COST Action FP1004

Final Meeting

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Strength grading of sawn timber in Europe - an explanation for engineers

Dan Ridley-Ellis[1], Peter Stapel[2] & Vanesa Baño[3]

[1] Edinburgh Napier University, United Kingdom

[2] Technische Universität München, Germany

[3] Universidad de la República, Uruguay

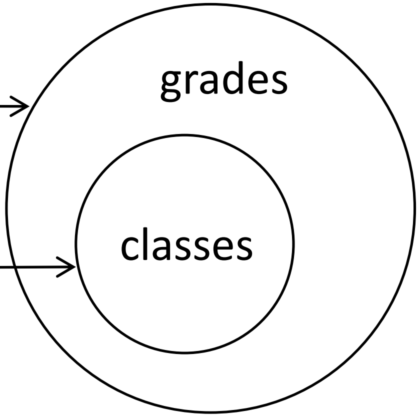
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Contents

1. **What grades cannot do**
2. **Why grades are not limiting**

A fuller explanation of grading, common misconceptions, and future direction is in the paper

Firstly – some terms
Grades and classes



Strength grade

- Sets (e.g. “looks good” and “looks bad”

Strength class

- Has numerical properties (for design calcs)

Strength grading

1. Timber is sorted to grades
2. Grades are assigned to a class

A strength class is special kind of strength grade (one that has numerical properties)

Grade-determining properties (of a class)

Strength

- Usually major axis bending strength

Stiffness

- Usually major axis bending stiffness

Density

- An indirect measure of strength in some elements of timber design

All other properties are estimated from those 3 properties

e.g. shear strength and stiffness

tension and compression strength perpendicular to grain

What grades cannot do

Grading does not operate on individual pieces

(any individual piece could, in principle, correctly belong to several different strength classes)

(grading is concerned with collective properties of timber in a grade)

Having the same strength class does not make pieces equal

(strength classes are broad statistical distributions that overlap)

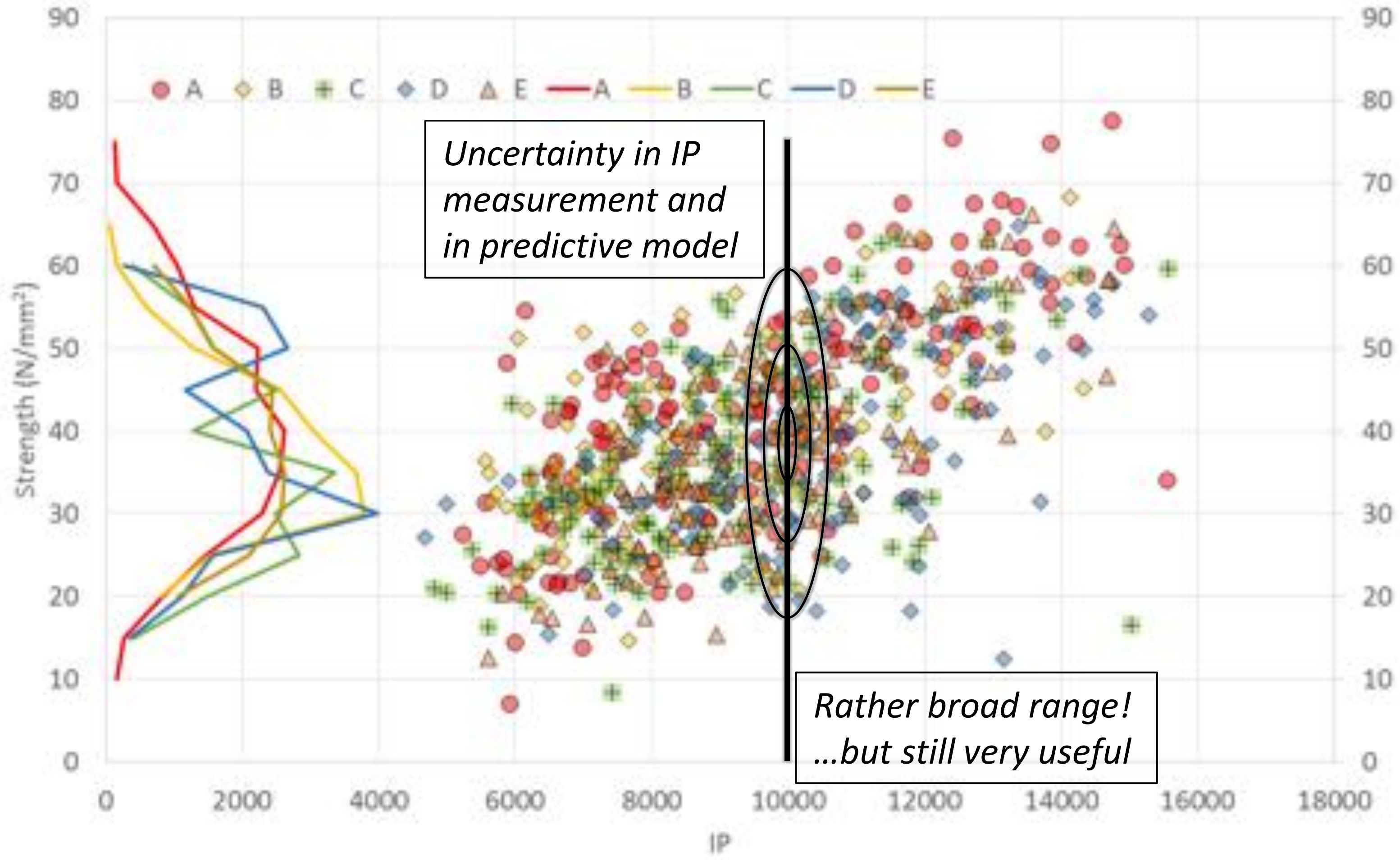
The strength class does not tell you what the properties are

(not of individual pieces)

What you need for design

(and only specifies a lower limit for timber, collectively, in the grade)

An indicating property (IP) e.g. predicting bending strength from E_{dyn}

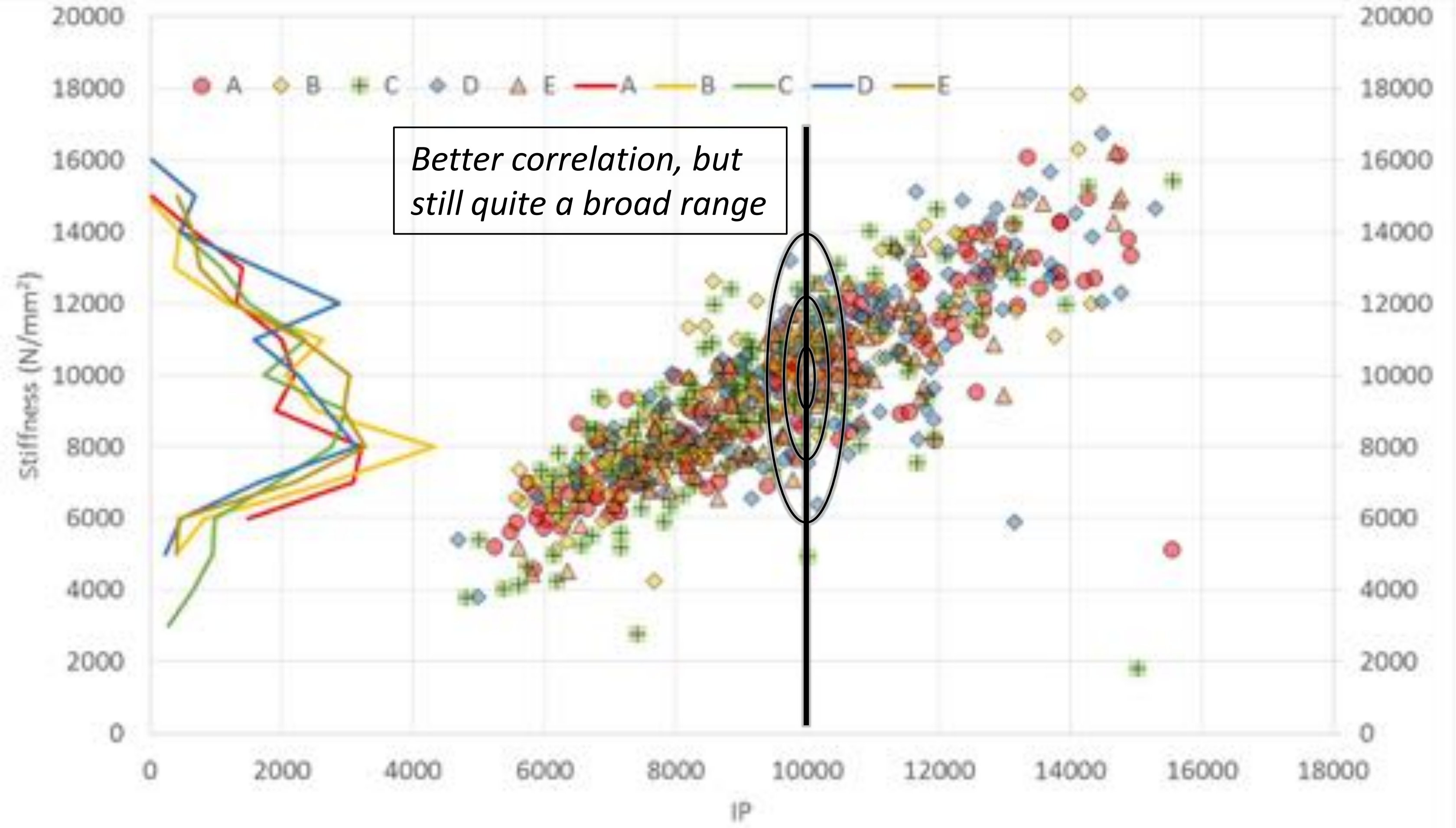


Uncertainty in IP measurement and in predictive model

Rather broad range! …but still very useful

(Dynamic modulus of elasticity from longitudinal resonance)

An indicating property (IP)
e.g. predicting bending stiffness from E_{dyn}



Better correlation, but still quite a broad range

(Dynamic modulus of elasticity from longitudinal resonance)

The indicating property can…

Tell you something about the properties

- Although there is uncertainty in the values
- And you need to know the relationship between IP and the property

Importantly - this relationship between IP and the property varies

- By species
- By growth area

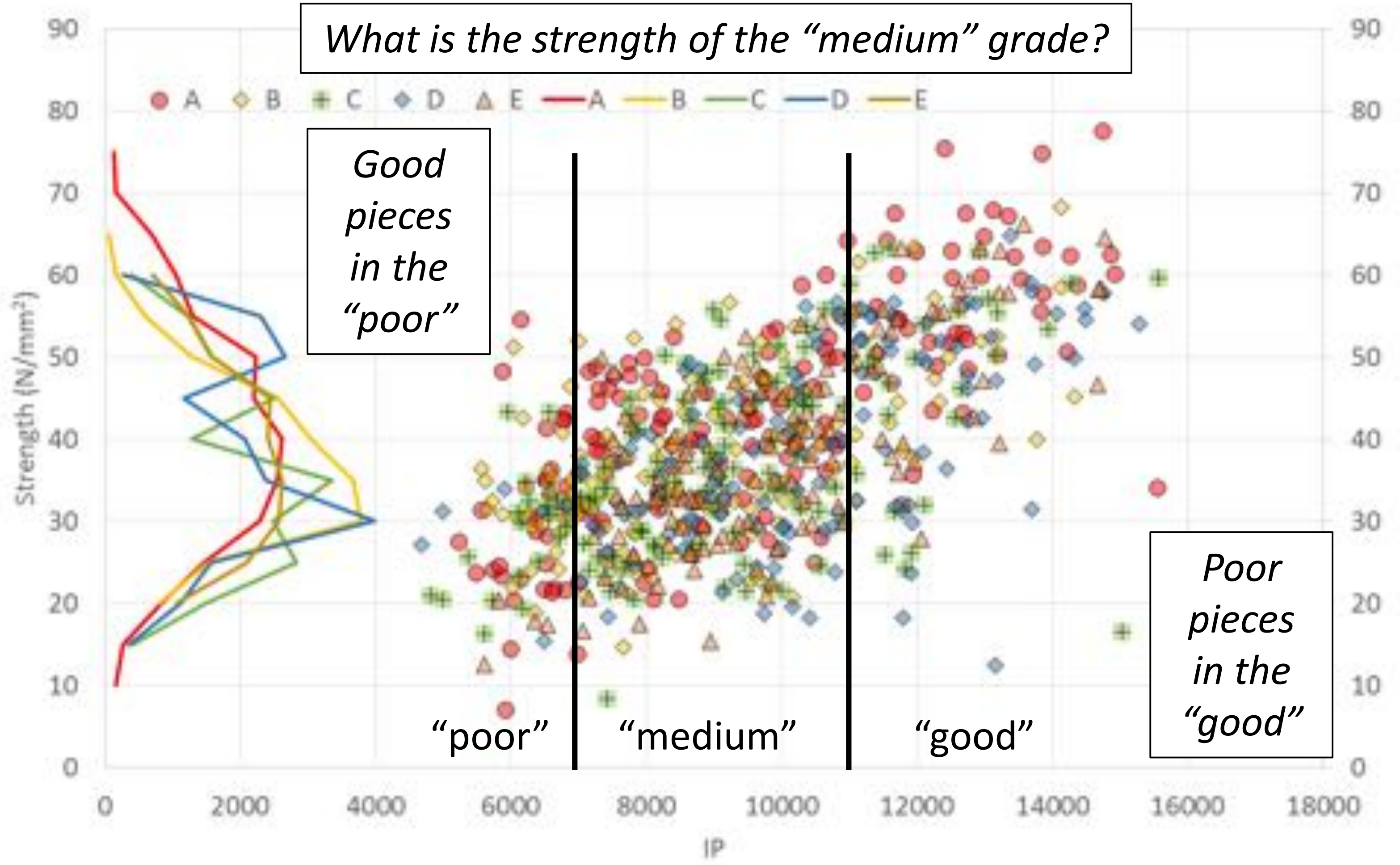
Grading is limited by growth area.
You cannot use relationships established for one growth area on timber from another (matching species is not enough!)

…in terms of

- Gradient and intercept of the line…but also
- Average value of the property
- Standard deviation of the property
- The "goodness of the correlation"
- Also, the relationship between the important properties

Influenced by climate and forest management

Grades are not single IP values
They are discrete sets defined by boundaries of IP



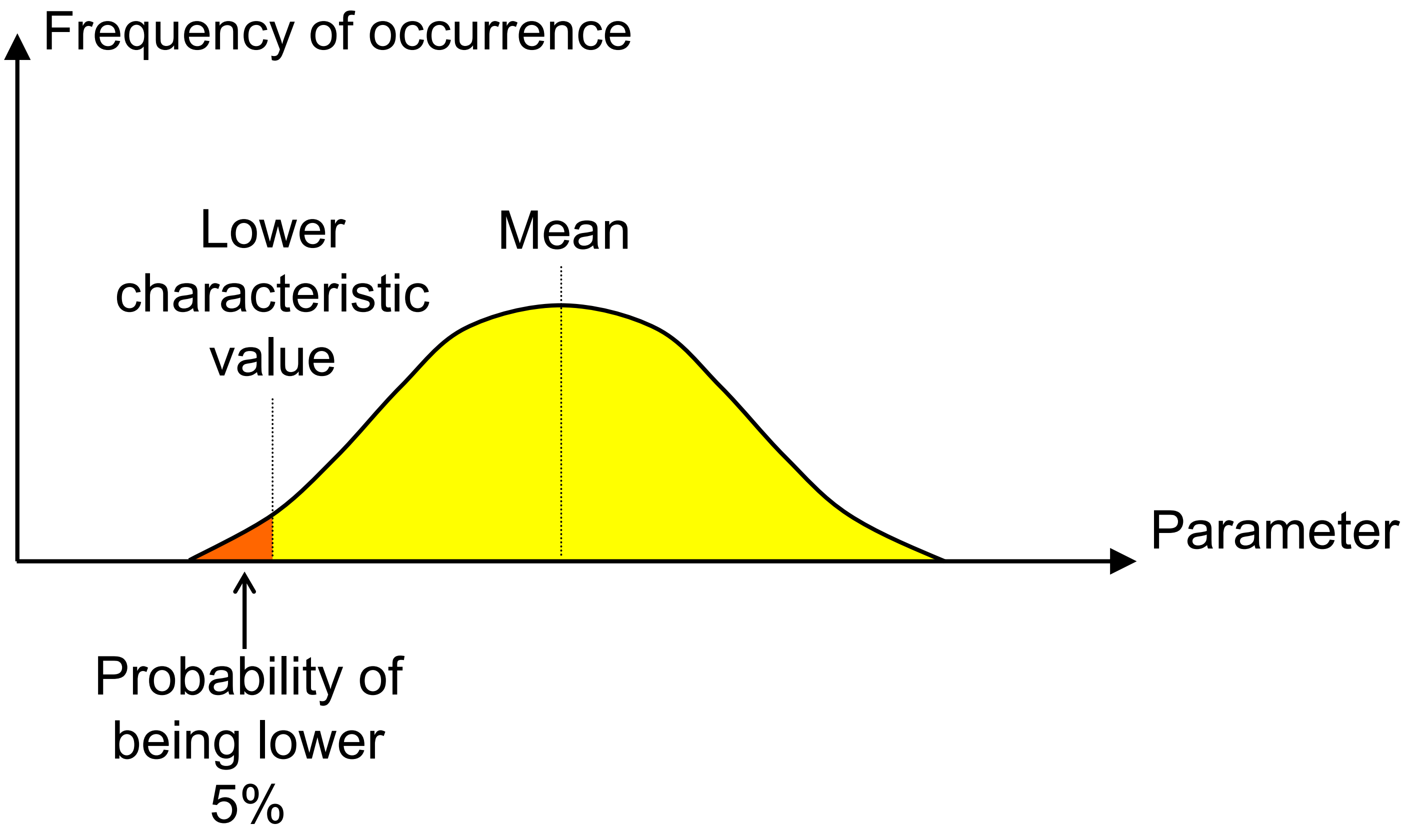
What is the strength of the "medium" grade?

