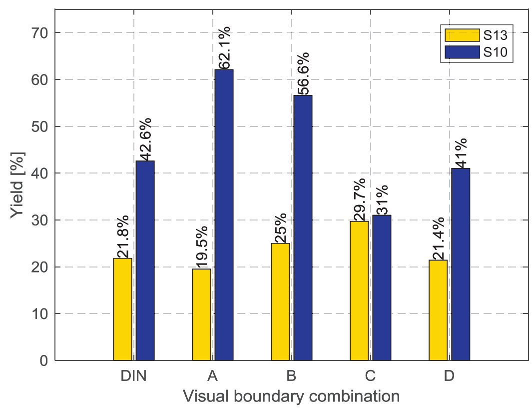


Figure 6: Yield to the visual grades S13 and S10 for Norway spruce graded using different boundary combinations

5.3.2 Grading to S10+

The grading in accordance with DIN 4074 to S10+ results in characteristic strength values of as high as T16 class. Using the optimized boundaries the yield can be increased from 64.4 % to 78.2 % if the edge knot criteria are not considered by the standard (Table 5). The pareto-optimal solutions include the combinations of grading boundaries that result in other, e.g. lower strength classes, with obviously higher yields. For assigning S10+ to T14.5 and/or T14 the knot cluster is the major grading criteria and the single knot is not needed to assign the species.

***Table 5:** Optimization results for Norway spruce graded to S10+ with different combinations*

	SK	KC	E	Pith	T class	Yield [%]
DIN	0.333	0.5	0.666	1	T16	64.4
A	1	0.4	0.5	1	T18	45.1
B	0.3	0.5	1	1	T16	78.2
C	0.3	0.6	1	1	T15	87.3
D	1	0.6	1	1	T14.5	92.8
E	1	0.7	1	1	T14	97.4

5.4 OPTIMIZING THE VISUAL GRADING BOUNDARIES FOR THE EUROPEAN BEECH

5.4.1 Grading to L13-LS10

The visual grading in accordance with German visual grading standard DIN 4074-5 is used as a reference for the optimization of the grading boundaries for the European beech. As no tensile strength classes for hardwoods are evident in the FprEN 338:2015, for these species the same tensile strength classes as for softwoods are used. Using the boundaries given in DIN 4074-5 the following assignment to the strength classes is possible: LS13 assigned to T26 and LS10 to T16.

The characteristic properties for the optimized solutions are presented in Table 7. For all solutions the MOE is the grade limiting property, whereas the density, as expected, exceeds the required values for softwoods.

Using the optimized solutions, the total yield to LS13 and LS10 can be increased. Figure 7 shows the yields to S13 and S10 achieved using different combinations of the grading boundaries. The combination "C" shows the highest possible yield to T26 with yields to LS13 and LS10 higher than the one achieved by visual grading according to DIN 4074-5. "A" shows the case with the same characteristic properties achieved for LS13 as in visual grading in accordance to DIN 4074-5. In this case the yield to LS13 is slightly higher. Combination "B" represents the case with the highest possible yield to LS10, if grading in combination with T26. It should be noted that the combination "D" shows the case where the higher strength class for LS13 is desired. The assignment of LS13 to T28 leads also to the higher tensile strength class – T18 – possible for LS10. The total yield to LS13 and to LS10 for the option "D" amounts 100%. Other combinations, not presented here are possible as well.

The boundary values of the solutions are shown in Table 6. The Knot cluster remains a major criterion whereas the presence of the pith can be excluded as grading criteria, even for the class T28. However, in this case (combination "D") the boundaries for the edge knot and knot cluster are stricter. For the assignment of LS10 to T16 or T18 the presence of the pith, single knot and edge knot can be excluded.

***Table 6:** Boundary values of the grading criteria for European beech graded with selected boundary combinations*

Grade	Solution	SK	KC	E	Pith
LS13	DIN	0.2	0.333	0.333	0
	A	0.2	0.5	0.3	0
	B	0.1	0.2	0.2	1
	C	0.4	0.3	0.1	1
	D	0.5	0.1	0.1	1
LS10	DIN	0.333	0.5	0.666	0
	A	1	0.9	1	1
	B	1	0.9	1	1
	C	0.5	0.6	0.8	1
	D	1	0.9	1	1

***Table 7:** Characteristic properties and Strength classes obtained with different boundary combinations for European beech*

