WCTE 2018
2018 World Conference on Timber Engineering
August 20 - 23, 2018 | Seoul, Republic of Korea

SOME THRESHOLDS FOR GRADING BRITISH GROWN SPRUCE TO OPTIMISED STRENGTH CLASSES USING LONGITUDINAL RESONANCE

Dan Ridley-Ellis[1], Steven Adams[1] and Stefan Lehneke[1]

ABSTRACT: The main commercial species in the UK and Ireland is Sitka spruce (*Picea sitchensis*), which is graded in combination with a small amount of Norway spruce (*P. abies*). It is typically graded to the European strength class C16, but actually has superior strength and density, meaning that some performance capability is exchanged for trade convenience. When grading timber as part of the construction processes, rather than putting structural timber on the general market, it makes sense to use user-defined strength classes that better match the real properties of the timber and also allow better grading yields than the general grades. This paper is an illustration of the European method for calculating machine controlled grading settings (both EN 14081-2:2010+A1:2012 and draft revision FprEN 14081-2:2018), but with non-standard strength classes designed to maximise overall yield and timber potential. Grading thresholds are presented for a generic grading device based on longitudinal resonance, mass and moisture content. The yields with the current and revised standard are compared.

KEYWORDS: Grading, Sorting, NDT, Resonance, Sitka spruce, Norway spruce, User defined strength classes

1 INTRODUCTION

In Europe, structural timber can be graded by machine using fixed settings ("machine control") under the harmonised standard EN 14081 [1]. Usually, the timber is assigned to strength classes listed in EN 338 [2]. While these generic strength classes are good for general trade, they do not always make sense when grading timber for a specific project, as one or more of the real characteristic properties of the timber may be significantly higher than those of the generic strength class [3]. Modern grading machines, particularly those based on longitudinal resonance, can be portable and relatively inexpensive which opens up the possibility for grading to be done by the builder or pre-fabricator rather than the processor. In this case, it makes more sense to use user-defined strength classes.

This paper shows the calculation of settings for user-defined grades that fit better to the actual properties of spruce grown in the United Kingdom and the Republic of Ireland. They are made according to the current [4] and proposed new [5] versions of EN 14081-2 illustrating the application and basis of that standard, and the differences between the two versions. The symbols and units used in this paper are listed in Table 1.

The settings are for a grading machine working on the principal of longitudinal resonance with mass measurement. This paper serves as an illustration only, and additional steps are necessary for use in grading according to EN 14081.

2 SAMPLING

Representative sampling is a critical step in the development of machine control grading and the timber tested must resemble the population to be graded as well as possible [5,6,7].

The species combination known as "British spruce" (WPCS) is made up Sitka spruce (*Picea sitchensis*) and Norway spruce (*Picea abies*) [1]. In the UK and Ireland this is approximately 92% Sitka. Sawmills do not differentiate between these two species and they are processed and sold together. The primary wood processing industry is active across the border of the two countries and so, to be representative, the sampling needs to cover both species and both countries.

The sampling also needs to represent the geographic distribution of the timber resource within the countries, and take into account what is known about geographical variation in wood properties. The sampling was grouped into five subsamples and comprised timber sourced from normal production (I,J,K,L), plus one subsample from a scientific study (H) that is similar to industrially produced timber (both the logs and the cutting patterns).

[1] Dan Ridley-Ellis, Edinburgh Napier University, Centre for Wood Science and Technology, Edinburgh, United Kingdom, d.ridleyellis@napier.ac.uk
Steven Adams, Edinburgh Napier University, Centre for Wood Science and Technology, Edinburgh, United Kingdom, s.adams@napier.ac.uk
Stefan Lehneke, Edinburgh Napier University, Centre for Wood Science and Technology, Edinburgh, United Kingdom, s.lehneke@napier.ac.uk

Table 1: *Symbols and units*

	Description	Units
General		
n	Count of pieces	-
CoV	Coefficient of Variation	%
Piece measurements at moisture content u		
f_u	Longitudinal natural frequency	Hz
L_u	Length	mm
M_u	Mass	kg
T_u	Thickness	mm
W_u	Width	mm
Grading		
IP	Indicating property	N/mm^2
IP_{12}	Indicating property, 12% mc	N/mm^2
IP_u	Indicating property at mc u	N/mm^2
Bending strength, adjusted to 150 mm width		
$f_{m,mean}$	Mean	N/mm^2
$f_{m,k}$	5th percentile	N/mm^2
Modulus of elasticity in bending, parallel to grain		
$E_{0,mean}$	Mean, adjusted to 12% mc	kN/mm^2
Density		
ρ_{mean}	Mean, adjusted to 12% mc	kg/m^3
ρ_k	5th percentile, adj. 12% mc	kg/m^3
Moisture content of the timber		
u	Of a piece, or mean of a batch	%
$u_{test,mean}$	Mean at time of testing	%
$u_{grade,mean}$	Mean at time of grading	%

Table 2: *Sampling, nominal dimensions*

Thickness (mm)	38	47	47	47	75
Width (mm)	100	100	120	150	150
Length (m)	2.4	3.0	3.0	3.0	3.6
H (North of UK)		149		75	
I (North of UK)		70			39
J (North of UK)	10		79		39
K (Ireland)	50	75			40
L (South of UK)	10	49			40
Total (n = 725)	70	343	79	75	158

Table 3: *Summary of properties of the sample*

Subsample*	H	I	J	K	L	All
n	224	109	128	165	99	725
$f_{m,mean}$	31.3	31.0	31.6	32.6	31.9	31.7
$f_{m,k}$	15.4	17.9	20.3	16.7	18.3	17.2
CoV	35	27	24	29	28	30
$E_{0,mean}$ **	8.22	8.71	8.39	8.33	8.57	8.40
CoV	27	27	25	29	25	27
ρ_{mean}	399	409	391	406	394	400
ρ_k	334	344	315	336	323	332
CoV	11	12	11	10	12	11
$u_{test,mean}$	11.0	15.7	13.9	11.9	14.0	12.8
$u_{grade,mean}$	13.3	14.2	12.9	11.4	13.6	13.0

* Strength, stiffness and density differences between the subsamples are likely to be random effects rather than genuine regional differences (see [12] for this topic).