Good pieces in the "poor"

Poor pieces in the "good"

(Dynamic modulus of elasticity from longitudinal resonance)

Characteristic values



Critical property

Strength classes are defined by characteristic

- Strength (lower 5th percentile)
- Stiffness (mean)
- Density (lower 5th percentile)

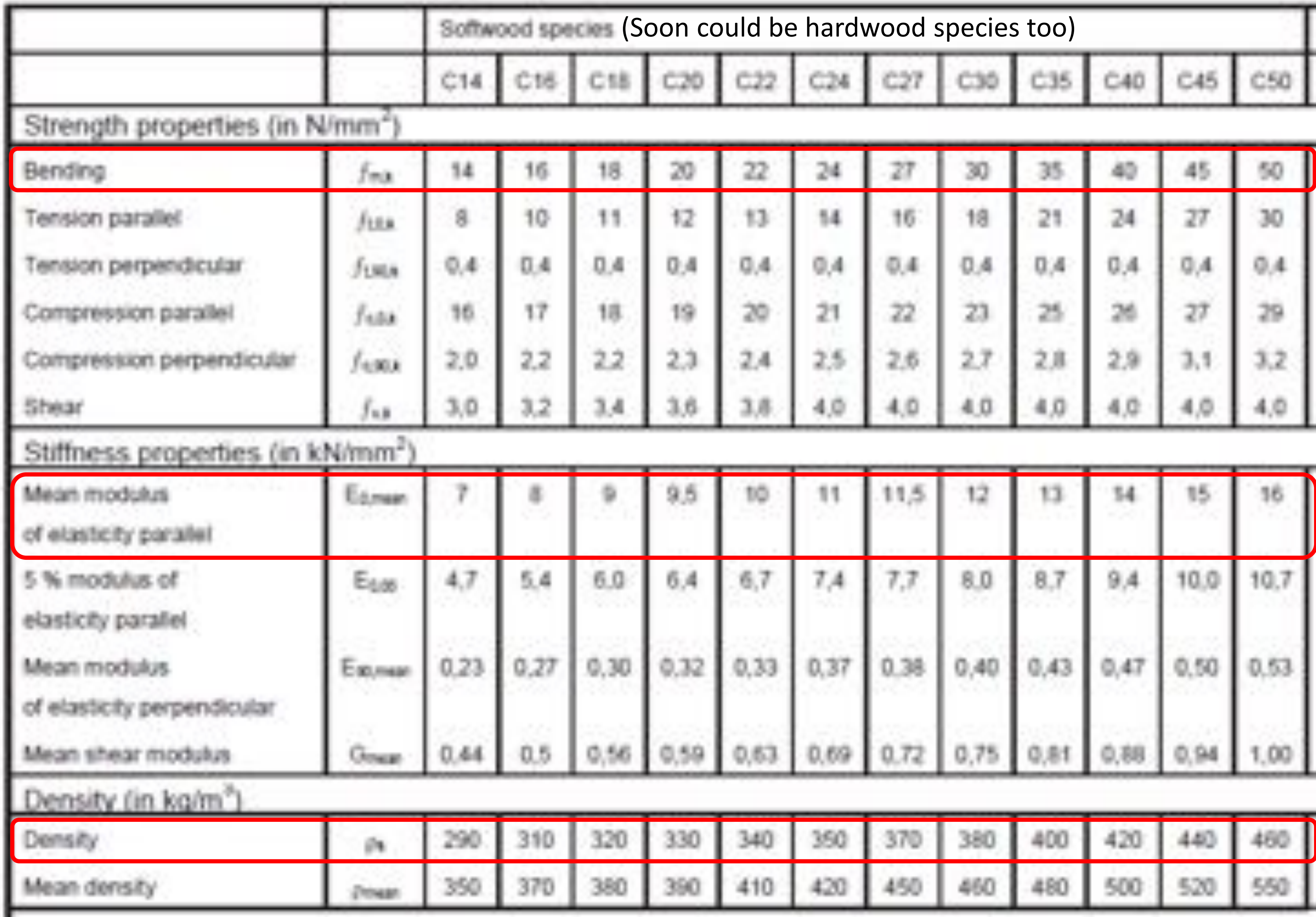
For standard strength classes, the limits are general across species

- “Softwoods” (EN338 C classes...major axis bending)
- Hardwoods (EN338 D classes...major axis bending)
- Softwoods (prEN338 tension classes…tension)

Other strength class systems exist

- And you can make up your own!
- By specifying characteristic strength, stiffness and density

EN338



		Softwood species (Soon could be hardwood species too)											
		C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
Strength properties (in N/mm^2)													
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
Tension parallel	$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30
Tension perpendicular	$f_{t,90,k}$	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
Compression parallel	$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29
Compression perpendicular	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,1	3,2
Shear	$f_{v,k}$	3,0	3,2	3,4	3,6	3,8	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Stiffness properties (in kN/mm^2)													
Mean modulus of elasticity parallel	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12	13	14	15	16
5 % modulus of elasticity parallel	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,0	10,7
Mean modulus of elasticity perpendicular	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53
Mean shear modulus	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00
Density (in kg/m^3)													
Density	ρ_k	290	310	320	330	340	350	370	380	400	420	440	460
Mean density	ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550

Critical property

To comply with the grade, characteristic values must be met (at least)*

Together with some visual override requirements including

- Fissures
- Distortion

For a species and grade combination usually one property is limiting

- Strength
- Stiffness
- Density

So strength grading isn't *always* about predicting strength

*** Well, not quite…there is a bit more to it…**

The bit more…

The mean (bending or tension) stiffness only needs only to exceed 95% of the mean stiffness value of the strength class

(Because testing is currently done centred on the worst location in a specimen to get the lowest strength. In practice, the stiffness of the sample in general is more important)

For machine grading, the characteristic bending strength of strength classes up to C30 (and equivalent) only needs to exceed 89% of the characteristic bending strength of the strength class

(The k_v factor of 1.12 accounts for the reduced human involvement in machine grading and the additional confidence that this is supposed to afford)

There is a size factor (k_h) that modifies the requirement for strength to do the opposite of the (k_h) in EN1995-1

(It is not really known if there is a size factor for wood anyway)

And so…for graded timber

For the set of graded timber

It is probable that at least one of the grade determining properties exceeds the requirements of the strength class (all three might)

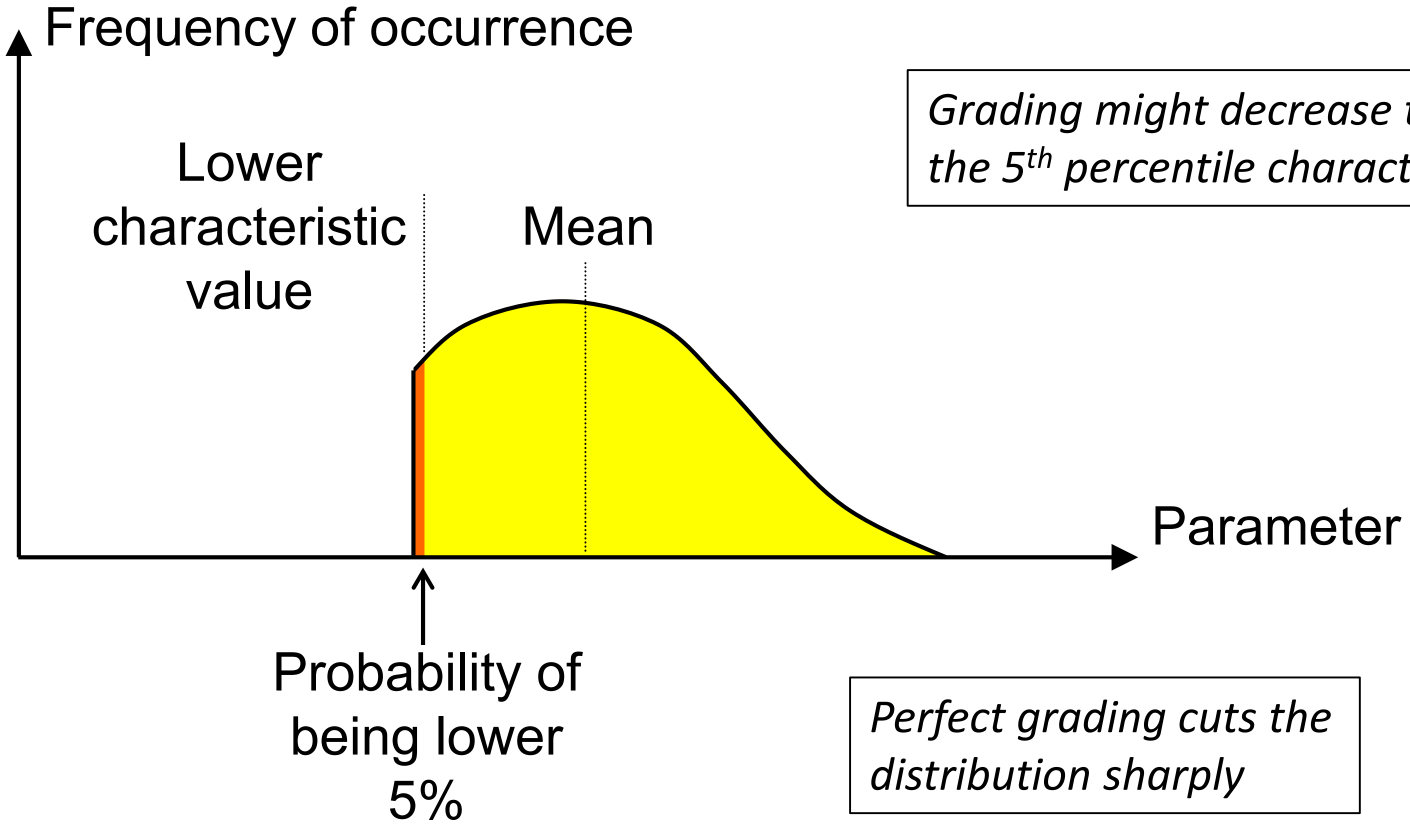
The secondary properties will exceed what is listed for that strength class – probably by quite a lot (because they are conservative estimates that have to work for all species)

For an single piece of correctly graded timber

For strength and density all you can really say is that there is at least 95% chance that the property for that piece will exceed the characteristic value of the strength class (subject to the previous slide)

For stiffness, the expected value for the piece is at least the value of the strength class (×95%), but you don't know the spread of values

Characteristic values
Grading influences the distributions



Frequency of occurrence

Lower characteristic value

Mean

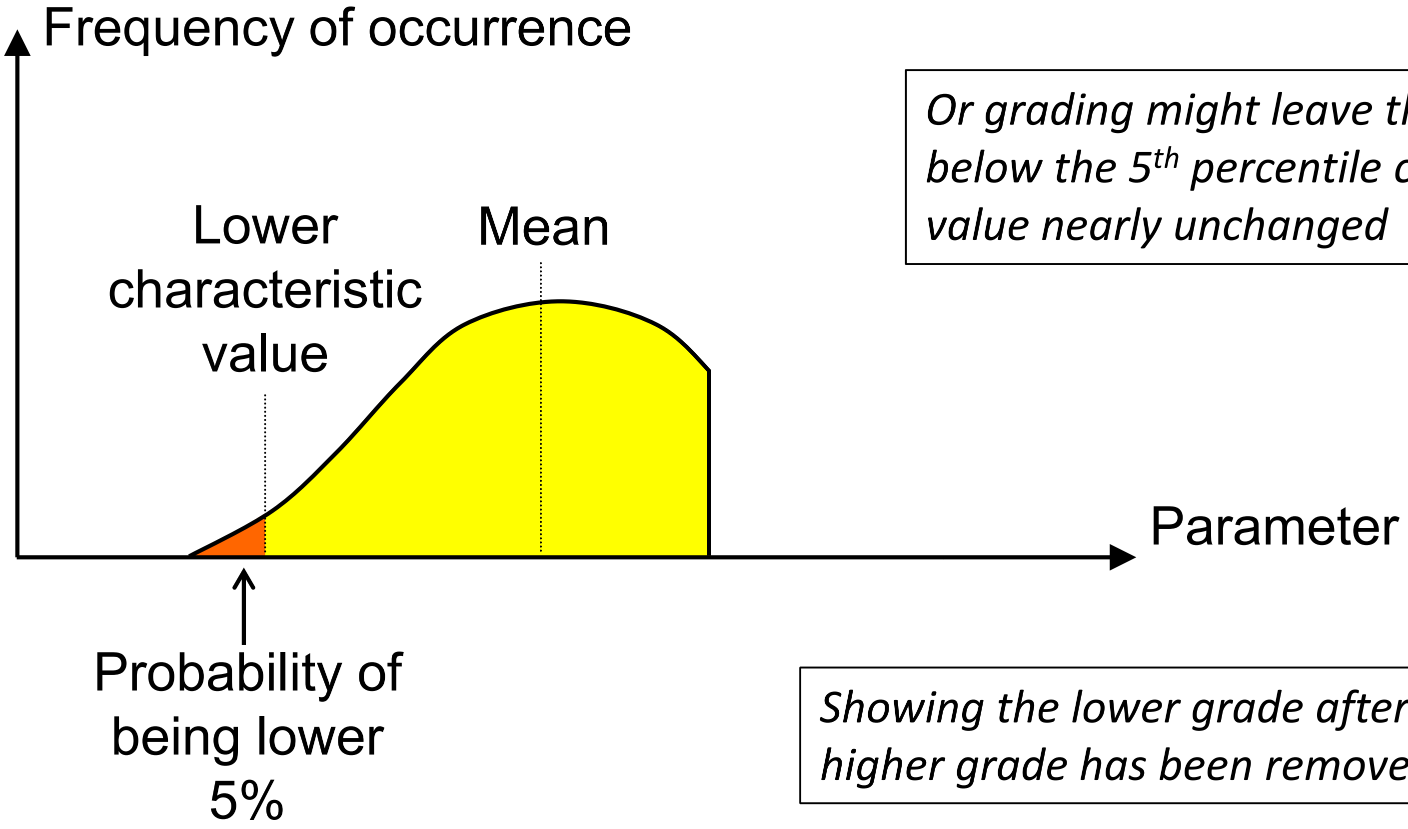
Parameter

Probability of being lower 5%

Grading might decrease the spread below the 5th percentile characteristic value

Perfect grading cuts the distribution sharply

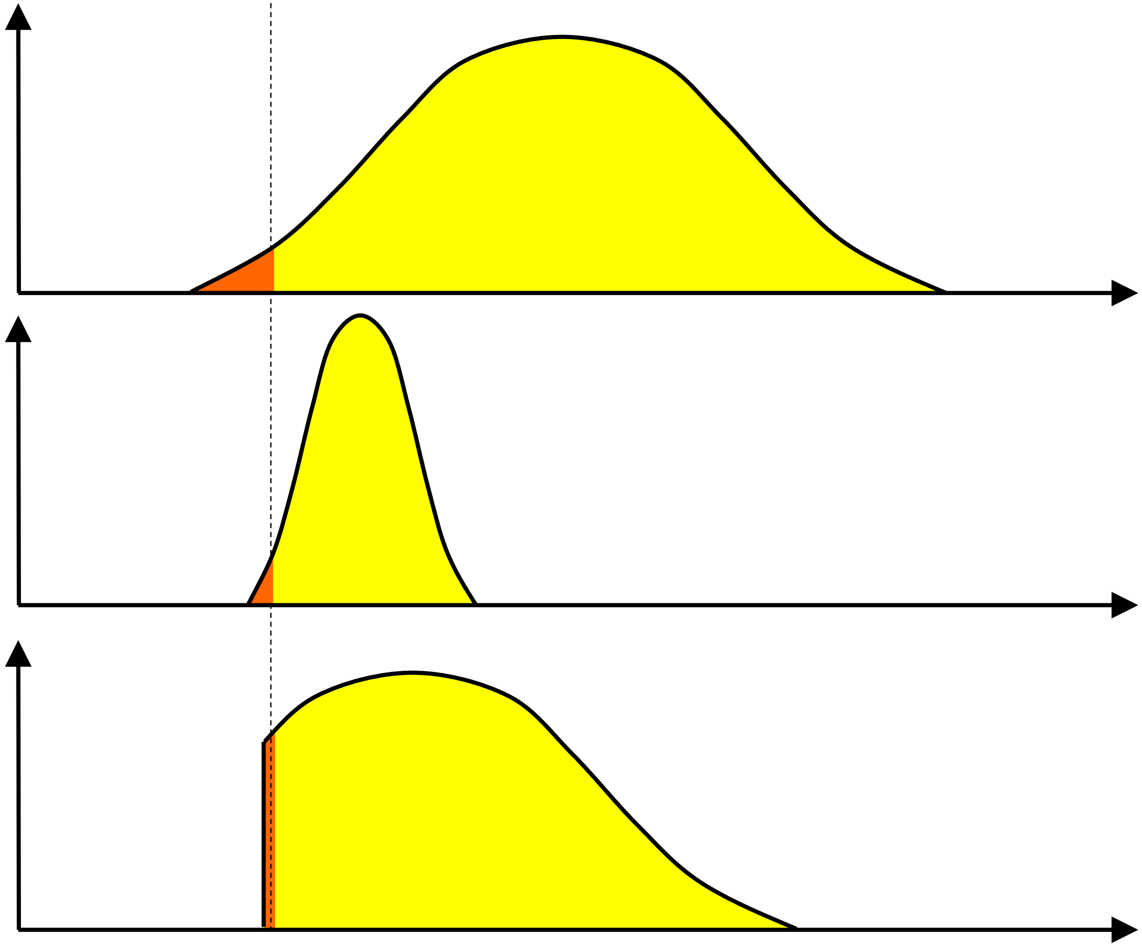
Characteristic values
Grading influences the distributions



