SOME AWKWARD QUESTIONS ABOUT DENSITY

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SUMMARY

There are several different concepts of wood density, such as specific gravity, basic density, dry density, and oven dry density. These are often confusing, and sometimes poorly described in the literature, but they can be unambiguously defined and measured in simple and repeatable ways. This makes density a popular measurement in wood science and timber processing, but also leads to a general over-estimation of how well we can actually know the density of a particular wood resource, especially when it is reported with a spuriously high level of precision.

For construction timber in Europe, the standard reference value for density is usually equivalent to mass at 12% moisture content, divided by volume at 12% moisture content. Even in this, apparently very straightforward, case there are some open questions about how we measure, and use, density. The answers to these are unknown (and possibly unknowable), yet they could have practical, real-world, implications if we over-reach the true level of knowledge of density. We should not forget that there is still uncertainty, even in one of the most well-known, and least variable wood properties for any species. This paper illustrates some of these questions using data collected on spruce from the British Isles.

KEYWORDS: Strength Grading; Standards; Characteristic Values; Distributions

INTRODUCTION

Density is one of the most important physical properties of wood, and since it is thought to be easy to measure and express, it is very commonly used as an indicator of several different aspects of wood performance. This regular use of density often lends an apparent certitude in how good density actually is as an indicator, which exceeds the reality. Even more overlooked are the aspects of uncertainty and inaccuracy in the *way* that density is measured and expressed.

For construction timber in Europe, the standard reference value for density is defined at a reference moisture content consistent with 65 % relative humidity and 20 °C (see Ridley-Ellis *et al.* 2016 for more on the normative basis). For most species this is consistent with mass at 12% moisture content, divided by volume at 12% moisture content. Other reference points are used, such as the 20% threshold for "dry" timber (EN14081), but the density values that pass through to the structural design calculations (usually via EN338) are adjusted to this 12% reference value.

When building with wood, there are two kinds of concern about density:

1. Density is sufficient for providing things like fastener performance and fire resistance
2. Density in how it contributes to the self-weight of the structure

In the first case, low density is the concern. This is the reason that grading, and the calculations that establish the grading rules, are based on the 'characteristic density'; the lower 5th percentile. In the second case, the mean value of density is more important. Mean density is also sometimes used in arriving at the first kind of concern for strength; for example the constancy of mean density of the resource is an inherent assumption when using frequency-only grading machines (since dynamic modulus of elasticity is a function of density as well as resonant frequency). For some situations, we may be more interested in the upper end of the likely density, the 95% percentile, but for structural design (EN1995) the main parameters are 5th percentile density and mean density.

The first thing to realise about grading is that it works to ensure that the 5th percentile density of the graded timber is at least as high as the value specified in the definition of the strength class. There is no upper limit on the density, and it will usually be the case that the real density of the graded timber is higher. In the case of species that are relatively dense for their strength and stiffness the difference can be considerable. For example, EN338 gives a value of mean density for C16 of 370 kg/m^3. Grading British spruce (the mixture of mostly Sitka spruce, *Picea sitchensis*, and Norway spruce, *P. abies* grown in UK and IE) to C16/reject will result in a mean density ~5% higher than this, but grading Douglas-fir or larch from the UK to C16/R would result in mean densities ~25% and ~35% higher. This could potentially cause problems for transportation and handling (and possibly building self-weight) if not appreciated. That said, the mean density is not considered at all in the establishment of the grading, and the mean density values for the strength classes are based on assumption of normal distribution and coefficient of variation (CoV) of ~10% (EN384). When establishing grading (EN14081 and EN384), the density used is that of a clear wood density sample, taken near to the break in an EN408 test. Although often more convenient to measure (especially in tropical hardwoods), the use of whole board density is, since the 2016 revision of EN384, limited only to historical data. The standard says that: "mass and volume of the test piece and adjusted to the density of the small defect-free prisms, by dividing by 1.05 in case of softwood. For hardwood no adjustment is necessary". This adjustment is partly to do with the higher density of knots increasing the whole board density and partly a conservative adjustment factor to encourage measurement by defect-free density samples cut from the board. Some awkward questions appear:

- Is coefficient of variation about 10%?
- Is density normally distributed?
- Given that grading, when working well, removes only the worst pieces, how well does the distribution stay like a normal distribution after grading?
- Since density varies along the length of the board, and there is a choice where the density sample is cut, how well do we characterise the density of that piece of timber, and how does this relate to the mean whole board density of the graded timber that would be relevant to self-weight?
- How does density vary in the resource, and how well can we characterise it by sampling boards to test?

DISCUSSION

The density of wood is not truly random as there are some underlying processes for tree growth and biomechanics. For UK-grown spruce, research has revealed that 23% of the variation in density is related to site, 51% is due to variation from tree to tree in a site, and 26% is due to variation within the tree. When sawmills process timber, the logs are sorted in the yard, but the timber from each log is processed all at the same time, and the resulting packs of timber usually contain more than one board from the same tree. Density of boards is therefore random only in the way that a partially shuffled deck of cards is random. Sawmills shuffle like magicians and not like casinos. There are some additional random effects that act on top of this; especially the random effect of actual dimensions deviating from the dimensions used in the calculation. The confusing topic of how poorly dimensions are covered by the standards is too long for this paper, but it is sufficient to say that we expect to see more variation in apparent density in industrial production data than in scientific data, and that even in the latter the difficulty in properly measuring dimensions alone is an argument against reporting density to more than three significant figures in most situations. For practical reasons we assume that volume above fibre saturation does not change, although research with more detailed measurements does suggest that it can (Figure 1, Ho 2008 & Bowers 2008). However the error is small enough to be insignificant compared to the other errors, and even in these careful, laboratory measurements the experimental error in dimension measurements is apparent, and possibly even the explanation for this apparent green volume change.

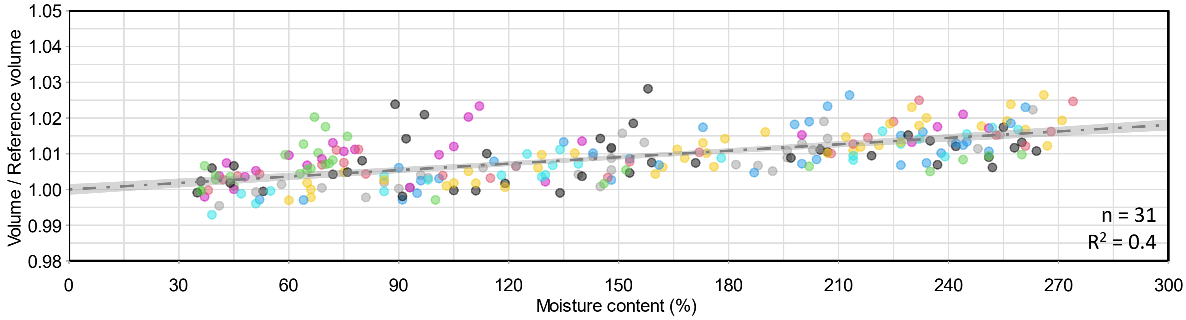

Figure 1: Slight reduction in volume of 31 small clear spruce specimens as they air dried from 'as-cut green' to 'just above fibre saturation green'.

Figure 2a shows data across numerous studies on structural-sized British spruce timber from UK and Ireland. Density sample density is plotted against whole board density, and while the correlation is strong there is a big enough level of variation to have practical significance. Here the adjustment factor of EN384 (1.05) seems to fit the reality and this is consistent across all the sources used in the research. Figure 2b,c,d show the relationships between whole board and density sample density between boards that have been cross- or rip-cut from one original board. There is also a high correlation here suggesting that the location at which the density sample is taken with a board is not so important, but also that boards processed in this way are not statistically independent. It is common to find rip-cut boards in single packs of timber. Comparing the spruce data with larch Figure 2e,f shows considerable overlap between two species that are considered to have very different density, and also that the difference between whole board density and density sample density seems to be less in the case of the larch.