** Stiffness is measured global modulus of elasticity [9] adjusted to equivalent shear free with an equation based on test data [10] for British spruce.

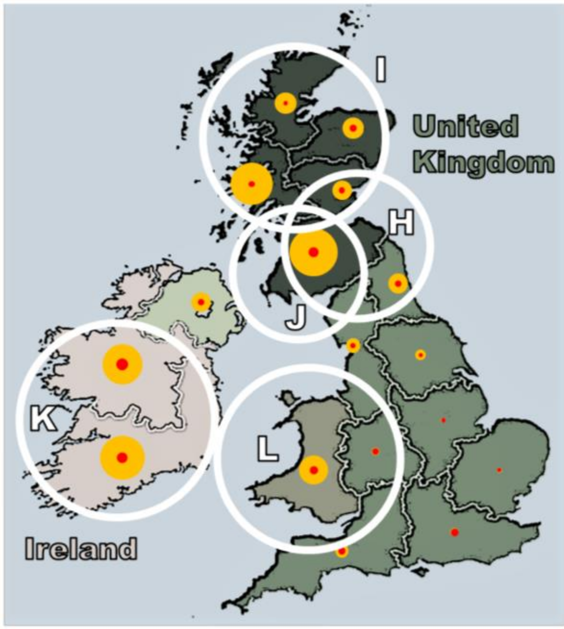

Figure 1: *Sampling locations and spruce resource*

Figure 1 shows the approximate locations from where sub-samples of timber were taken, and the distribution of the spruce resource by region (indicated by area of the circles). The proportion of Norway spruce is indicated by the red inner circle.

Since it is known that the Sitka and Norway spruce have very similar properties [8] it was not necessary to distinguish which pieces were which species, only to reflect the typical mix of the two in normal production.

The size range also needed to be representative of typical production while also including sufficient number (≥40) of specimens at the smallest and largest end of the range to be graded. Cross-section sizes (Table 2) ranged from 38 mm x 100 mm up to 75 mm x 150 mm and timbers were long enough to enable edgewise four-point bending testing with worst defect positioned centrally as required in Europe [9,10]. The properties of the timber (ungraded) are summarised in Table 3, where density and bending stiffness are adjusted to reference moisture content of 12% and the bending strength to a reference width of 150 mm [10]. Fifth percentile is calculated by ranking (non-parametric method) without confidence limits [10,11]. Differences between the subsamples are likely to be random effects from small sample size, rather than genuine regional differences (see [12] for this).

Both the current [4] and the revised [5] version of EN 14081-2 require sub-samples to contain at least 100 specimens. Subsample L is only 99 pieces since some specimens had to be removed due to problems with the destructive measurement.

The total number of pieces required by the current standard is 450, since this type of machine has previously had settings approved in Europe (otherwise it would be 900). The revised standard only requires 450 in either case. Both versions of the standard require at least four subsamples and for each country to have at least one subsample (for the current standard this country requirement is added by the TG1 decision list [13])

3 INITIAL GRADING AND TESTING

The timber was non-destructively measured with a Brookhuis MTG 960 portable grading machine in production conditions, prior to destructive measurement [9] of modulus of elasticity and strength in bending. and also density and moisture content by the oven dry method. The MTG 960 is an approved grading machine in Europe, but it serves here as a generic device measuring longitudinal natural frequency and mass. Dimensions and moisture content are measured by the operator.

The Indicting Property (IP) used here is the dynamic modulus of elasticity in N/mm², adjusted to a reference moisture content of 12% in the same way that static modulus of elasticity is adjusted in EN 384 [10] (Equation 1).

$$IP_u = \left(\frac{M_u}{T_u \times W_u \times L_u}\right) \times (2 \times L_u \times f_u)^2$$
$$IP_{12} = IP_u \times \left(1 + 0.01 \times (u - 12)\right) \quad (1)$$

$8\% \leq u \leq 18\%$

For British spruce from UK and Ireland, this indicating property is well correlated with modulus of elasticity in bending (Figure 2). There is one erroneously measured IP which is kept in the analysis since it is a mistake by the machine (it picked the wrong harmonic, the IP should be half this) which may happen in practice from time to time. The grading settings need to account for machine performance under production conditions.

The correlation is reasonably good for strength (Figure 3) and density (Figure 4). Density from mass measurement is much better as a predictor for density, but since density is not critical in the grading, in this case, it is most convenient to simply use dynamic modulus of elasticity as a single IP for all properties. An IP that includes density in its own right, or dimensions, is possible, but in this case the dynamic modulus of elasticity alone is the best predictor.

Four user-defined strength classes were created as part of this calculation. As with the normal EN 338 classes [2] they are defined by requirements for 5th percentile strength, mean stiffness, and 5th percentile density (Table 4), with other (secondary) properties calculated from these by the equations in EN 384 [10]. These user-defined strength classes are for use in pairs (an upper grade, a lower grade, and reject) aiming for minimal reject and, roughly, grading yields of 25%/75% and 50%/50%.