Or grading might leave the spread below the 5th percentile characteristic value nearly unchanged

Showing the lower grade after a higher grade has been removed

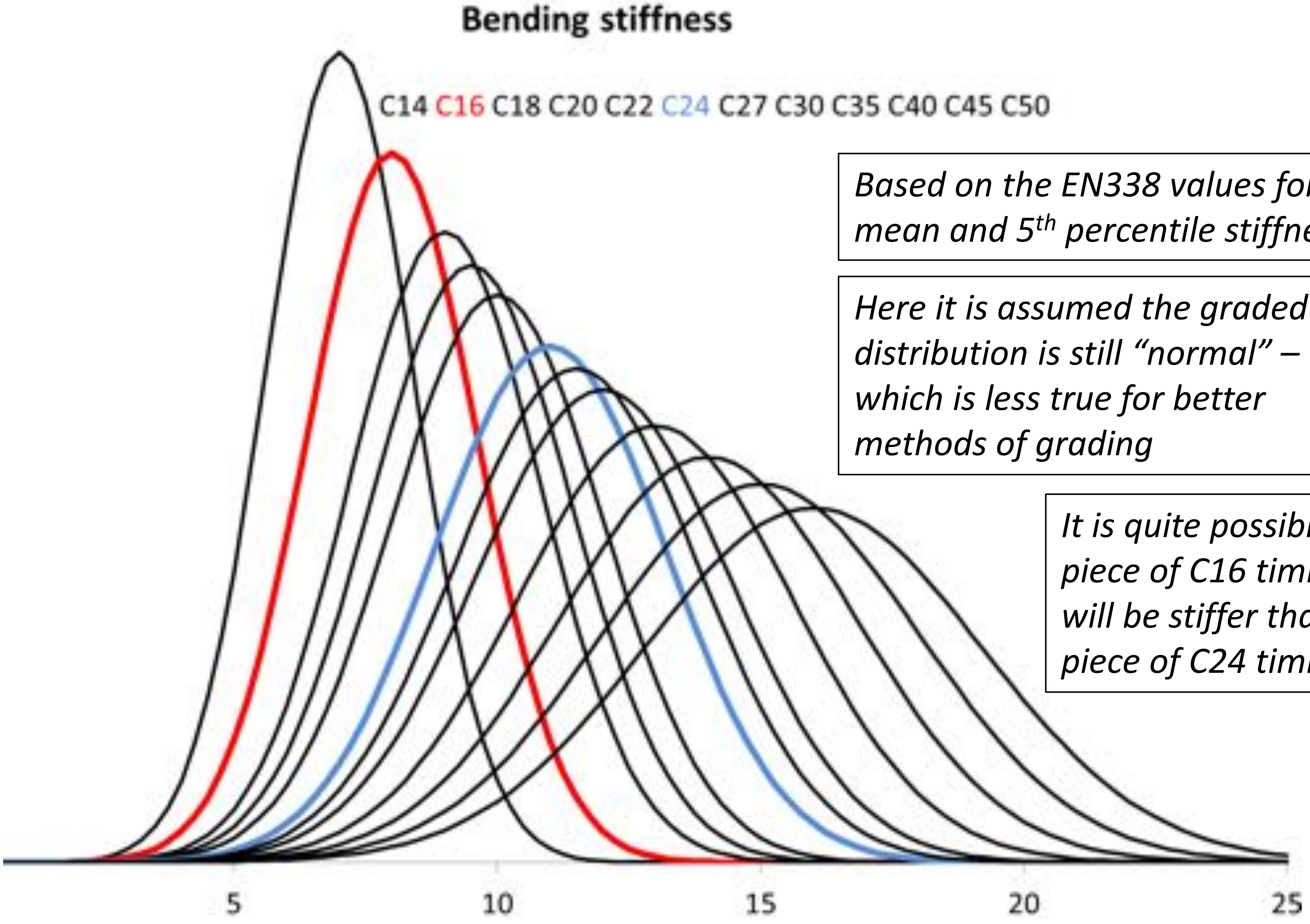
Distributions with the same 5%ile



There are many ways a distribution can comply with the strength class requirements

…even before considering that any distribution with a higher 5th percentile than is required would also comply

Strength classes are not distinct things
Bending stiffness distributions implied by EN338

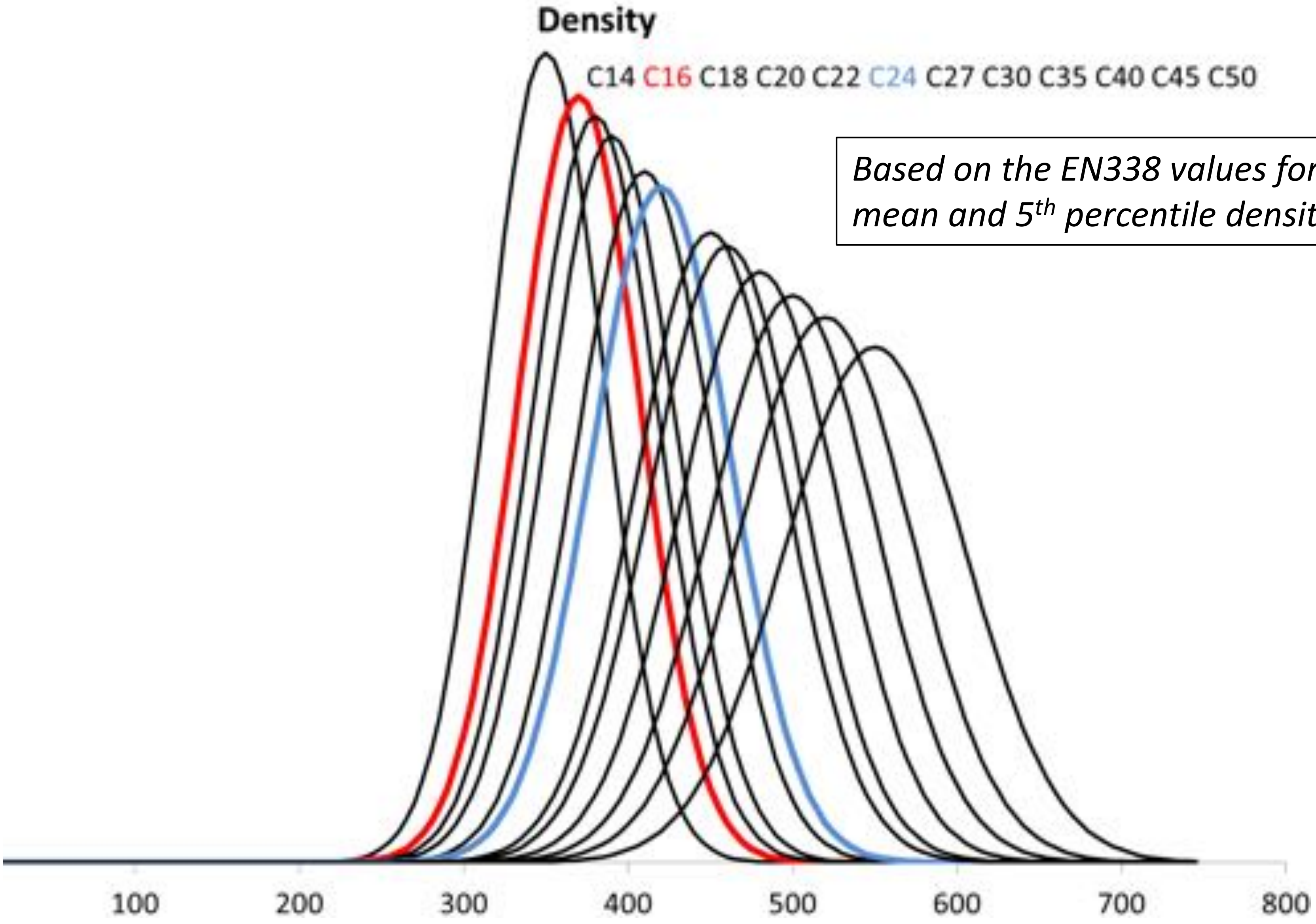


Based on the EN338 values for mean and 5th percentile stiffness

Here it is assumed the graded distribution is still "normal" – which is less true for better methods of grading

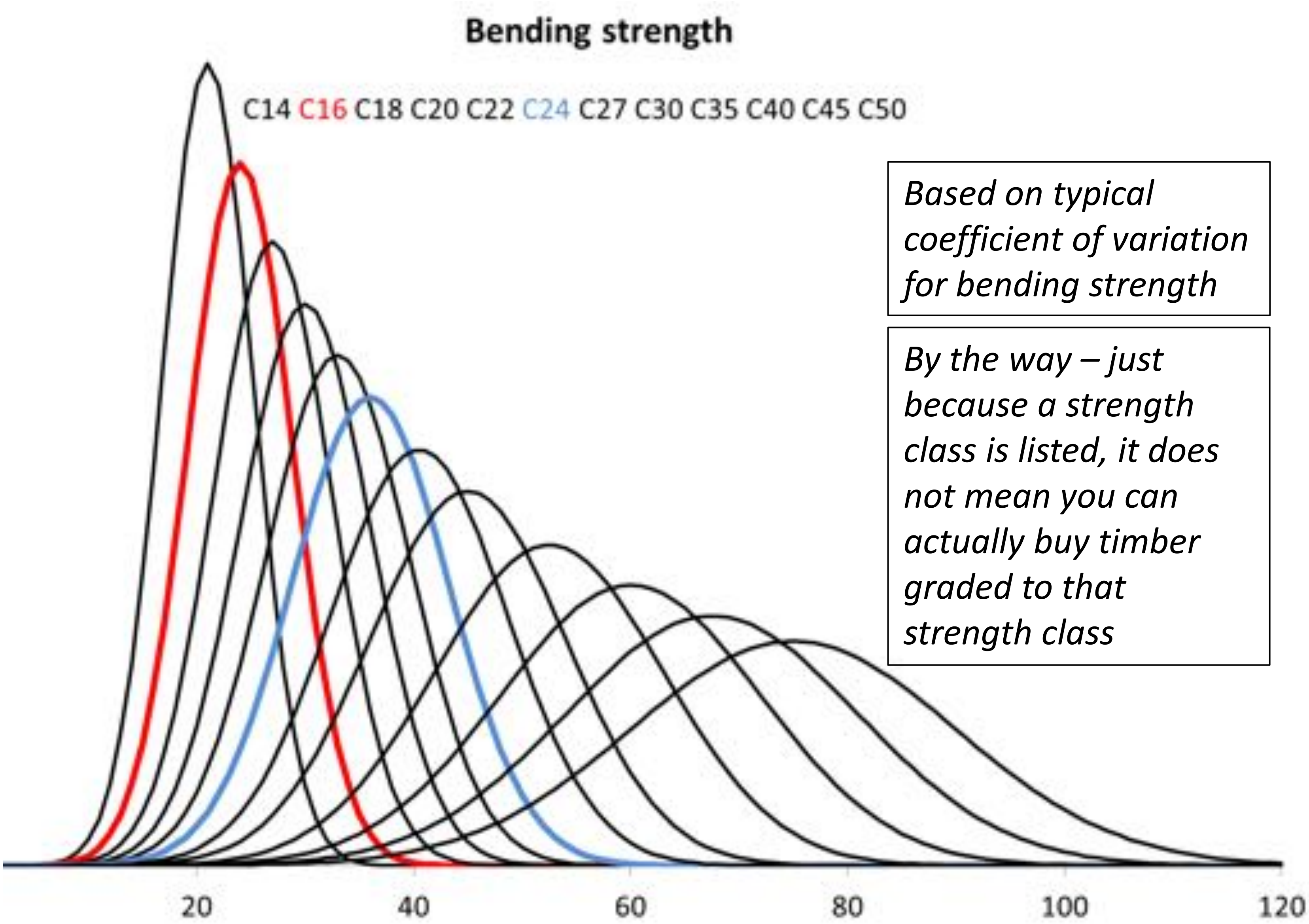
It is quite possible a piece of C16 timber will be stiffer than a piece of C24 timber

Strength classes are not distinct things
Density distributions implied by EN338



Based on the EN338 values for mean and 5th percentile density

Strength classes are not distinct things
Bending strength distributions implied by EN338



Based on typical coefficient of variation for bending strength

By the way – just because a strength class is listed, it does not mean you can actually buy timber graded to that strength class

Systems of grading
All governed by EN 14081 (and EN384)

Visual grading

1. Create grading rules (usually national standards)
2. Sort timber into the grades
3. Do destructive testing to see what properties the grades have
4. Assign grades to strength classes (some listed in EN1912)

Machine control grading

1. Do destructive testing to establish relationships between IP and properties
2. Decide the strength class combination for which settings are required
3. Determine the required IP thresholds so that the grades match the required strength classes (also satisfying some other requirements)

Output control grading (also by machine)

1. Develop initial settings from destructive testing
2. Periodically proof test timber and adjust settings if required

The bodies

CEN TC124 “Timber Structures”

- WG1 “Test Methods”
- **WG2 “Solid Timber”**
  - **TG1 “Grading”**
    - For machine settings, & assignments in EN 1912

National Mirror Committees

SG18 “Sector Group 18” (Notified Bodies)

Approval of settings and assignments

Visual grading

If to be listed in EN1912 needs to be approved by CEN TC124 WG2 TG1

Otherwise examined by a Notified Body with appropriate competence

Machine control

Both machine and settings need to be approved by CEN TC124 WG2 TG1

Output control

Examined by a Notified Body with appropriate competence

Visual grading and machine control require a lot of test data – so if research is being done on wood properties it makes sense to do it in a way that allows the results to be used to for grading settings or visual assignments. This means representative sampling and passing timber through grading machines to get IP data / visually grading the timber before testing.

Representative sampling
Some rules in EN14081 & EN384 but not all

Timber is representative of what will be graded in production

Needs to be full-sized timber (not small clears*)

Ideally taken from normal sawmill production

Need to know the source – not just the country, but the geographic region within it where it grew

The specimens are long enough that they can be tested at the critical section (worst point within their length)

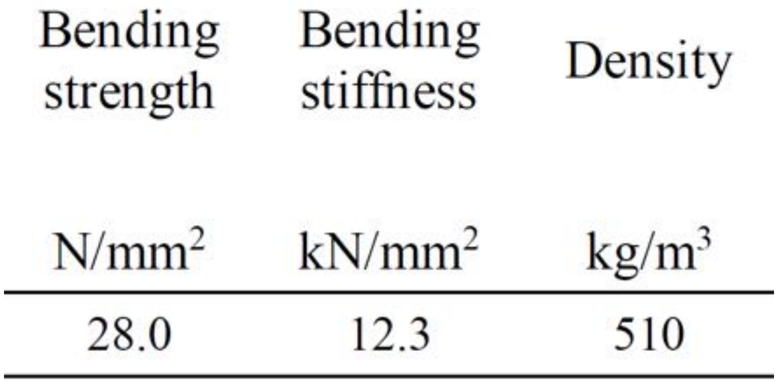
Nothing has been done that might bias the sampling

- No pre-grading (other than removal of visual overrides)
- No selection of unusual cross-sections, lengths or trees

* Small clears can be used for tropical timbers under certain circumstances

Illustration with real data (1)
Spanish sweet chestnut (visual grading)

Strength class assignments for sweet chestnut (*Castanea sativa*) grown in Spain visually graded as "MEF" (structural hardwood) to the Spanish standard UNE 56546.