Grade	Solution	N	ρ_k [kg/m³]	$E_{0,mean}$ [N/mm²]	$f_{t,k}$ [N/mm²]	T class
LS13	DIN	437	660	14500	35.6	T26
	A	439	660	14500	35.6	T26
	B	355	660	14900	40.6	T26
	C	539	660	14100	29.2	T26
	D	327	660	15000	41.7	T28
LS10	DIN	106	660	11600	23.0	T16
	A	265	660	11600	16.8	T16
	B	349	660	11900	17.9	T16
	C	155	670	11600	16.3	T16
	D	377	660	12100	18.4	T18

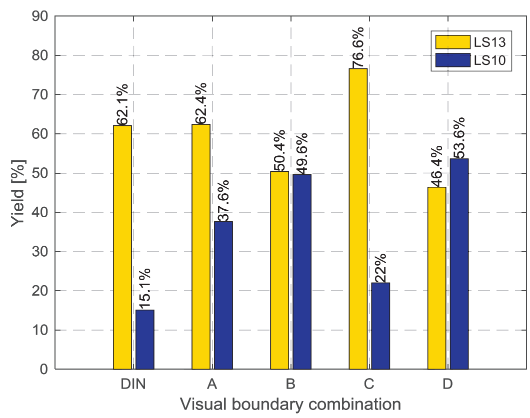


***Figure 7:** Yield to the visual grades LS13 and LS10 for European beech graded using different boundary combinations*

5.4.2 Grading to LS10+

In general, grading of European beech to LS10+ leads to yields of as high as 77.1 %. Even in this case, using optimization a higher yield to LS10+ is possible. The adjusted boundaries presented as a solution "A" in Table 8 result in by 8.4 % higher yield. Therefore, the value of E should be adjusted and the single knot criteria can be abandoned. Using the optimized boundaries assignment to other classes (T24) with higher yields (98 %) is possible ("B").

Table 8: *Optimization results for European beech graded to LS10+ with different combinations*

Solution	SK	KC	E	Pith	T class	Yield [%]
DIN	0.333	0.5	0.666	0	T26	77.1
A	1	0.3	1	1	T26	85.5
B	1	0.5	0.8	1	T24	98.0

6 DISCUSSION AND CONCLUSIONS

In the current study the boundaries of the visual classes were optimized using a NSGA-II algorithm for grading of Norway spruce to S13-S10 and S10+ and of European beech to LS13-LS10 and LS10+. The optimization procedure returns a combination of boundaries that satisfy the two optimization objectives: 1) maximize the yield; 2) grade timber to the desired strength classes.

For both spruce (section 5.3) and beech (section 5.4) a higher yield compared to the grading in accordance with the German visual grading standard DIN 4074 could be achieved. Furthermore, the timber can be graded to the other strength. Exemplarily, for spruce boundaries to assign S13 to T22 (section 5.3) or even to T24 (section 5.2) could be found. For spruce the grading in accordance with DIN 4074-1 allows the assignment of S13 to T18 only.

For beech boundaries to assign S13 to T28 and S10+ to T26 could be found. This assignment to the strength classes is higher than the one achieved by grading according to DIN 4074-5 (S13 – T26, S10+ - T24). Moreover, the assignments are above those reported by Glos & Lederer [10] and Glos & Denzler [11].

The reason for the assignment of the visual grades to higher strength classes for beech is attributed not only to the optimized boundaries. 486 out of 704 beech specimens were tested in tension over a length of 200 mm. Comparing these specimens to specimens tested over 9 times the height, a higher correlation of the defects to the strength can be found. If tested over a large testing range, the specimens would probably break frequently outside the selected 200 mm position. For this reason the results for beech should be taken as indicative only.

The optimized boundaries, returned by the algorithm, could be applied by GLT producers to grade timber to higher strength classes, or to optimize the yield of the currently used classes. The algorithm returns a finite set of pareto-optimal solutions. Hence, the producer has to make a trade-off which specific solution out of the entire set returned by the algorithm should be selected. The decision making might incorporate additional aspects not included into the algorithm, such as a demand for a lamella of a certain class.

The use of optimized boundaries is easier to implement if camera systems for grading timber are used. These systems measure knots with a higher precision compared to the human eye. Thus, the timber is assigned to the visual grades using new, optimized boundaries in a reliable manner. Moreover, for a human the visual grading using adjusted boundaries requires some extra time for accommodation. An increasing number of visual grading parameters makes it even harder and more time for the grading is needed. Therefore, for the visual grader the aspect of simplicity is important.

In the present study some simplification of the grading boundaries could be achieved. For Norway spruce graded to S10 and S10+ the edge knot and the single knot had no effect on the grading and only the threshold value for the knot cluster was returned by the algorithm. For S13, contrary, the threshold value is returned for all the criteria, even for the edge knot that is hard to measure. This finding differs from the one made by Stapel & van de Kuilen [3], who suggested alternative board rules without any threshold value on the edge knot criteria but adjusted the knot cluster value instead.