The user-defined strength class NapierSA is paired with NapierSC, and NapierSB is paired with NapierSD. For comparison, the requirements of the usual EN 338 classes C24, C22, C16 and C14 are also listed.

NapierSA has slightly better strength and density than C24, and NapierSC has slightly better density than C16. C24 and C16 are the commonly specified timber strength classes in UK and Ireland so this combination is particularly relevant, especially as NapierSA could be treated as if it were C24 and NapierSC as if it were C16.

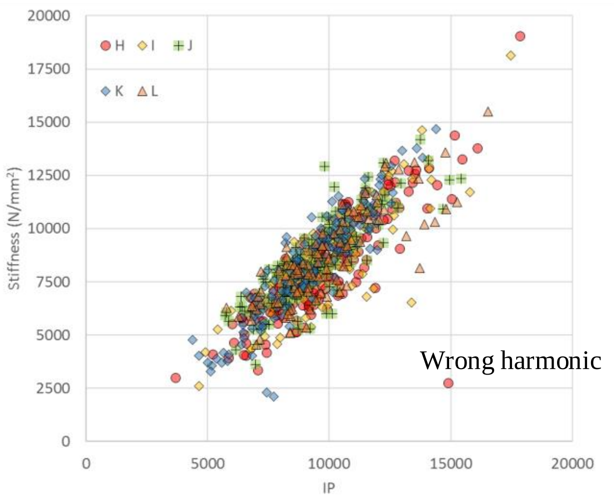

Figure 2: *IP_{12} and stiffness (R^2 0.67 to 0.82, overall 0.71)*

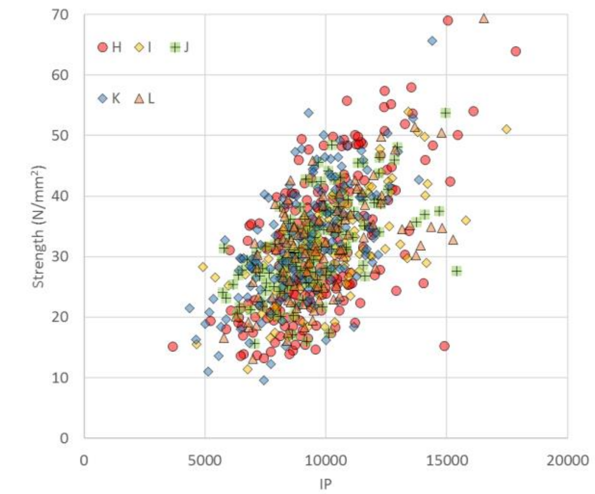

Figure 3: *IP_{12} and strength (R^2 0.36 to 0.44, overall 0.35)*

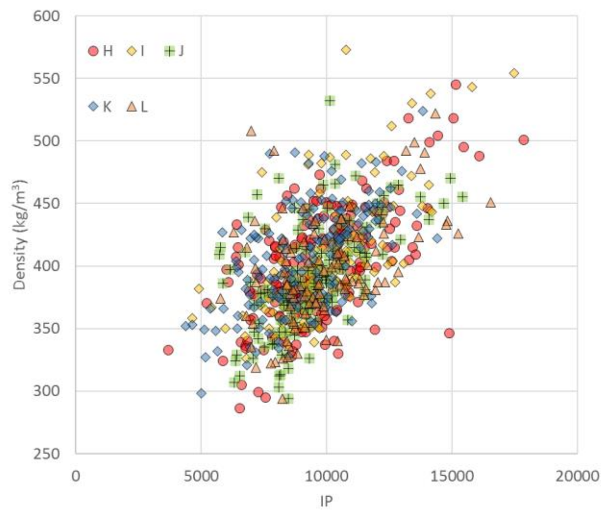

Figure 4: *IP_{12} and density (R^2 0.21 to 0.43, overall 0.32)*

Table 4: User defined strength classes

Name	$f_{m,k}$ (N/mm²)	$E_{0,mean}$ (kN/mm²)	ρ_k (kg/m³)	≥ class [2]
NapierSA	25	11	375	C24
NapierSB	22	10	360	C22
NapierSC	16	8	320	C16
NapierSD	15	7	310	C14
C24	24	11	350	
C22	22	10	340	
C16	16	8	310	
C14	14	7	290	

4 CALCULATION OF SETTINGS

4.1 GENERAL

The basis of grading settings calculation is to calculate thresholds for IP that satisfy the required grade properties (Table 4), subject to some adjustments. The requirement for stiffness is actually only 95% of the grade mean (compensating for testing with critical section placed centrally [7]). For machine grading, the strength target can also be reduced by the k_v factor in EN 384 [10], but this is not applied in this case as these settings are intended to be useable by a portable grading machine.

Grading is either NapierSA/NapierSC/reject or NapierSB/NapierSD/reject. The combination of C24/C16/reject is shown for comparison. The settings calculations are only summarised is this paper.

4.2 SETTINGS TO EN 14081-2:2010+A1:2012

Settings were calculated according the procedures currently approved for use [4] including the decision list of CEN TC124 WG2 TG1 [13]. The calculated grading thresholds are summarised in Section 5.

The first step is optimum grading, which simulates a machine with perfect knowledge of the timber properties. This step assumes that the aim for grading is to maximise yield in the highest grade, rather than minimise reject, and this can cause some artificial problems with the current standard (as will be shown for C24/C16/reject below, where the "cost matrix" part of the check causes increased reject).