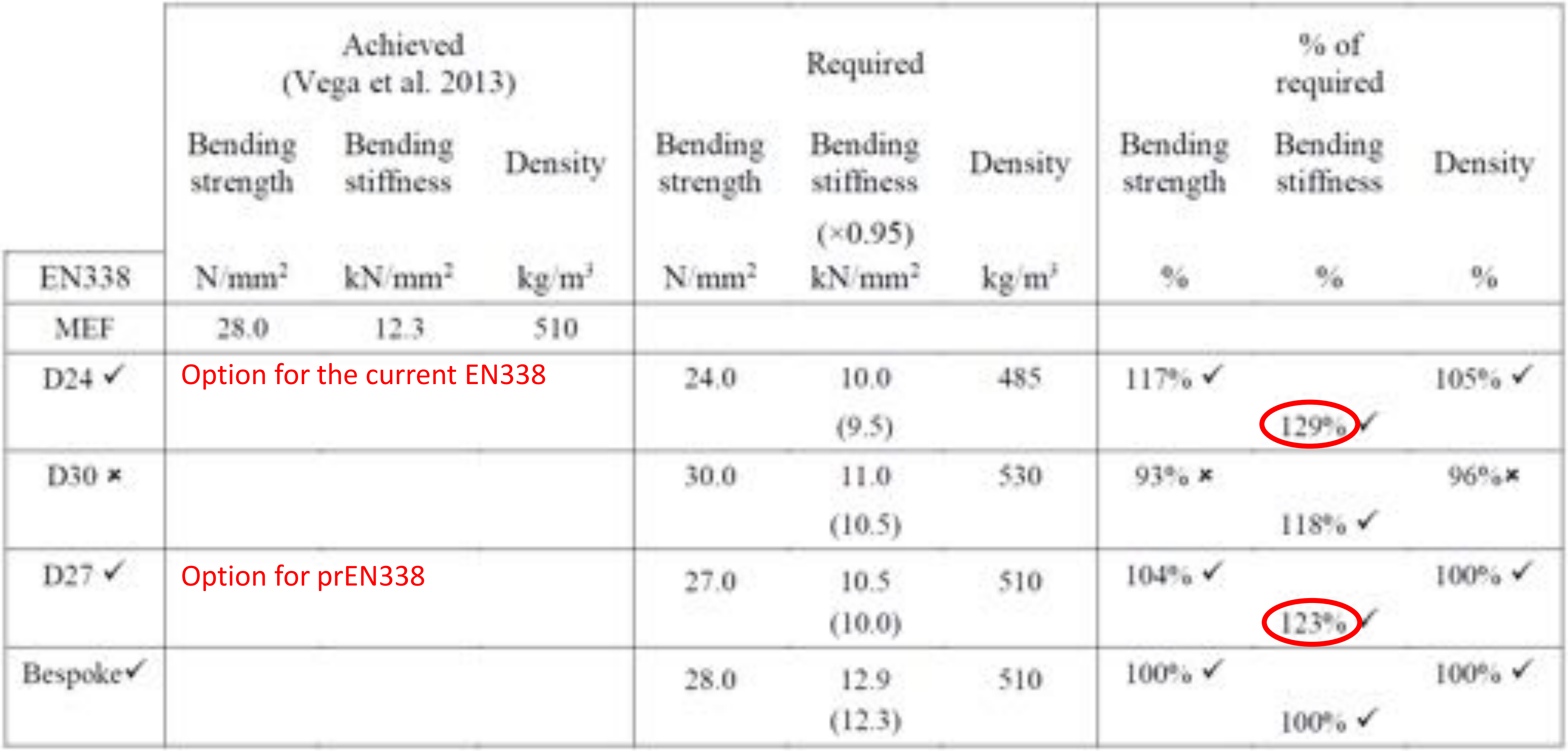
Bending strength	Bending stiffness	Density
N/mm²	kN/mm²	kg/m³
28.0	12.3	510

Characteristic values for timber sampled from 5 provenances in Spain (800 pieces in grade MEF)

After necessary adjustments for size, moisture, test span, sample size etc

Vega A, Arriaga F, Guaita M, Baño V (2013) Proposal for visual grading criteria of structural timber of sweet chestnut from Spain. Eur. J. Wood Prod. (2013) 71:529–532 doi 10.1007/s00107-013-0705-4

Illustration with real data (1)
Spanish sweet chestnut (visual grading)



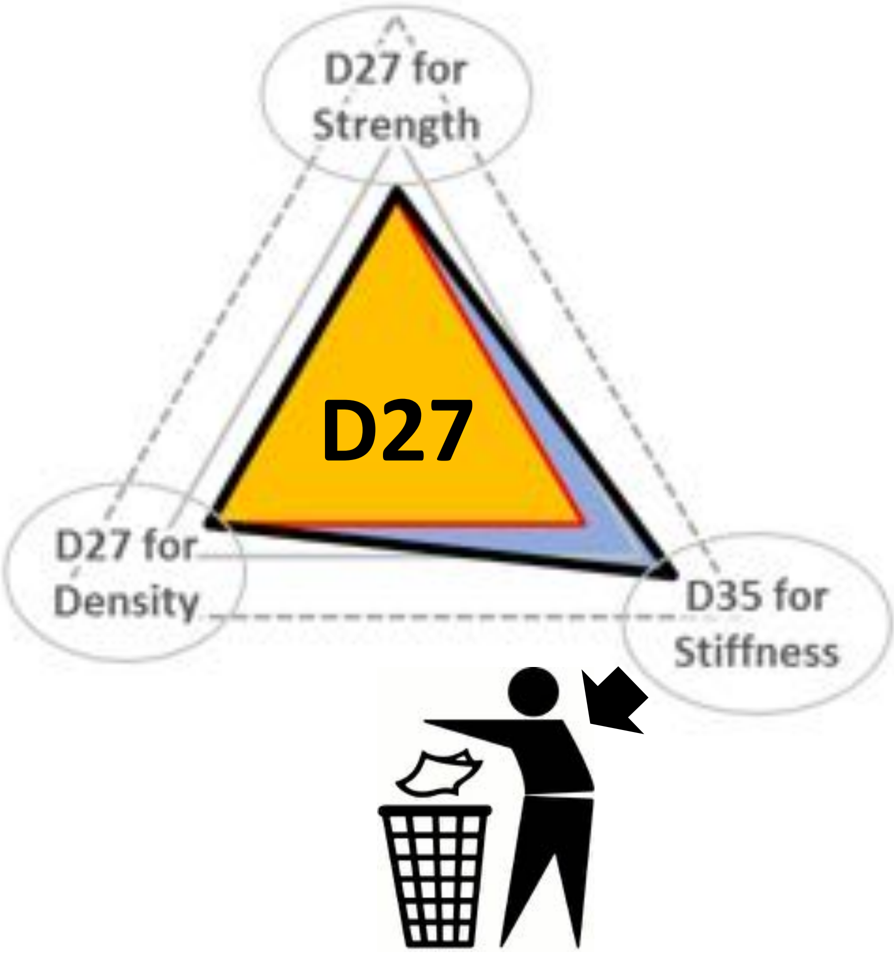
	Achieved (Vega et al. 2013)			Required			% of required		
	Bending strength	Bending stiffness	Density	Bending strength	Bending stiffness (×0.95)	Density	Bending strength	Bending stiffness	Density
EN338	N/mm²	kN/mm²	kg/m³	N/mm²	kN/mm²	kg/m³	%	%	%
MEF	28.0	12.3	510						
D24 ✓	Option for the current EN338			24.0	10.0 (9.5)	485	117% ✓	129% ✓	105% ✓
D30 ✗				30.0	11.0 (10.5)	530	93% ✗	118% ✓	96% ✗
D27 ✓	Option for prEN338			27.0	10.5 (10.0)	510	104% ✓	123% ✓	100% ✓
Bespoke ✓				28.0	12.9 (12.3)	510	100% ✓	100% ✓	100% ✓

D27 is a new strength class being added to EN338

With the new version of EN338, C-classes are also an option

Using a generic strength class means losing 29% of the stiffness! (or 23% with prEN338)

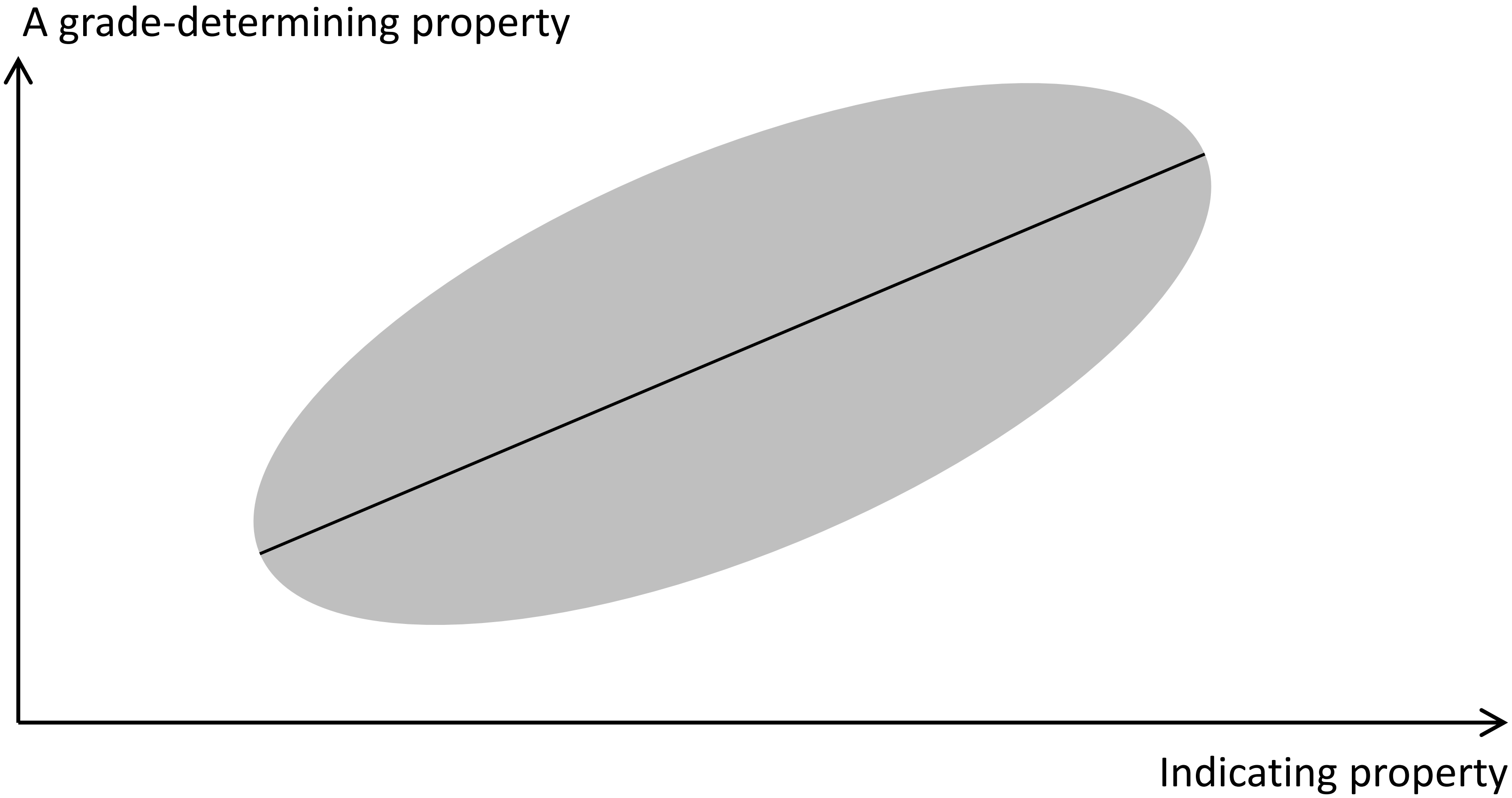
Illustration with real data (1)
MEF visual grade of Spanish sweet chestnut



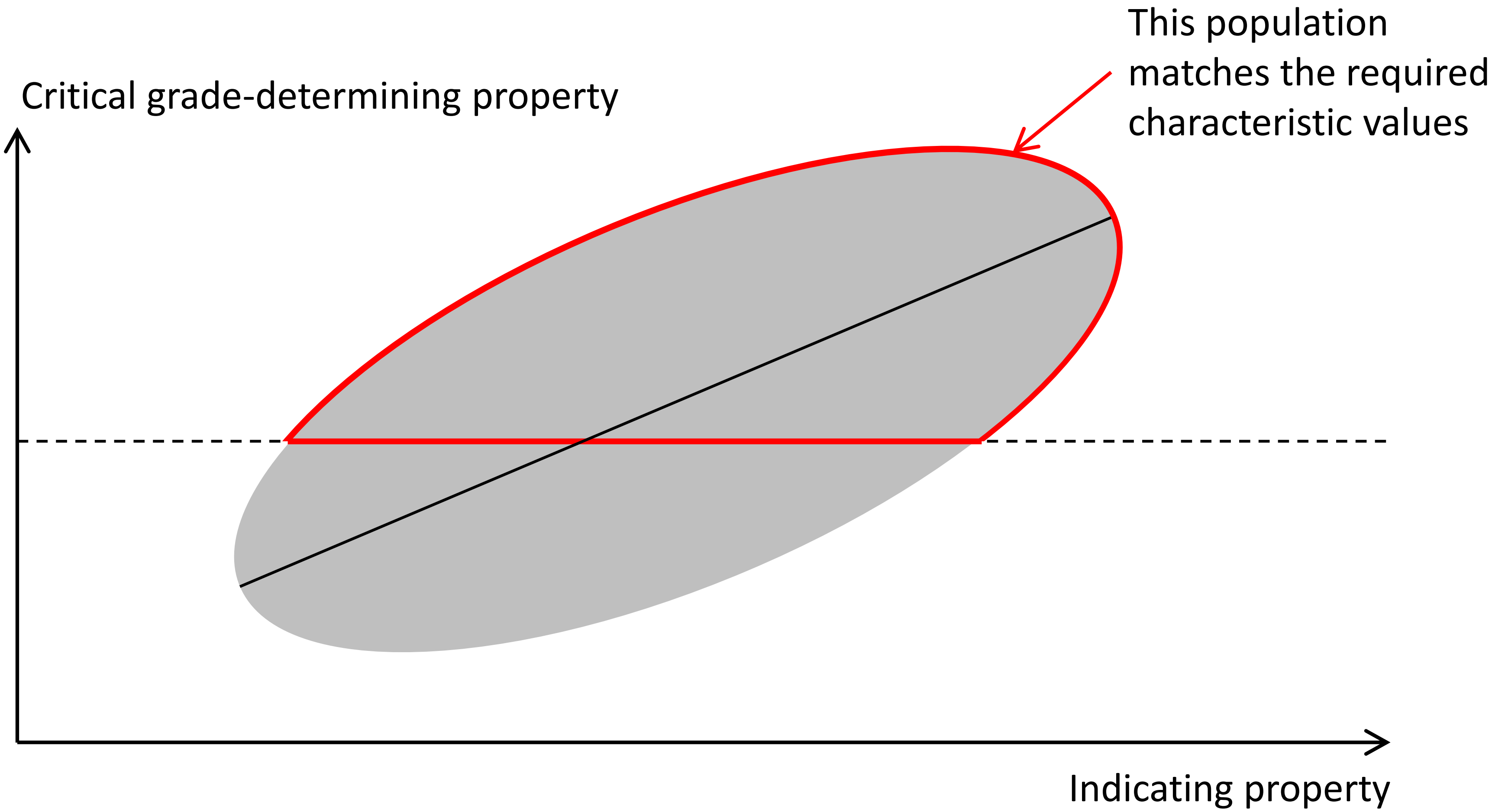
For the generic "D" strength classes in EN338 the density is limiting…followed closely by strength. Stiffness, however, greatly exceeds what is required for the strength class. Assigning to a D class lowers performance in exchange for easy trade – but what if you are grading for a specific job? Why throw away this stiffness? – especially when this might be the property that actually limits design.