The algorithm does not guarantee to make the grading procedure easier. The evolutionary algorithm NSGA-II searches for the optimal solution in the objective space (yield, tensile strength class) and not in the decision space (grading criteria). Thus, easy to handle grading boundaries are not selected if the solution is not the optimal one. If easy to grade boundaries are required, some additional constrains on the decision variable, grading boundaries in our case, should be taken as an input to the algorithm. The possibility to eliminate grading criteria that are difficult to measure exists.

If taking a simplified grading rule the elimination of grading criteria should be examined carefully. For beech the optimization results suggest that the pith criteria could be eliminated. However, this is accompanied by stricter rules for the other knot criteria, such as knot cluster and edge knot in case of grading to T28. Glos & Lederer [10] reported that for limited number of beech specimens tested in tension the presence of the pith results in lower characteristic values and cracks, while no effect was found for the characteristic bending strength.

For the use of the algorithm a representative sample, covering several cross – sections, growth regions, sawing pattern, etc. is an essential requirement. As the algorithm adapts the boundaries of the visual grading parameters to the data set used for the optimization, the choice of the data is an important factor for valid results. Therefore, some additional samples should be taken to validate the optimized boundaries.

Finally, the potential of the algorithm to optimize the production of hardwood lamellas should be highlighted. In the current study the NSGA-II was used to find the optimal threshold values for the visual grading parameters only. However, for glulam out of hardwoods, regulated in Europe in national and European technical approvals, some additional requirements on the visually graded hardwood lamellas are frequently defined. For instance, German technical approval for glulam out of beech [12] requires some threshold values on the dynamic modulus of elasticity to be fulfilled. Such machine grading parameters can be incorporated into the optimization algorithm to determine threshold values for all parameters of interest (visual and machine grading parameters).

Overall, the use of a genetic algorithm, such as NSGA-II shows a large potential when optimizing visual grading rules. The current visual grading rules can be optimized for the needs of specific producers, both: with regard to the yield and strength. Higher yields or higher characteristic properties can be used by the developed optimization routine.

ACKNOWLEDGEMENT

The research was supported by the Federal Ministery of Food and Agriculture of Germany (BMEL).

REFERENCES

[1] Johansson C. J., Brundin J., Gruber R.: Stress grading of Swedish and German Timber. A comparison of machine stress grading and three visual grading systems. SP Report, 23:94, 1992.

[2] Stapel P., van de Kuilen J.-W. G: Efficiency of visual strength grading of timber with respect to origin, species, cross section, and grading rules. A critical evaluation of the common standards. In: *Holzforschung.* 68 (2), 2013.

[3] Stapel P., van de Kuilen J.-W. G: Influence of cross-section and knot assessment on the strength of visually graded Norway spruce. In: *Eur. J. Wood Prod*. 72 (2): 213–227, 2014.

[4] DIN 4074:2012 Strength grading of wood - Part 1: Coniferous sawn timber.

[5] Glos P., Richter C.: Sortierhilfen und Erläuterungen zur Anwendung der DIN 4074 in der Praxis. Holzforschung München, final report Nr. 01510, 2002.

[6] DIN 4074-5:2008 Strength grading of wood - Part 5: Sawn hard wood.

[7] FprEN 338:2015 Structural timber - Strength classes.

[8] Deb K., Pratap A., Agarwal S. and Meyarivan T.: A fast and elitist multi-objective genetic algorithm: NSGA-II. Evolutionary Computation, *IEEE Transactions on*, 6(2): 182-197, 2002.

[9] Konak A., David W. C., and Alice E. S.: Multi-objective optimization using genetic algorithms: A tutorial. *Reliability Engineering & System Safety,* 91(9), 992-1007, 2006.

[10] Glos P., Lederer B.: Sortierung der Buchen- und Eschenschnittholz nach der Tragfähigkeit und Bestimmung der zugehörigen Festigkeits- und Steifigkeitskennwerte. Holzforschung München, final report Nr. 98508, 2000.

[11] Glos P., Denzler J.: Allocation of Central European Hardwoods into EN1912, paper 39-6-1. In: *Proceedings of the 39th Meeting, CIB-W18.* Florence, Italy, 2006.

[12] Z-9.1-679: German technical building approval issued by DIBt for “Glulam from beech wood and beech hybrid glulam beams” (in German); approval issued first on 07. Oct. 2009; approval holder: Studiengemeinschaft Holzleimbau e. V.,2013.