For each grade combination the optimum grade that each piece of timber could be assigned to was determined in accordance with Clause 6.2.4.5 in EN 14081-2:2010+A1:2012 [4]. Characteristic values of bending strength, modulus of elasticity and density were calculated for each grade according to EN 384:2016 [10]. Checks were made to verify that these characteristic values satisfied the requirements for each grade (Table 4).

The next step is subsample grading. In accordance with Clause 6.2.4.6 of EN 14081-2:2010+A1:2012 [4], settings were determined for each grade in the grade combination so that the required characteristic values were achieved for the total sample less one subsample in turn. A check was made to ensure that the mean setting did not differ by more than 15% from the most conservative setting and that each assigned grade contained the minimum number of pieces (20). These settings may be further increased to satisfy other checks or to improve yield in another grade.

In line with the TG1 decision list [13], a country check was made to ensure that at least 90% of the required target value for strength and density and stiffness was met in each country individually. This does not necessarily accurately represent the actual grading.

A size matrix was calculated for each grade or grade combination giving the number of pieces in each of the optimum and assigned grades. For each grade combination the elementary cost matrix was determined using Annex A of EN 14081-2:2010+A1:2012 [4]. The cost associated with wrongly upgraded pieces was calculated using the simplification of equation A.1 of that standard with unadjusted stiffness and strength values (Table 5). The global cost matrix was calculated by multiplying each cell in the size matrix by the corresponding cell in the elementary cost matrix and then dividing the result by the total number of pieces in the assigned grade. A check was made that none of the cells corresponding to wrongly upgraded pieces in this global cost matrix exceeded 0.20.

Table 5: *Elementary cost matrix for the user-defined grades*

Optimum grade	Assigned grade: NapierSA	NapierSC	Reject
NapierSA	0	1.12	2.24
NapierSC	1.87	0	1.01
Reject	3.61	1.11	0

Optimum grade	Assigned grade: NapierSB	NapierSD	Reject
NapierSB	0	1.26	2.40
NapierSD	1.55	0	1.01
Reject	3.18	1.11	0

Finally, a check was made that not less than 5 specimens, or 0.5% of the total (whichever is larger, in this case 5 pieces) were assigned as rejects.

Characteristic values for graded timber were calculated according to EN 14358:2016 [11] using the non-parametric method for strength and density without confidence interval when the number of pieces is at least 40, and the parametric method with 75% confidence interval when there are fewer pieces (normal for density and log normal for strength). The stiffness was evaluated as the mean without confidence interval.

Settings calculation tables are presented in Table 6, Table 7 and Table 8. The cost matrix causes a problem for the C24/C16/reject combination which does not occur for the corresponding NapierSA/NapierSC/reject combination because the optimum grading to the highest grade is less, meaning that less optimum grade reject is graded to the lower grade. This means the grading yields for NapierSA/NapierSC are higher than for C24/C16 even though the properties of NapierSA are slightly better than C24 and the properties of NapierSC are slightly better than C16. This problem is artificial since, in any case, the strength class requirements are still met.

Table 6: *Settings calculation NapierSA/NapierSC (current)*

Optimum grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	296	25.2	10.5	376	41%
NapierSC	321	18.3	7.60	327	44%
Reject	108	13.1	5.11	308	15%

Subsample grading for upper grade

NapierSA	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	*IP*
Less H	189	25.9	10.5	375	10062
Less I	174	25.0	10.7	376	10491
Less J	174	25.0	10.7	376	10575
Less K	182	25.2	10.6	376	10426
Less L	182	25.3	10.7	376	10491
Setting					**10800**

Increased setting to get a better yield overall

Subsample grading for lower grade

NapierSC	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	*IP*
Less H	379	17.3	7.66	326	4378
Less I	479	16.5	7.60	327	4378
Less J	446	16.5	7.61	332	4912
Less K	416	16.9	7.61	326	4912
Less L	475	16.5	7.60	329	4639
Setting					**5140**

Increased setting to satisfy the cost matrix

Overall grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	174	25.5	10.9	376	24%
NapierSC	544	16.9	7.65	328	75%
Reject	7	8.88	3.65	288	1%

Size matrix

Optimum grade	Assigned grade: NapierSA	NapierSC	Reject
NapierSA	157	139	0
NapierSC	16	305	0
Reject	1	100	7

Global cost matrix

Optimum grade	Assigned grade: NapierSA	NapierSC	Reject
NapierSA		0.29	0.00
NapierSC	0.17		0.00
Reject	0.02	0.20	

Country check for United Kingdom

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	142	25.4	10.9	376	25%
NapierSC	415	16.9	7.61	326	74%
Reject	3	6.13	3.25	280	1%

Country check for Republic of Ireland

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	32	24.4	11.2	379	19%
NapierSC	129	17.0	7.75	335	78%
Reject	4	7.54	3.94	266	2%

Table 7: *Settings calculation NapierSB/NapierSD (current)*

Optimum grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	479	22.3	9.51	362	66%
NapierSD	205	16.1	6.65	314	28%
Reject	41	11.0	4.07	298	6%

Subsample grading for upper grade

NapierSB	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	*IP*
Less H	291	22.5	9.75	362	9106
Less I	284	22.6	9.99	360	9562
Less J	275	22.8	10.1	362	9642
Less K	256	22.8	10.0	362	9650
Less L	301	22.3	9.95	360	9539
Setting					**9540**

Increased setting to fulfil the requirement for density

Subsample grading for lower grade

NapierSD	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	*IP*
Less H	258	16.3	6.96	322	4378
Less I	329	15.5	6.92	322	3682
Less J	303	15.2	6.89	327	3682
Less K	284	15.6	6.99	320	3682
Less L	326	15.4	6.91	326	3682
Setting					**4920**