If density had been more limiting – it may have made sense to assign to a C-class (a possibility opened up by the revision of EN338)

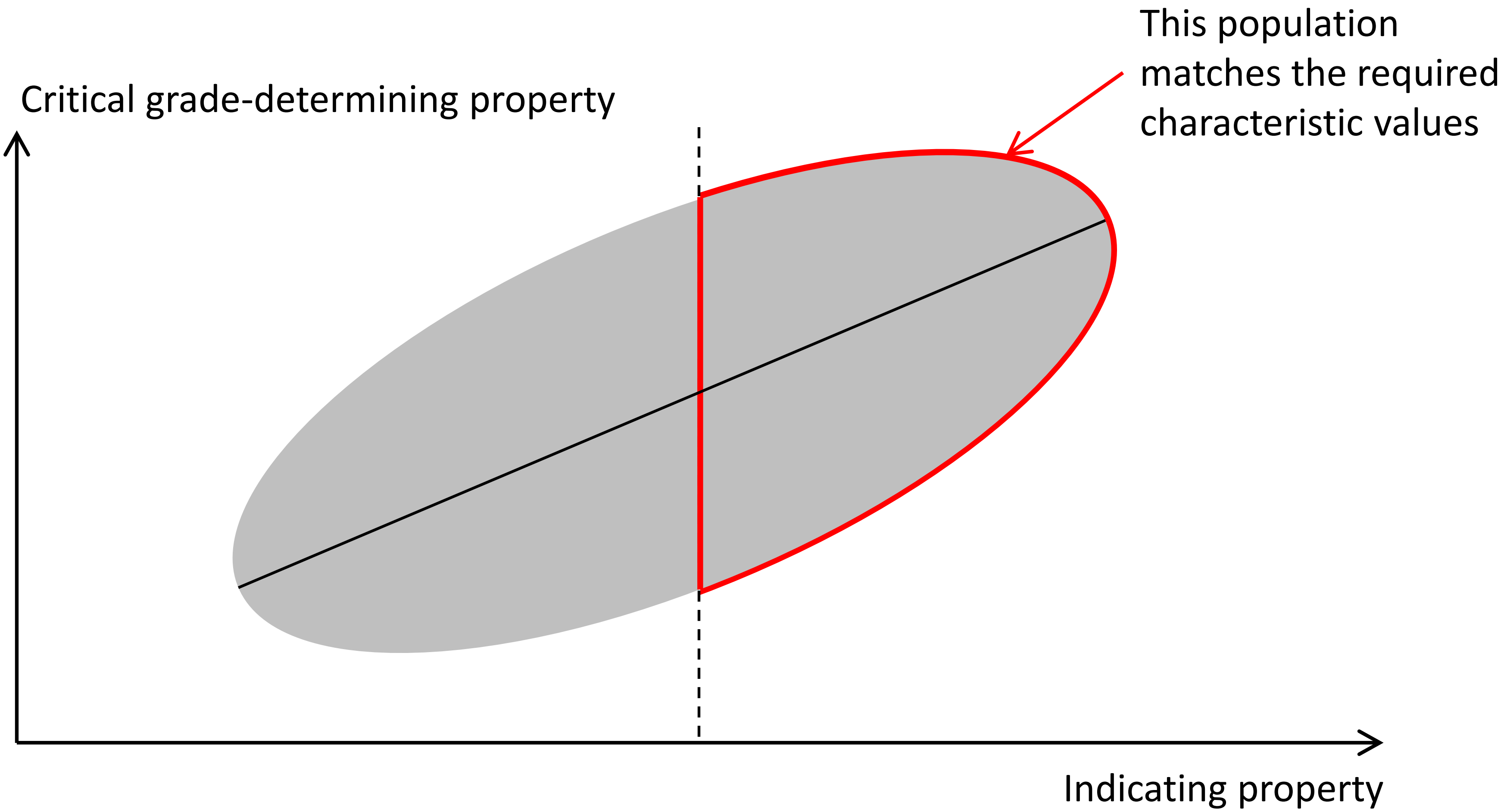
The principle of machine control (simplified)
1) Data obtained from destructive tests



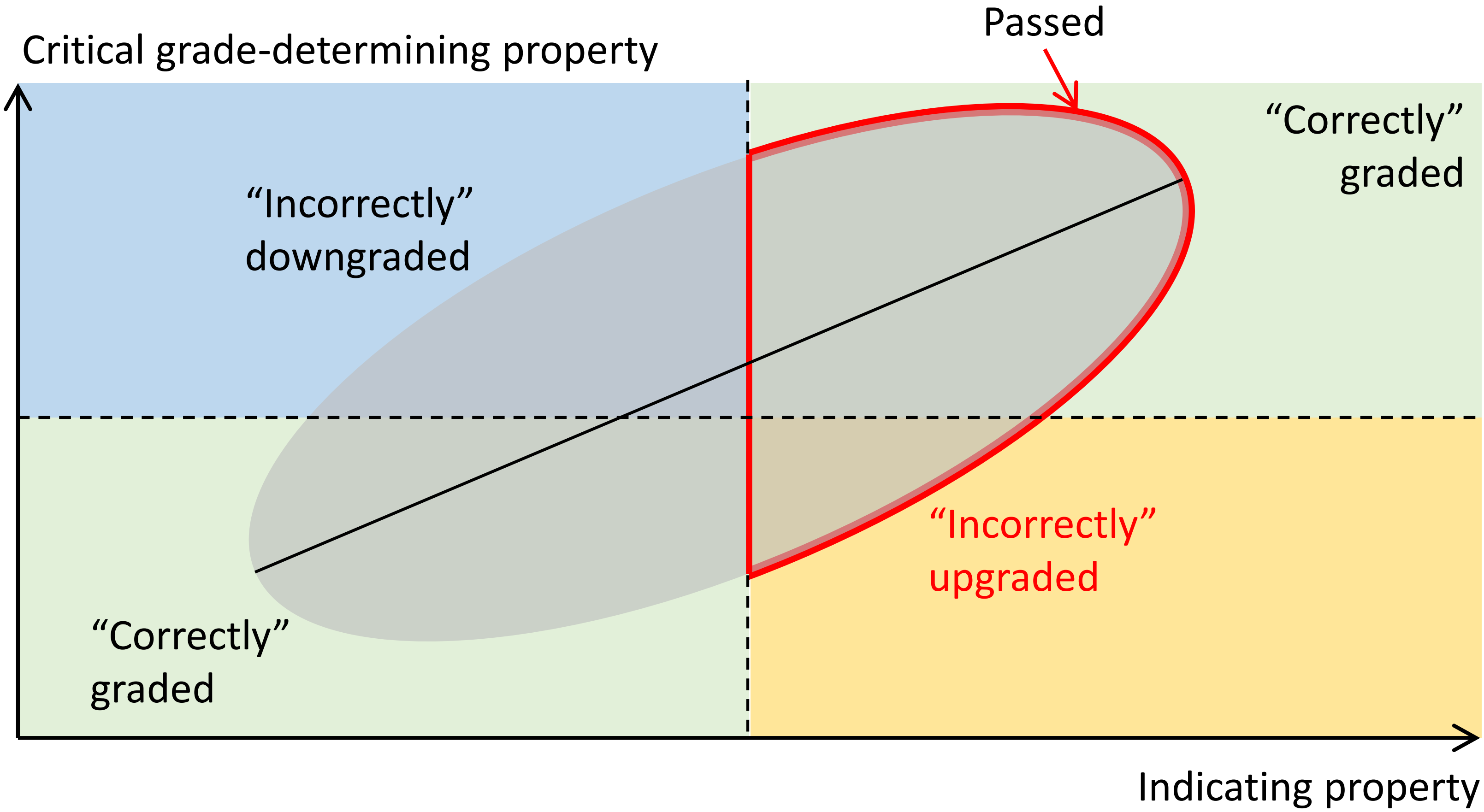
2) Optimum grade (a perfect grading machine)



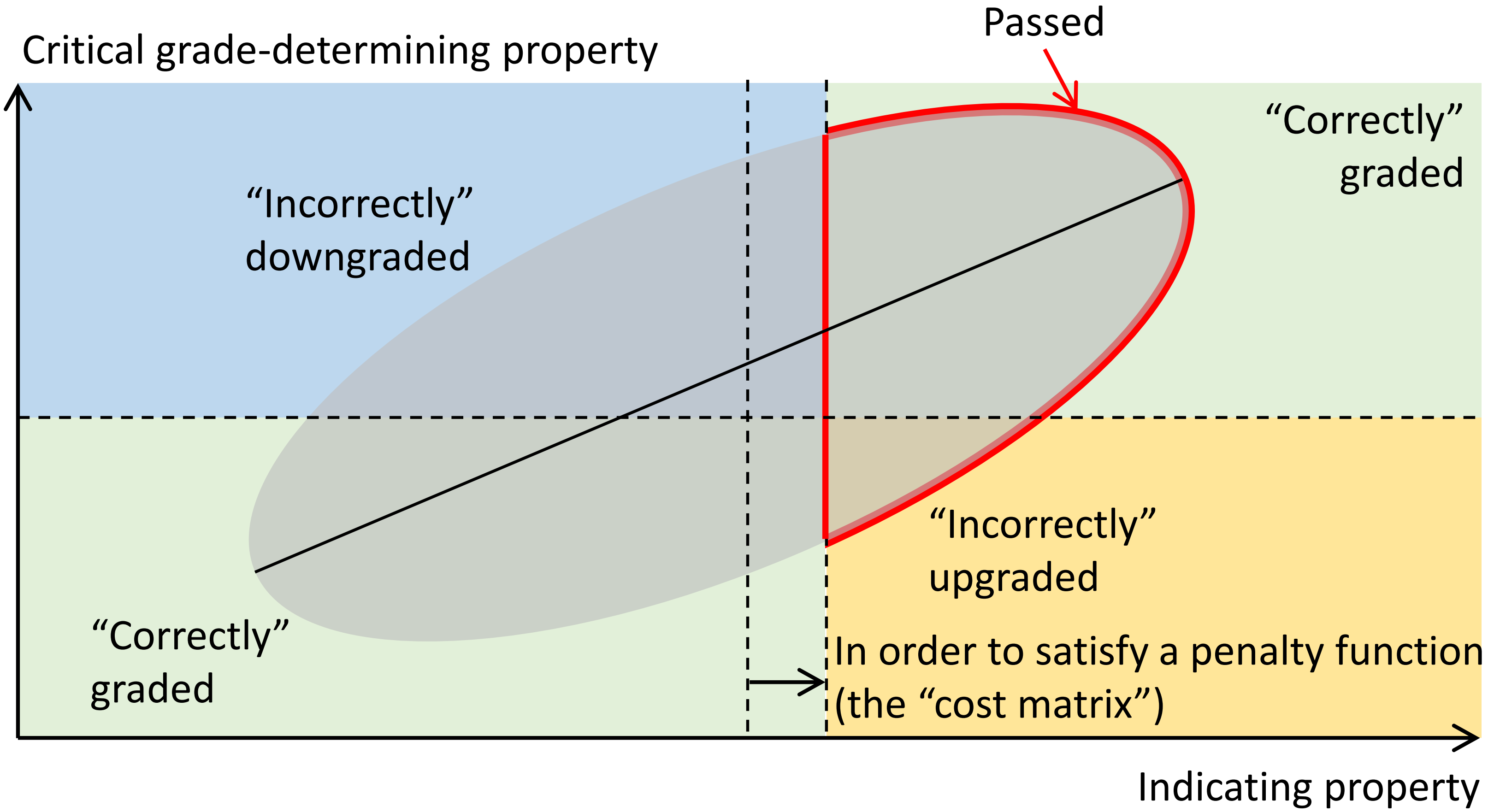
3) Using IP
The actual grading machine



4) Cost matrix



4) Cost matrix



In order to satisfy a penalty function (the "cost matrix")

Why a powerful IP is better
Encouraged by the cost matrix

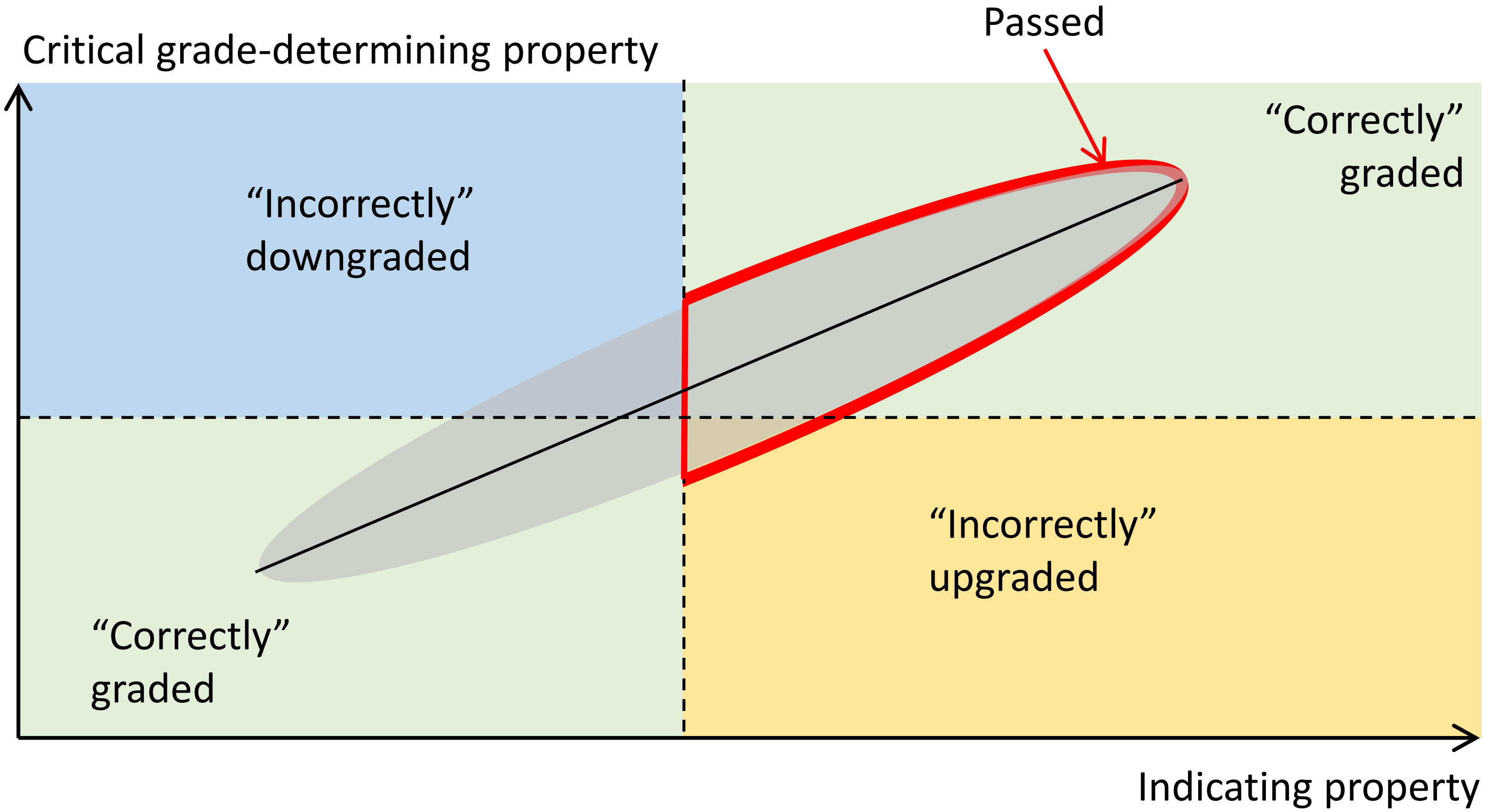
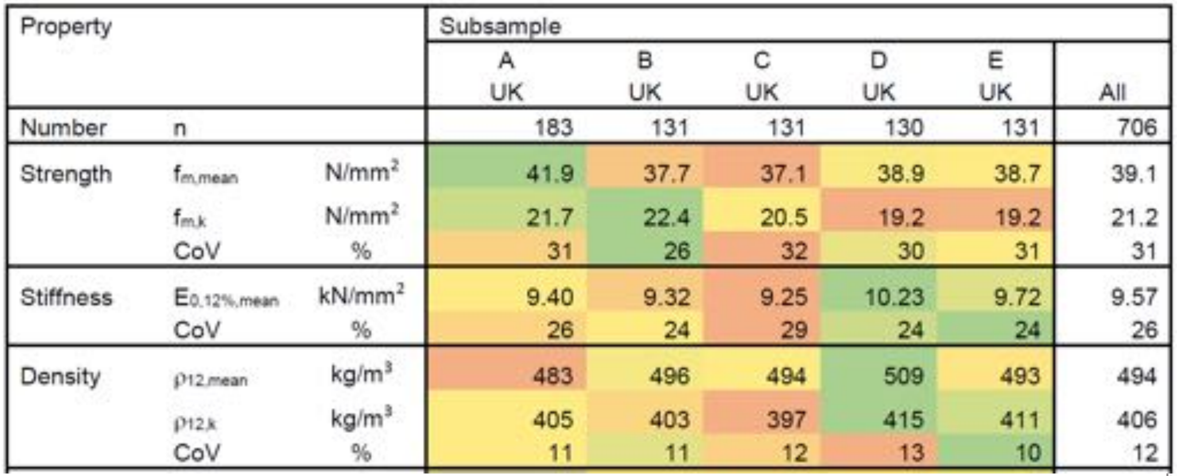
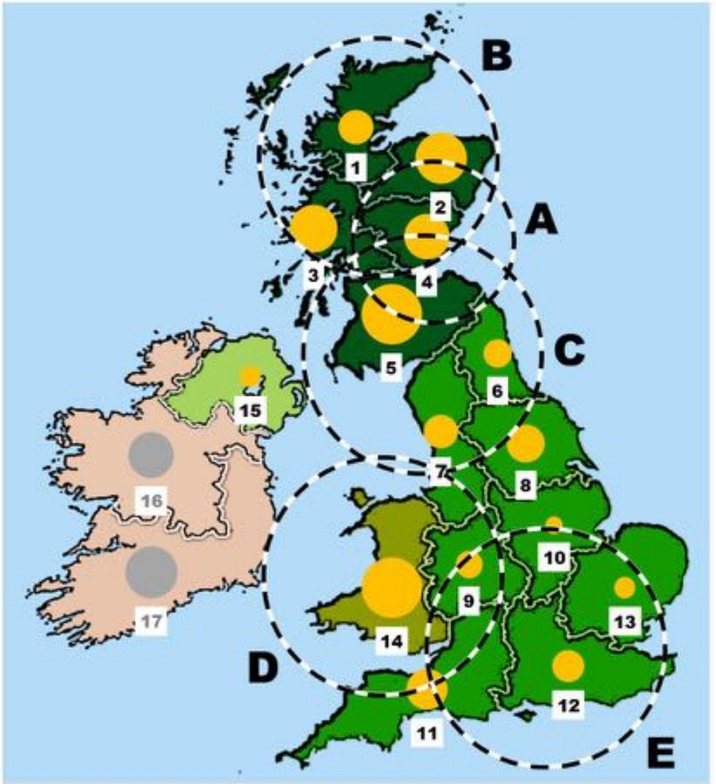


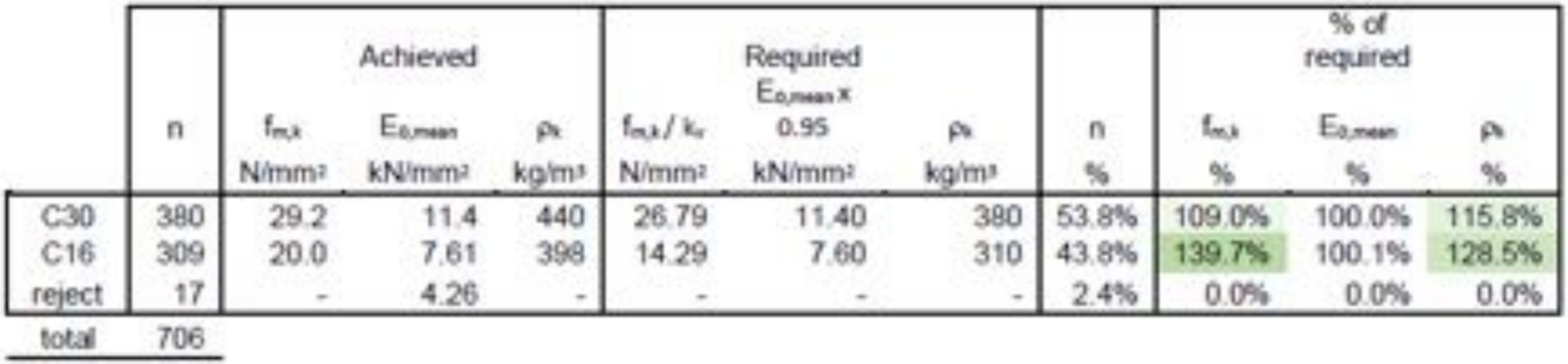
Illustration with real data (2)
UK larch (C16/C30 combination)



Property			Subsample					
			A UK	B UK	C UK	D UK	E UK	All
Number	n		183	131	131	130	131	706
Strength	$f_{m,mean}$	N/mm^2	41.9	37.7	37.1	38.9	38.7	39.1
	$f_{m,k}$	N/mm^2	21.7	22.4	20.5	19.2	19.2	21.2
	CoV	%	31	26	32	30	31	31
Stiffness	$E_{0,12\%,mean}$	kN/mm^2	9.40	9.32	9.25	10.23	9.72	9.57
	CoV	%	26	24	29	24	24	26
Density	$\rho_{12,mean}$	kg/m^3	483	496	494	509	493	494
	$\rho_{12,k}$	kg/m^3	405	403	397	415	411	406
	CoV	%	11	11	12	13	10	12

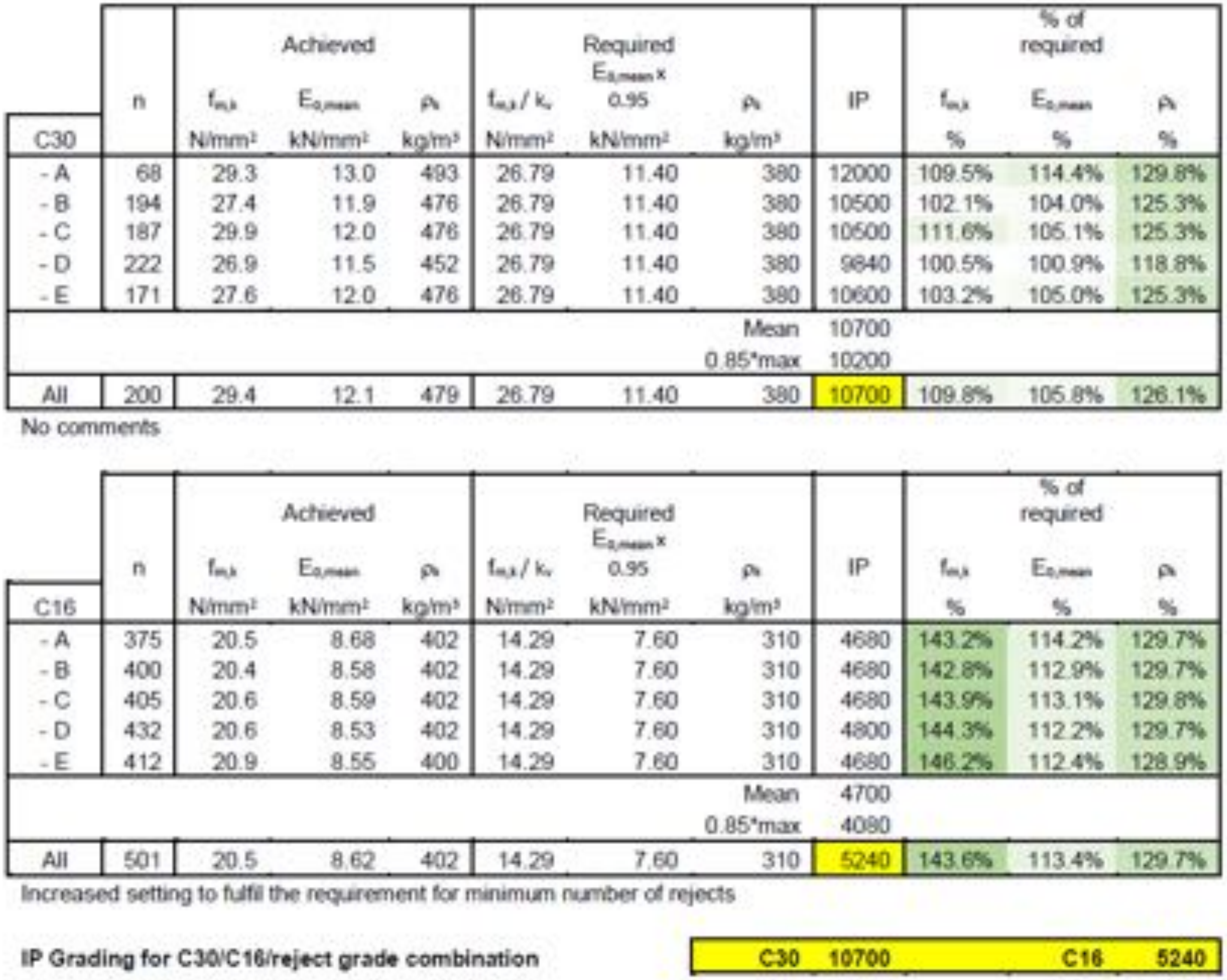


Optimum grading for C30/C16/reject grade combination
(a perfect grading machine)



	n	Achieved			Required				% of required		
	n	$f_{m,k}$ N/mm^2	$E_{0,mean}$ kN/mm^2	ρ_k kg/m^3	$f_{m,k}$ / k_v N/mm^2	$E_{0,mean}$ x 0.95 kN/mm^2	ρ_k kg/m^3	n %	$f_{m,k}$ %	$E_{0,mean}$ %	ρ_k %
C30	380	29.2	11.4	440	26.79	11.40	380	53.8%	109.0%	100.0%	115.8%
C16	309	20.0	7.61	398	14.29	7.60	310	43.8%	139.7%	100.1%	128.5%
reject	17	-	4.26	-	-	-	-	2.4%	0.0%	0.0%	0.0%
total	706										

Illustration with real data (2)
UK larch (C16/C30 combination)



C30	n	Achieved $f_{m,k}$ N/mm^2	Achieved $E_{0,mean}$ kN/mm^2	Achieved ρ_k kg/m^3	Required $f_{m,k}/k_v$ N/mm^2	Required $E_{0,mean} \times 0.95$ kN/mm^2	Required ρ_k kg/m^3	IP	% of required $f_{m,k}$ %	% of required $E_{0,mean}$ %	% of required ρ_k %
- A	68	29.3	13.0	493	26.79	11.40	380	12000	109.5%	114.4%	129.8%
- B	194	27.4	11.9	476	26.79	11.40	380	10500	102.1%	104.0%	125.3%
- C	187	29.9	12.0	476	26.79	11.40	380	10500	111.6%	105.1%	125.3%
- D	222	26.9	11.5	452	26.79	11.40	380	9840	100.5%	100.9%	118.8%
- E	171	27.6	12.0	476	26.79	11.40	380	10600	103.2%	105.0%	125.3%
							Mean	10700			
							0.85*max	10200			
All	200	29.4	12.1	479	26.79	11.40	380	10700	109.8%	105.8%	126.1%

No comments

C16	n	Achieved $f_{m,k}$ N/mm^2	Achieved $E_{0,mean}$ kN/mm^2	Achieved ρ_k kg/m^3	Required $f_{m,k}/k_v$ N/mm^2	Required $E_{0,mean} \times 0.95$ kN/mm^2	Required ρ_k kg/m^3	IP	% of required $f_{m,k}$ %	% of required $E_{0,mean}$ %	% of required ρ_k %
- A	375	20.5	8.68	402	14.29	7.60	310	4680	143.2%	114.2%	129.7%
- B	400	20.4	8.58	402	14.29	7.60	310	4680	142.8%	112.9%	129.7%
- C	405	20.6	8.59	402	14.29	7.60	310	4680	143.9%	113.1%	129.8%
- D	432	20.6	8.53	402	14.29	7.60	310	4800	144.3%	112.2%	129.7%
- E	412	20.9	8.55	400	14.29	7.60	310	4680	146.2%	112.4%	128.9%
							Mean	4700			
							0.85*max	4080			
All	501	20.5	8.62	402	14.29	7.60	310	5240	143.6%	113.4%	129.7%

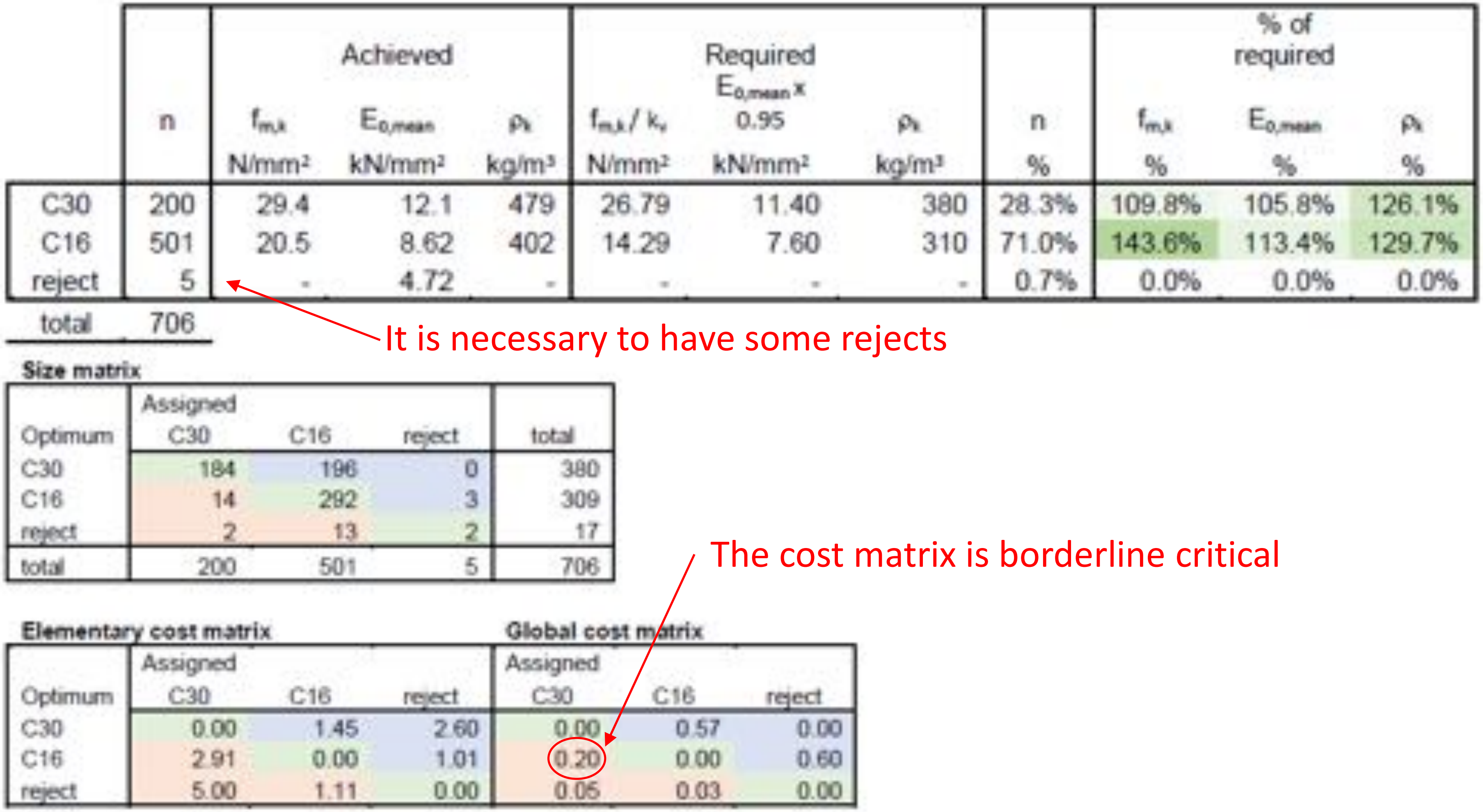
Increased setting to fulfil the requirement for minimum number of rejects

IP Grading for C30/C16/reject grade combination C30 10700 C16 5240

A process in which IP thresholds are calculated on the whole sample less one geographic subsample

First the upper grade, and then the lower grade

Illustration with real data (2)
UK larch (C16/C30 combination)



	n	Achieved $f_{m,k}$ N/mm²	 $E_{0,mean}$ kN/mm²	 ρ_k kg/m³	Required $f_{m,k}$ / k_v N/mm²	 $E_{0,mean}$ x 0.95 kN/mm²	 ρ_k kg/m³	n %	% of required $f_{m,k}$ %	 $E_{0,mean}$ %	 ρ_k %
C30	200	29.4	12.1	479	26.79	11.40	380	28.3%	109.8%	105.8%	126.1%
C16	501	20.5	8.62	402	14.29	7.60	310	71.0%	143.6%	113.4%	129.7%
reject	5	-	4.72	-	-	-	-	0.7%	0.0%	0.0%	0.0%
total	706										

It is necessary to have some rejects

Size matrix

Optimum	Assigned C30	 C16	 reject	total
C30	184	196	0	380
C16	14	292	3	309
reject	2	13	2	17
total	200	501	5	706