Increased setting for minimum number of rejects

Overall grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	350	22.8	9.96	361	48%
NapierSD	370	15.8	6.98	324	51%
Reject	5	9.65	3.71	312	1%

Size matrix

Optimum grade	Assigned grade: NapierSB	NapierSD	Reject
NapierSB	324	155	0
NapierSD	25	180	0
Reject	1	35	5

Global cost matrix

Optimum grade	Assigned grade: NapierSB	NapierSD	Reject
NapierSB		0.53	0.00
NapierSD	0.11		0.00
Reject	0.01	0.11	

Country check for United Kingdom

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	276	22.6	9.88	357	49%
NapierSD	281	16.0	7.03	319	50%
Reject	3	6.13	3.25	280	1%

Country check for Republic of Ireland

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	74	23.9	10.3	366	45%
NapierSD	89	14.3	6.80	329	54%
Reject	2	6.87	4.40	262	1%

Table 8: *Settings calculation C24/C16 (current)*

Optimum grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	308	24.7	10.5	362	42%
C16	283	19.0	7.60	327	39%
Reject	134	13.5	5.35	311	19%

Subsample grading for upper grade

C24	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	*IP*
Less H	189	25.9	10.5	375	10062
Less I	196	24.2	10.5	369	10325
Less J	200	24.4	10.6	371	10394
Less K	192	24.0	10.5	376	10333
Less L	213	24.1	10.5	371	10239
Setting					**10800**

Increased setting to get a better yield overall

Subsample grading for lower grade

C16	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	*IP*
Less H	379	17.3	7.66	326	4378
Less I	479	16.5	7.60	327	4378
Less J	446	16.5	7.61	332	4912
Less K	416	16.9	7.61	326	4912
Less L	475	16.5	7.60	329	4639
Setting					**6580**

Increased setting to satisfy the cost matrix

Overall grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	174	25.5	10.9	376	24%
C16	511	17.0	7.81	331	70%
Reject	40	13.6	4.85	298	6%

Size matrix

Optimum grade	Assigned grade C24	C16	Reject
C24	157	151	0
C16	16	266	1
Reject	1	94	39

Global cost matrix

Optimum grade	Assigned grade C24	C16	Reject
C24		0.33	0.00
C16	0.15		0.03
Reject	0.02	0.20	0

Country check for United Kingdom

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	142	25.4	10.9	376	25%
C16	393	16.9	7.74	328	70%
Reject	25	13.9	5.17	291	5%

Country check for Republic of Ireland

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	32	24.4	11.2	379	19%
C16	118	18.7	8.06	339	72%
Reject	15	11.4	4.32	296	9%

4.3 SETTINGS TO FprEN 14081-2:2017

EN 14081-2 is being revised, and there are some different procedures in the version which passed to CEN formal vote stage in May 2018 [5]. There are differences in the calculation approach, but not (in this case) major differences in the calculated grading settings or yields (Section 5).

There is no cross-checking of thresholds on the whole sample less one subsample. As the number of subsamples increases this check does less, which is one reason the country check was added into the TG1 decision list [13]. Instead each subsample is to be checked on its own, in much the same way that the country check is done in Section 4.2. The only difference is that the requirement for stiffness is now 95% of the stiffness target rather than 90%. These are called "verification samples" in the revised standard.

The optimum grading and cost matrix requirement is retained, but the target is relaxed to prevent it causing the kind of artificial problem it does in Section 4.2 for the C24/C16 combination. Instead of ≤0.20, the cost matrix cells for the wrongly upgraded pieces are limited to ≤0.40. This part of the calculation was retained as it is thought that the cost matrix gives some information about the grading performance of the machine, even if it does not limit the settings.

The calculations are summarised in Table 9, Table 10 and Table 11. For this dataset, subsample H limits the grading in all cases, and so the settings for user-defined grades (especially NapierSA/NapierSC) are not as good as with the current approach. This is caused by the single erroneously measured IP (see Section 3) which becomes more influential on the results within the subsample alone (224 specimens). This is a random event that could have occurred for any of the subsamples.

Correcting or removing this single piece's measurement would make the settings the same as with the current method, as would combining subsamples H and J together. The first of these actions is not a legitimate solution since the erroneous measurement is real and representative of real world machine performance errors. The second action is more legitimate but not really within the spirit of the method. It might, nevertheless, be justifiable on the grounds that this is a random machine measurement error and not anything particular to a subsample.

It should therefore be noted that single pieces are more influential in the revised standard than the current standard (although the same would have happened with the current standard if H was a single country, or the erroneous measurement had happened instead on a piece in subsample K)

The relaxation of the cost matrix improves the C24/C16 settings making them much more viable for a producer that does not want increased machine rejects. The new standard also allows IP to be specified to 4 significant figures rather than 3, which certainly helps to find combinations of settings that satisfy all requirements.