The cost matrix is borderline critical

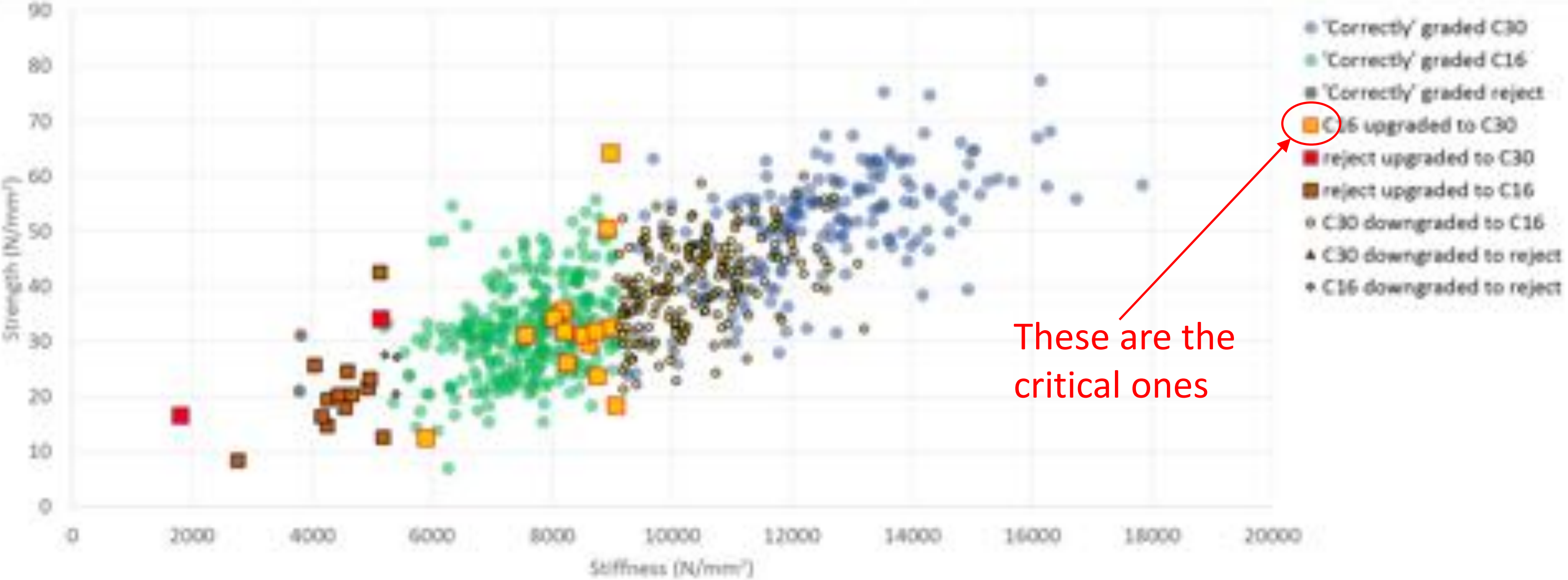
Elementary cost matrix

Optimum	Assigned C30	 C16	 reject
C30	0.00	1.45	2.60
C16	2.91	0.00	1.01
reject	5.00	1.11	0.00

Global cost matrix

Optimum	Assigned C30	 C16	 reject
C30	0.00	0.57	0.00
C16	0.20	0.00	0.60
reject	0.05	0.03	0.00

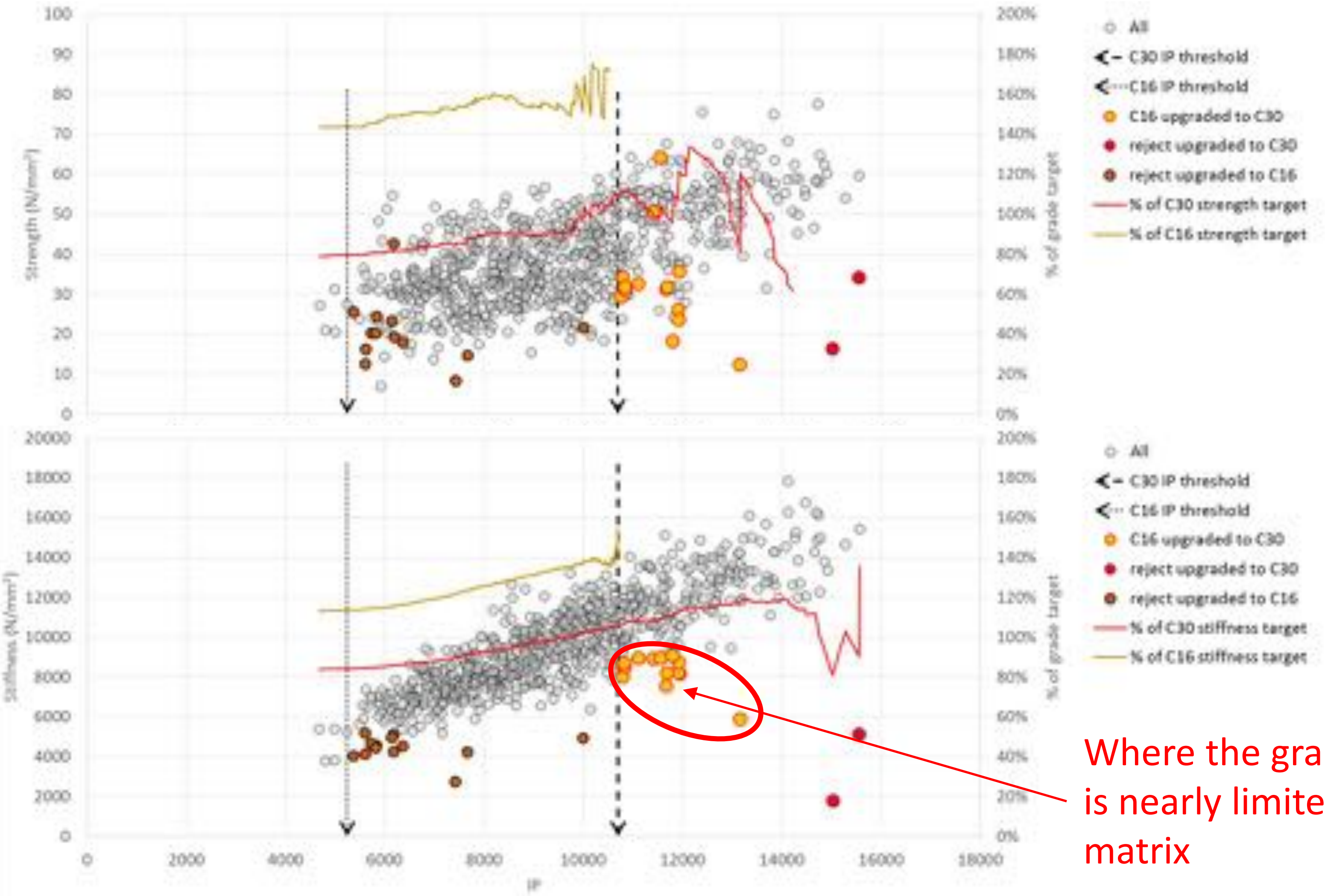
Illustration with real data (2)
UK larch (C16/C30 combination)



These are the critical ones

For a machine operating on dynamic MoE

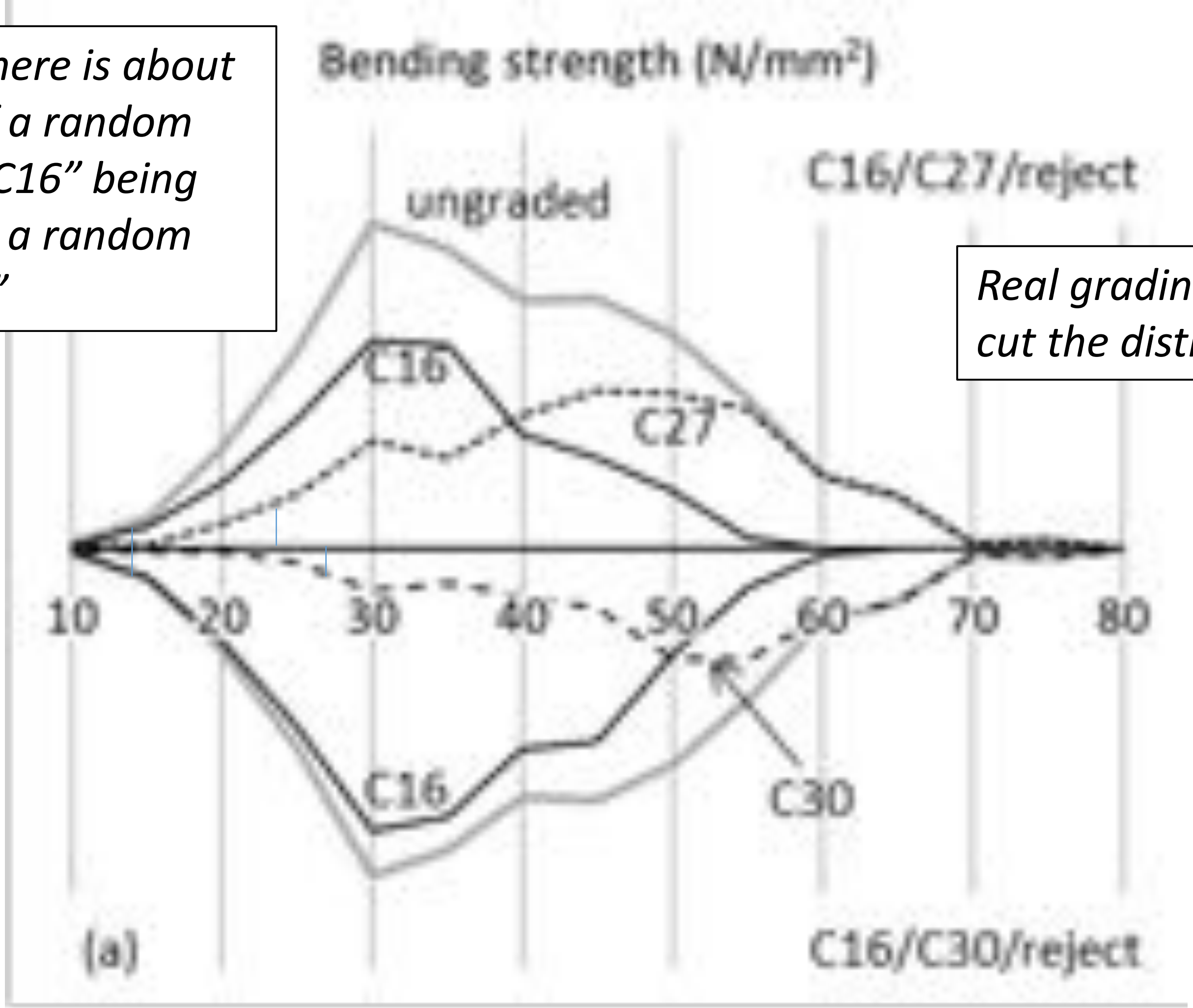
Illustration with real data (2)
UK larch (C16/C30 combination)



Where the grading process is nearly limited by the cost matrix

Real world illustration (2) UK larch (strength)

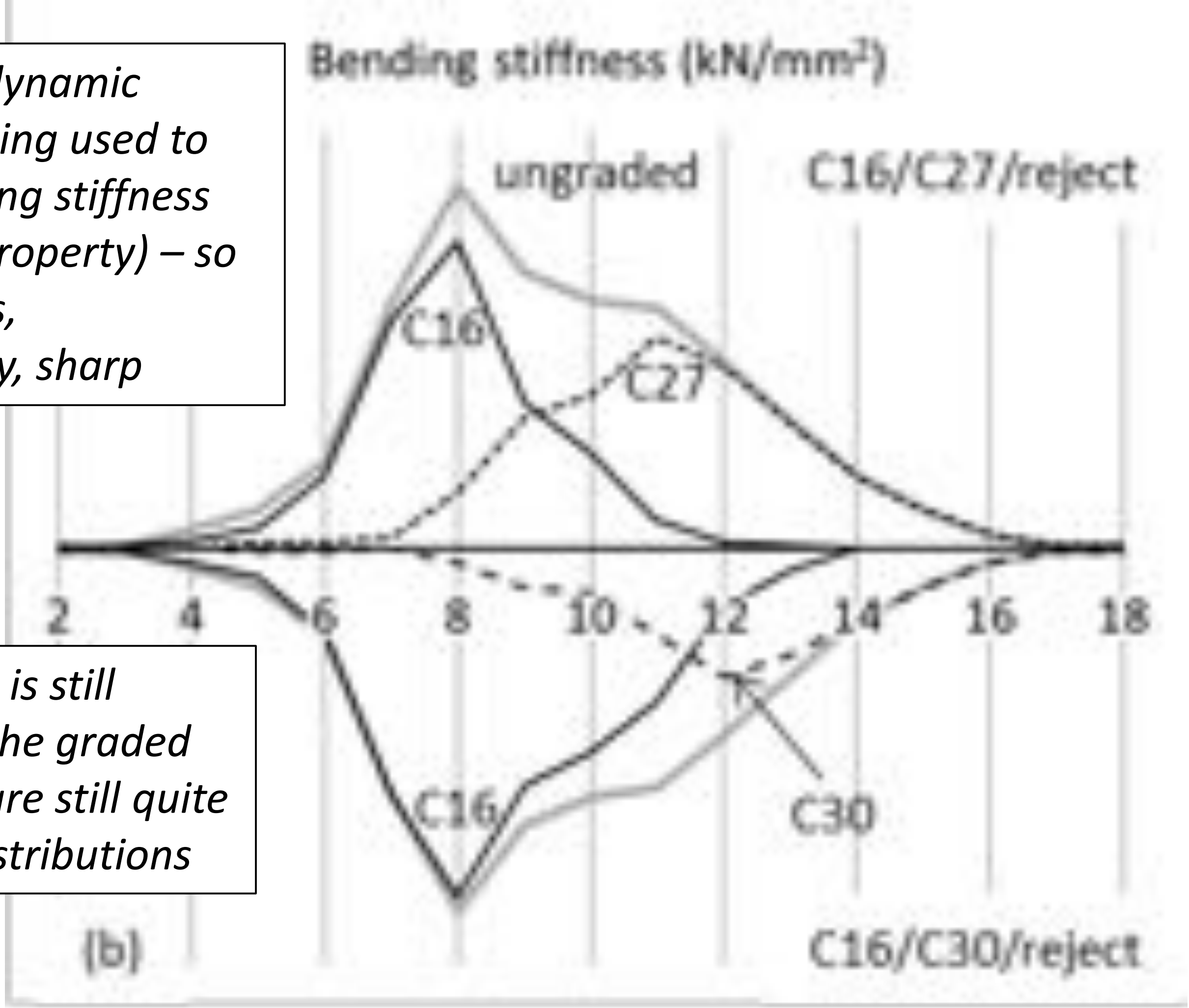
In this case, there is about 1/3 chance of a random piece of the "C16" being stronger than a random piece of "C27"



Real grading is not able to cut the distribution sharply

Real world illustration (2)
UK larch (stiffness)

In this case, dynamic stiffness is being used to predict bending stiffness (the critical property) – so the grading is, comparatively, sharp



Even so, there is still overlap, and the graded distributions are still quite like normal distributions

Real world illustration (2)
UK larch (density)

Density could be graded more accurately, as, in this case, mass is actually measured, but in this case density is not critical and so only dynamic stiffness is used as the IP