Table 9: *Settings calculation NapierSA/NapierSC (revised)*

Optimum grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	296	25.2	10.5	376	41%
NapierSC	321	18.3	7.60	327	44%
Reject	108	13.1	5.11	308	15%

Settings used		Threshold	
NapierSA	IP_{12}	≥	11320
NapierSC	IP_{12}	≥	4920
Reject	IP_{12}	<	4920

Overall grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	134	27.4	11.4	380	18%
NapierSC	586	16.9	7.76	328	81%
Reject	5	9.65	3.71	312	1%

Size matrix

Optimum	Assigned grade		
grade	NapierSA	NapierSC	Reject
NapierSA	125	171	0
NapierSC	8	313	0
Reject	1	102	5

Global cost matrix

Optimum	Assigned grade		
grade	NapierSA	NapierSC	Reject
NapierSA		0.33	0.00
NapierSC	0.11		0.00
Reject	0.03	0.19	

Verification checks

H (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	39	22.7	11.2	363	17%
NapierSC	184	15.4	7.62	333	82%
Reject	1				0%

I (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	27	26.1	11.3	358	25%
NapierSC	80	17.4	7.96	344	73%
Reject	2				2%

J (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	21	27.4	11.4	377	16%
NapierSC	107	20.1	7.80	312	84%
Reject	0				0%

K (IE)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	26	26.8	11.5	384	16%
NapierSC	137	16.1	7.78	334	83%
Reject	2				1%

L (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSA	21	25.9	11.5	345	21%
NapierSC	78	17.3	7.77	322	79%
Reject	0				0%

Table 10: *Settings calculation NapierSB/NapierSD (revised)*

Optimum grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	479	22.3	9.51	362	66%
NapierSD	205	16.1	6.65	314	28%
Reject	41	11.0	4.07	298	6%

Settings used		Threshold	
NapierSB	IP_{12}	≥	9610
NapierSD	IP_{12}	≥	4920
Reject	IP_{12}	<	4920

Overall grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	334	22.9	10.0	361	46%
NapierSD	386	15.7	7.03	324	53%
Reject	5	9.65	3.71	312	1%

Size matrix

Optimum	Assigned grade		
grade	NapierSB	NapierSD	Reject
NapierSB	310	169	0
NapierSD	23	182	0
Reject	1	35	5

Global cost matrix

Optimum	Assigned grade		
grade	NapierSB	NapierSD	Reject
NapierSB		0.55	0.00
NapierSD	0.11		0.00
Reject	0.01	0.10	

Verification checks

H (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	102	21.1	9.78	349	46%
NapierSD	121	14.3	6.95	328	54%
Reject	1				0%

I (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	60	23.5	10.0	375	55%
NapierSD	47	16.6	7.28	338	43%
Reject	2				2%

J (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	53	23.8	10.1	371	41%
NapierSD	75	19.4	7.17	311	59%
Reject	0				0%

K (IE)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	72	24.8	10.3	366	44%
NapierSD	91	14.5	6.84	330	55%
Reject	2				1%

L (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
NapierSB	47	23.1	10.2	349	47%
NapierSD	52	16.4	7.14	309	53%
Reject	0				0%

Table 11: Settings calculation C24/C16 (revised)

Optimum grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	308	24.66	10.45	362	42%
C16	283	19.02	7.60	327	39%
Reject	134	13.48	5.35	311	19%

Setting used		Threshold	
C24	IP_{12}	≥	10680
C16	IP_{12}	≥	5230
Reject	IP_{12}	<	5230

Overall grading

	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	190	25.5	10.8	376	26%
C16	526	16.8	7.60	328	73%
Reject	9	10.1	3.69	294	1%

Size matrix

Optimum grade	Assigned grade C24	C16	Reject
C24	170	138	0
C16	19	264	0
Reject	1	124	9

Global cost matrix

Optimum grade	Assigned grade C24	C16	Reject
C24		0.29	0.00
C16	0.17		0.00
Reject	0.02	0.26	

Verification checks

H (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	58	22.0	10.6	369	26%
C16	164	14.8	7.42	332	73%
Reject	2				1%

I (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	41	25.6	10.7	384	38%
C16	66	16.9	7.64	341	60%
Reject	2				2%

J (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	27	27.3	10.9	371	21%
C16	101	20.1	7.71	312	79%
Reject	0				0%

K (IE)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	35	24.5	11.1	374	21%
C16	125	16.7	7.74	336	76%
Reject	5				3%

L (UK)	n	$f_{m,k}$	$E_{0,mean}$	ρ_k	Yield
C24	29	26.5	11.0	345	29%
C16	70	17.0	7.58	321	71%
Reject	0				0%

5 THE GRADING SETTINGS

The grading settings are as specified by Table 12, Table 13 and Table 14. Figure 5 and Figure 6 illustrate how the grading separates pieces by stiffness, strength and density in this particular dataset.

The grading settings are for use with the IP model, and moisture content adjustment, given in Equation 1. They are presented for information only, and additional steps are necessary if grading according to EN 14081-1 [1].

Grading also requires an additional "visual override" check for distortion, fissures, rot, insect damage and similar issues not assessed by the grading machine [1].

The size range of both sets of settings are applicable to thickness between 34 and 83 mm and width between 90 and 165 mm (a 10% extrapolation of the tested sizes [4,5]).

The IP can be adjusted for each piece individually (moisture content of each piece measured) or adjusted for the whole batch (average moisture content measured). In the second case, the moisture content range in the batch needs to be controlled within a range.

Table 12: Grading settings comments

Species	"British spruce" (WPCS) Sitka spruce (*Picea sitchensis*) Norway spruce (*Picea abies*)
Growth area	United Kingdom (GB / UK) Republic of Ireland (IE)
Size range	Thickness 34 mm to 83 mm Width 90 mm to 165 mm
Machine	Longitudinal resonance with mass (portable or in line)
Moisture content	Mean moisture content of the batch between 10% and 20%. If IP is not adjusted for moisture content of each piece individually, then all pieces in the batch not deviating by more than four percentage points from the mean
IP model	IP model of this paper adjust mc ≥ 18% as if 18%
Other requirements	Timber surface planed or sawn Measurement end sawn flat Timber temperature > 0 C Additional factory production control measures are required These settings for information only Contact d.ridleyellis@napier.ac.uk
Definition of classes	Table 4 of this paper EN 338 [2]
Other grade properties	See EN 384 [10]

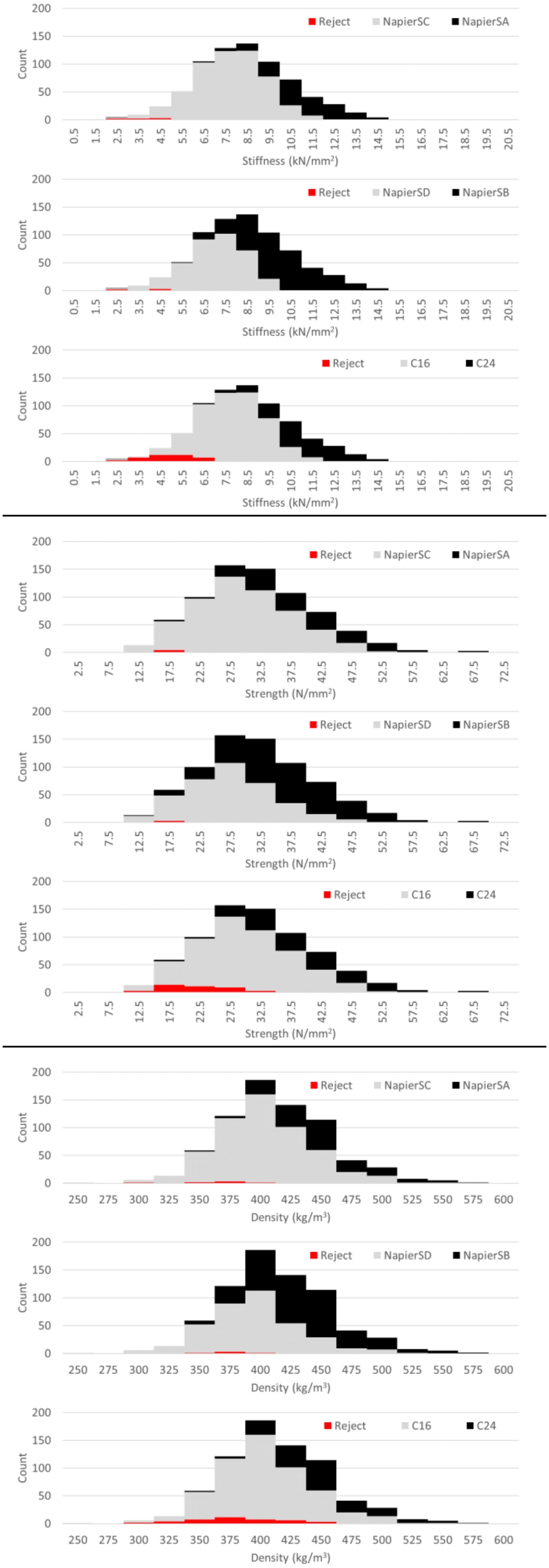

Figure 5: *Grading with current standard [4,13]*

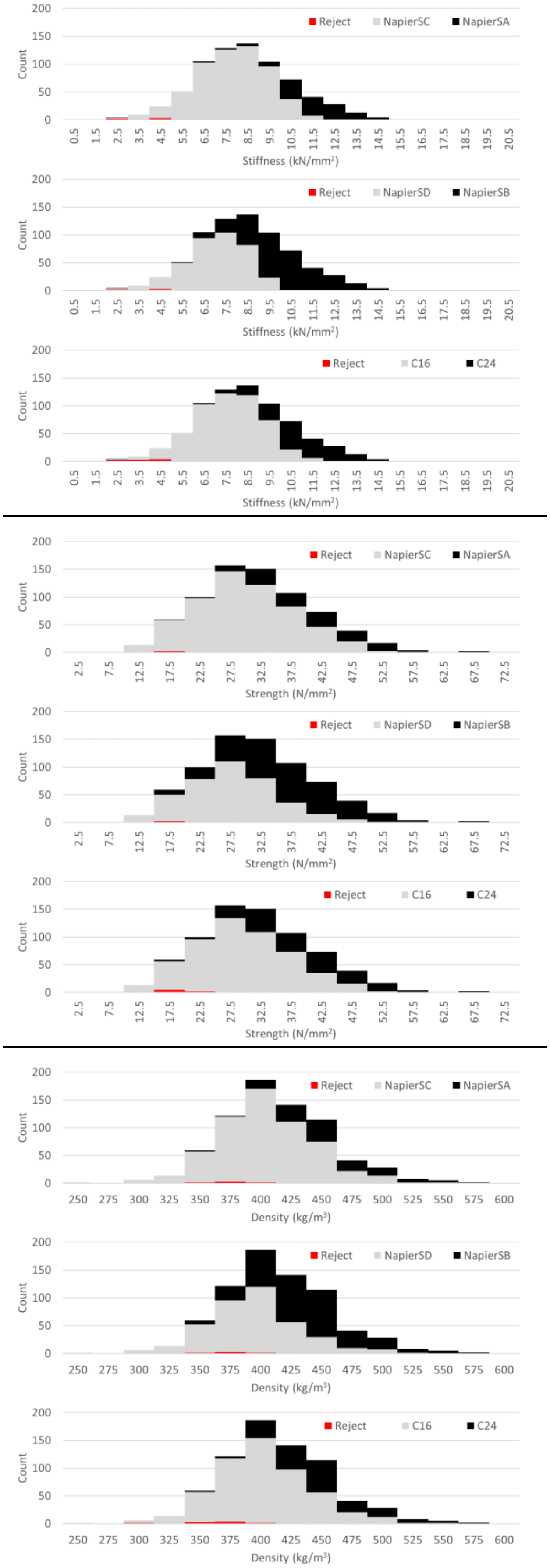

Figure 6: *Grading with revised standard [5]*

Table 13: *Grading thresholds to current standard [4,13]*

Name	Threshold			Approx yield
NapierSA	IP_{12}	≥	10800	24%
NapierSC	IP_{12}	≥	5140	75%
Reject	IP_{12}	<	5140	1%
NapierSB	IP_{12}	≥	9540	48%
NapierSD	IP_{12}	≥	4920	51%
Reject	IP_{12}	<	4920	1%
C24	IP_{12}	≥	10800	24%
C16	IP_{12}	≥	6580	70%
Reject	IP_{12}	<	6580	6%

Table 14: *Grading thresholds to revised standard [5]*

Name	Threshold			Approx yield
NapierSA	IP_{12}	≥	11320	18%
NapierSC	IP_{12}	≥	4920	81%
Reject	IP_{12}	<	4920	1%
NapierSB	IP_{12}	≥	9610	46%
NapierSD	IP_{12}	≥	4920	53%
Reject	IP_{12}	<	4920	1%
C24	IP_{12}	≥	10680	26%
C16	IP_{12}	≥	5230	73%
Reject	IP_{12}	<	5230	1%

6 CONCLUSIONS

When grading timber as part of the construction process, rather than placing on the market as graded timber, it makes sense to use strength classes that fit the actual properties of the timber. Settings can be calculated in the same way as for the general strength classes found in EN 338 [2].

In this case, there was not a huge difference in settings and yields for the revised standard [5] but it was seen that single specimens can have more influence on the calculation. The relaxation of the cost matrix requirement is certainly helpful in improving overall yield for some grade combinations and this helped here for the industrially relevant C24/C16/reject combination.

These settings are presented for information only, in order to illustrate the sampling, calculation and requirements for machine control grading in Europe. While they are calculated in accordance with the European standards [4,5,13] they are not formally approved for use in grading to EN 14081-1 [1].

There are equivalent settings for the Brookhuis MTG 960 grading machine which are approved [14], and have slightly different model values and, therefore, different grading thresholds.

ACKNOWLEDGEMENT