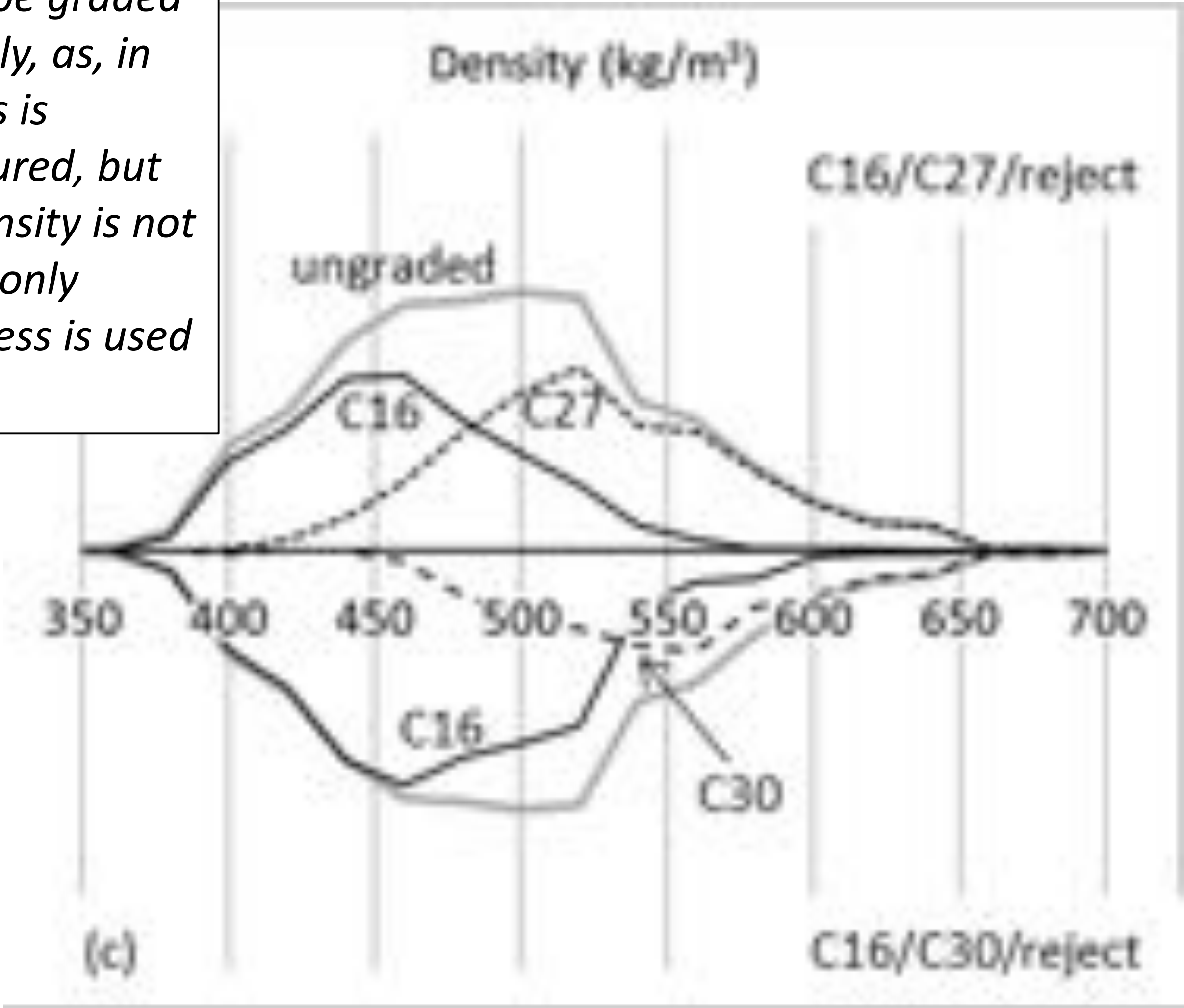
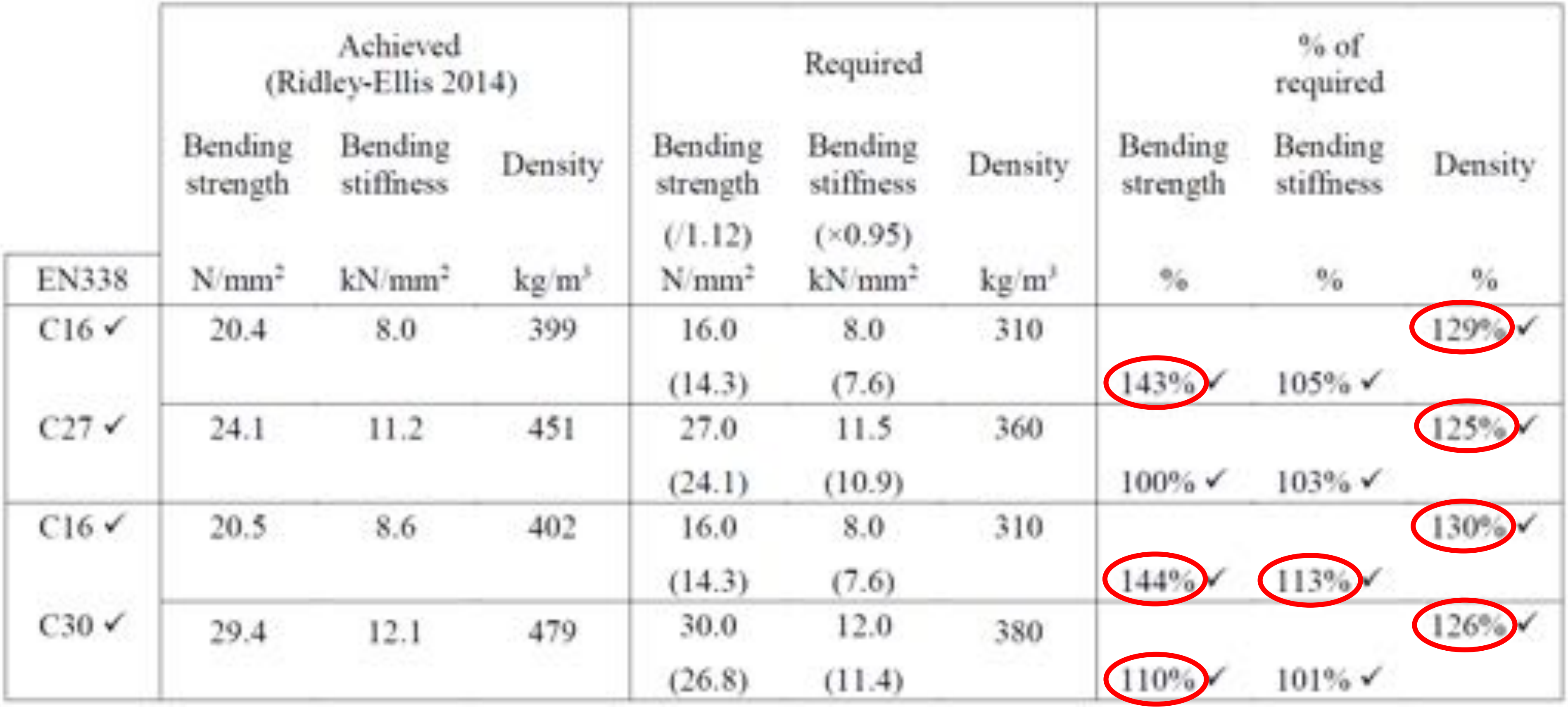


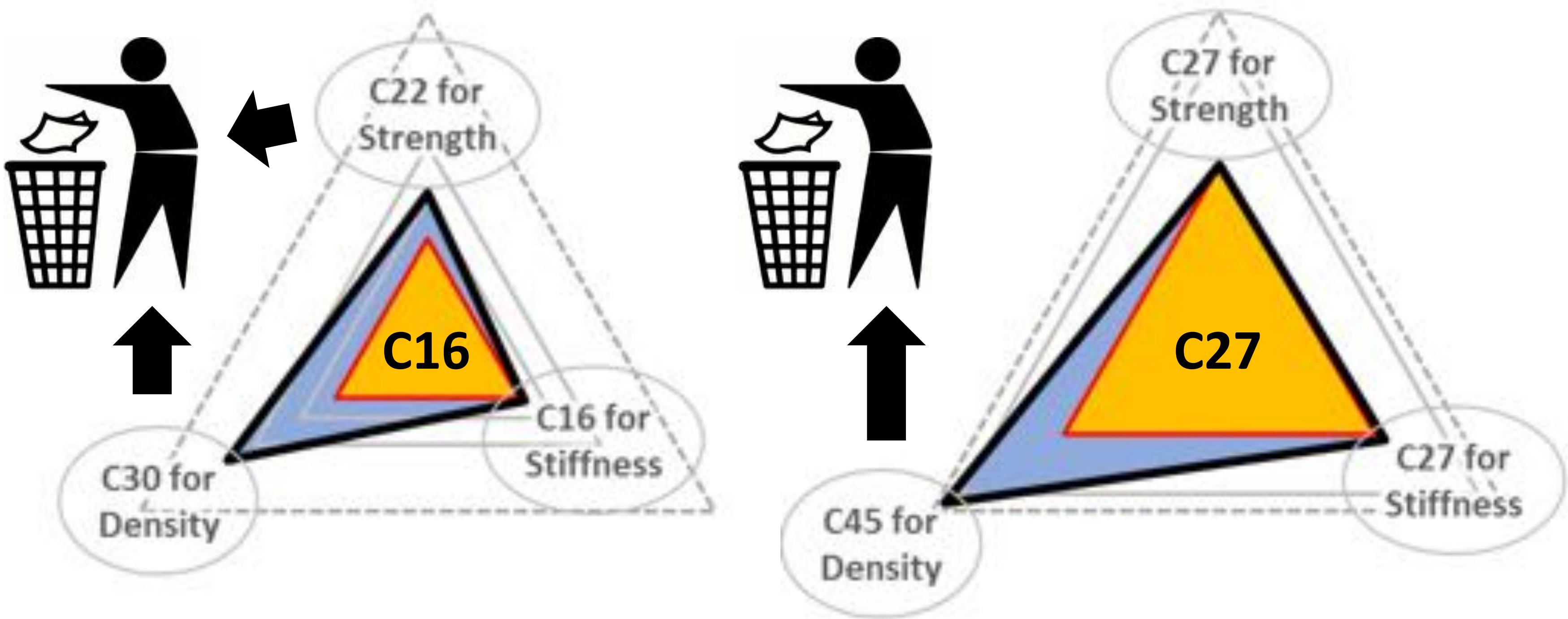
Illustration with real data (2)
UK larch



	Achieved (Ridley-Ellis 2014)			Required			% of required		
	Bending strength	Bending stiffness	Density	Bending strength (/1.12)	Bending stiffness (×0.95)	Density	Bending strength	Bending stiffness	Density
EN338	N/mm^2	kN/mm^2	kg/m^3	N/mm^2	kN/mm^2	kg/m^3	%	%	%
C16 ✓	20.4	8.0	399	16.0 (14.3)	8.0 (7.6)	310	143% ✓	105% ✓	129% ✓
C27 ✓	24.1	11.2	451	27.0 (24.1)	11.5 (10.9)	360	100% ✓	103% ✓	125% ✓
C16 ✓	20.5	8.6	402	16.0 (14.3)	8.0 (7.6)	310	144% ✓	113% ✓	130% ✓
C30 ✓	29.4	12.1	479	30.0 (26.8)	12.0 (11.4)	380	110% ✓	101% ✓	126% ✓

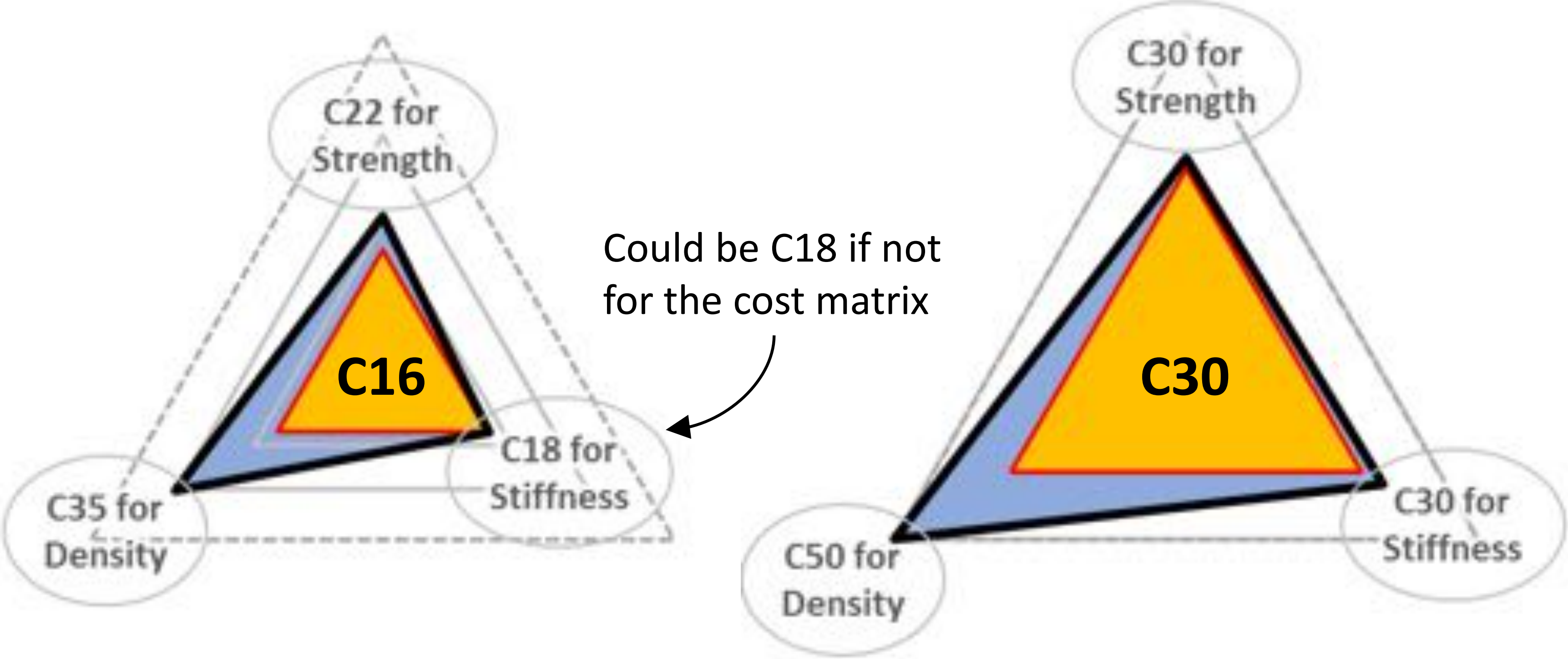
In all cases, the density greatly exceeds the value for the strength class. For C16 the strength greatly exceeds the strength class value.

Illustration with real data (2)
UK larch (C16/C27 combination)



For machine grading it is not quite as simple as for visual grading as a “bespoke strength class” has to be set in advance of the optimum grading – and this changes the cost matrix calculations. Even so, when machine grading timber and selling directly to a fabricator, it often makes little sense to use the generic EN338 strength classes – it discards some performance.

Illustration with real data (2)
UK larch (C16/C30 combination)



Could be C18 if not for the cost matrix

With machine grading, it is a pay off between strength class and yield. The cost matrix can do odd things. In this case, grading to a C18/C30 combination would result in a reject rate of 30% (compared to C16/C30 reject rate of less than 1%) even though the timber graded to C16 has the properties of C18.

A few other things
The meaning of dry-graded

Dry-graded timber is not the same as dry, graded timber.

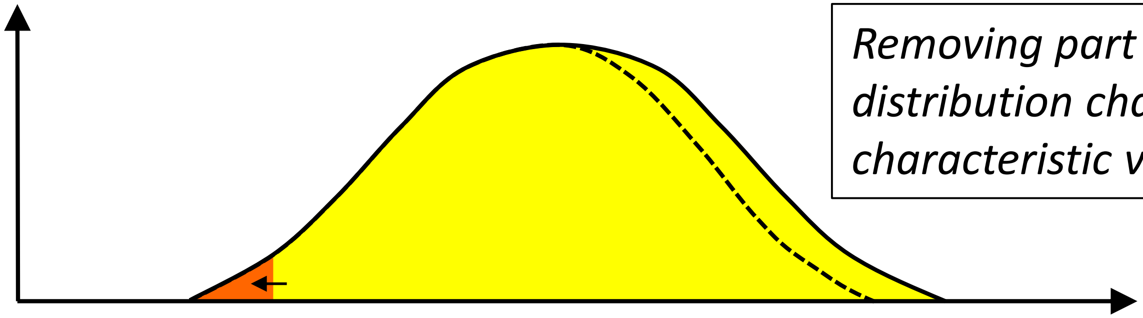
Dry-graded means grading is completed at a moisture content of 20% or less. Specifically this means it has been checked for fissures and distortion.

This is not the same as saying that the timber has a moisture content of 20% or less at the time you receive it.

Graded timber that is dry might not be dry-graded timber. It may have been graded at a higher moisture content and then been dried subsequently – and so still needs to be checked for fissures and distortion.

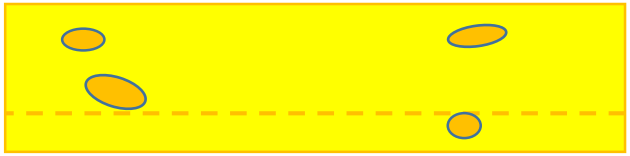
A few other things
Re-grading and re-sizing

Once timber has been graded – you cannot grade it again (unless you have accounted for the effect of the first grading). This applies to visual grading too!



Removing part of the distribution changes the characteristic value

If the cross-section of the timber is reduced, this changes the influence of knots, sloping grain and other characteristics. EN14081 has a limit on reprocessing. The reason for this limit still holds at the fabricator and on the construction site.



A few other things
Revision of the standards

The way grading is done has to change (mostly because of the findings of the Gradewood project).

The current system of output control cannot always adjust quickly enough to shifts in the quality of the incoming timber. It needs to be revised or it will mostly likely be removed from the Standard.

Machine control also needs to be able to better cope with shifts in resource quality. Currently settings, once approved, last forever but we know that changes in forest practice can affect wood properties.

This, and greater use of information technologies, might open up opportunities to get more from the timber resource. Why grade to generic strength classes if you don’t need to?

Summary
Things you cannot do include

Use the values of the strength class in models for lab testing

(although you can use grading methods to estimate properties if you have the background data for the species and growth area. See also EN14358)

Assume test specimens are equivalent because the strength class is the same

(although you can use grading methods to make sets of timber specimens with similar properties)

For example you cannot necessarily conclude that one method of reinforcement is better than another if they were tested on C24…and it was not checked that the C24 for the first set of tests really was similar to the C24 used for the other.

Use grading settings or assignments from other growth areas and expect them to work

Summary
Things you can do include

Define your own strength class that better matches the properties of the timber you have

For visual grading you can do this retrospectively, but for machine grading you need to have the strength class values before you do the calculation of the settings

Revision of the standards, less expensive (and simpler) grading machines, and greater use of information technologies, might open up opportunities to get more from the timber resource. Why grade to generic strength classes if you don't need to?

A fabricator grading their own timber, could easily gain ~30% uplift on some crucial properties, which may allow more efficient designs.

Additionally, strength classes could be better matched to what is actually required for particular elements