The authors are grateful to the funders of this work – particularly the projects: Wood Products Innovation Gateway, and Strategic Integrated Research in Timber.

REFERENCES

[1] EN 14081-1:2016: *Timber structures – Strength graded structural timber with rectangular cross section. Part 1: General requirements.* European Committee for Standardization, Brussels.

[2] EN 338:2016: *Structural timber. Strength classes*. European Committee for Standardization, Brussels.

[3] Ridley-Ellis, D., Adams, S. and Lehneke, S: Thinking beyond the usual strength grades – with examples of British spruce and larch. In *Proceedings of the World Conference on Timber Engineering (WCTE 2016), August 22-25, 2016, Vienna, Austria*, Eds.: J. Eberhardsteiner, W. Winter, A. Fadai, M. Pöll, Publisher: Vienna University of Technology, ISBN 978-3-903039-00-1, 2016

[4] EN 14081-2:2010+A1:2012: *Timber structures – Strength graded structural timber with rectangular cross section. Part 2: Machine grading; additional requirements for initial type testing.* European Committee for Standardization, Brussels.

[5] FprEN 14081-2:2017: *Timber structures – Strength graded structural timber with rectangular cross section. Part 2: Machine grading; additional requirements for initial type testing.* European Committee for Standardization, Brussels. (TC124 WG2 committee version)

[6] Sampling guidelines of CEN TC124 WG2 TG1 dated 12/10/ 2016 http://blogs.napier.ac.uk/cwst/tg1/

[7] Ridley-Ellis, D., Stapel, P. and Baño, V: Strength grading of sawn timber in Europe: an explanation for engineers and researchers. *European Journal of Wood and Wood Products*, 74 (3). pp. 291-306. ISSN 0018-3768, 2016

[8] Gil-Moreno, D. Ridley-Ellis, D. and McLean P.: *Timber properties of noble fir, Norway spruce, western red cedar and western hemlock grown in Great Britain*. Forestry Commission Research Note FCRN026, ISBN: 978-0-85538-952-9, December 2016.

[9] EN 408:2010+A1:2012: *Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties.* European Committee for Standardization, Brussels.

[10] EN 384:2016. *Structural timber – determination of characteristic values of mechanical properties and density*. European Committee for Standardization, Brussels.

[11] EN 14358:2016: *Timber structures. Calculation and verification of characteristic values*. European Committee for Standardization, Brussels.

[12] Moore, J.R., Lyon, A.J., Searles, G.J., Lehneke, S.A., and Ridley-Ellis, D.J: Within- and between-stand variation in selected properties of Sitka spruce sawn timber in the United Kingdom: implications for segregation and grade recovery. *Annals of Forest Science*, Volume 70, Issue 4, pp 403-415. DOI 10.1007/s13595-013-0275-y, 2013

[13] Decision list of CEN TC124 WG2 TG1 dated 8/3/2017 http://blogs.napier.ac.uk/cwst/tg1/

[14] Ridley-Ellis, D. *Derivation of MTG 960 grading machine settings for British spruce*, TG1/201703/27rev (approved grading report), 2017.