Figure 3a shows a histogram of the whole board and density sample density for the Napier spruce dataset. The 5th and 95th percentiles are also shown (calculated by simple ranking and without any statistical adjustments, per EN14358). Figure 3b adds whole board density data from a very large production dataset from Balcas timber (a Viscan Compact grading machine) compared to the Napier dataset. There is no difference between the two in 5th percentile density, but there are higher densities in the Balcas dataset. Figure 3c shows that this distribution is not normal, but that in this case the assumption of normality does not cause a large difference when calculating the 5th percentile by the parametric method. Again, no EN14358 statistical adjustments are applied in the data presented here, but as shown in Figure 3d there is a variation in density over time that would not be possible to correct for by a statistical adjustment on data sampled at one point in time. Due to this variation over time, we expect to see a higher CoV in long time series production data than in scientific sampling and this is borne out in a comparison (Figure 3e) of CoV with spruce data reported by the Gradewood project (Ranta-Maunus, Denzler and Stapel 2011). The CoV for the Napier spruce dataset is 11%.

Truly representative sampling is therefore rather difficult (Figure 4), even when compared to the relatively consistent density in the most recent 48 months of the Balcas dataset (Figure 5). The performance of three methods of sampling (including the unrealistic method of random sampling over the whole time period) are summarised in Tables 1 to 4. Drawing timber from several packs would be an improvement over taking all timber from a pack, but it is still unable to capture the variation that occurs over the timescale of months to years.

Table 1: Sampling method performance - characteristic density (whole period of Balcas data)

120 boards sampled	Sample result <95% of population 5th %ile	95% to 105% of population 5th %ile	Sample result >105% of population 5th %ile
Consecutively	12.0%	53.7%	34.3%
Every 100th board	11.2%	58.8%	30.0%
Random	2.2%	97.2%	0.6%

Table 2: Sampling method performance - characteristic density (last 48 months of Balcas data)

120 boards sampled	Sample result <95% of population 5th %ile	95% to 105% of population 5th %ile	Sample result >105% of population 5th %ile
Consecutively	9.7%	68.4%	21.9%
Every 100th board	8.0%	78.1%	13.9%
Random	1.7%	97.9%	0.4%

Table 3: Sampling method performance - mean density (whole period of Balcas data)

120 boards sampled	Sample result <95% of population mean	95% to 105% of population mean	Sample result >105% of population mean
Consecutively	22.7%	55.5%	21.8%
Every 100th board	20.1%	59.9%	20%
Random	0.0%	100.0%	0.0%

Table 4: Sampling method performance - mean density (last 48 months of Balcas data)

120 boards sampled	Sample result <95% of population mean	95% to 105% of population mean	Sample result >105% of population mean
Consecutively	14.9%	71.2%	13.9%
Every 100th board	9.9%	81.1%	9.0%
Random	0.0%	100.0%	0.0%

The results of a grading simulation (Figure 6 and Figure 7), based on consistent assumptions with the standard (EN384) of normal distribution and 10% CoV for the ungraded timber, show how an effective grading process reduces the ratio of mean density to 5th percentile density and that the 1.2 factor in EN384 really only holds true in the ungraded case. In reality, the higher density of the whole board, compared to the density sample, and the likelihood the timber is not limited by density in the grading means the actual density of the graded timber probably does have a higher mean density than given by EN338, but it can be very close for grades that have low yields, as shown in Table 5 (confidential report, Ridley-Ellis, 2014). Mean density is not considered as part of the grading calculation so this is not usually checked.

Table 5: Mean density achieved in a grading settings calculation for British spruce

Grade combination	Achieved mean density (kg/m^3)	Strength class mean density (kg/m^3)	Achieved mean / EN338 mean
C16 alone	401	372	108%
C20 alone	413	396	104%
C24 with C16	433 398	420 372	103% 107%

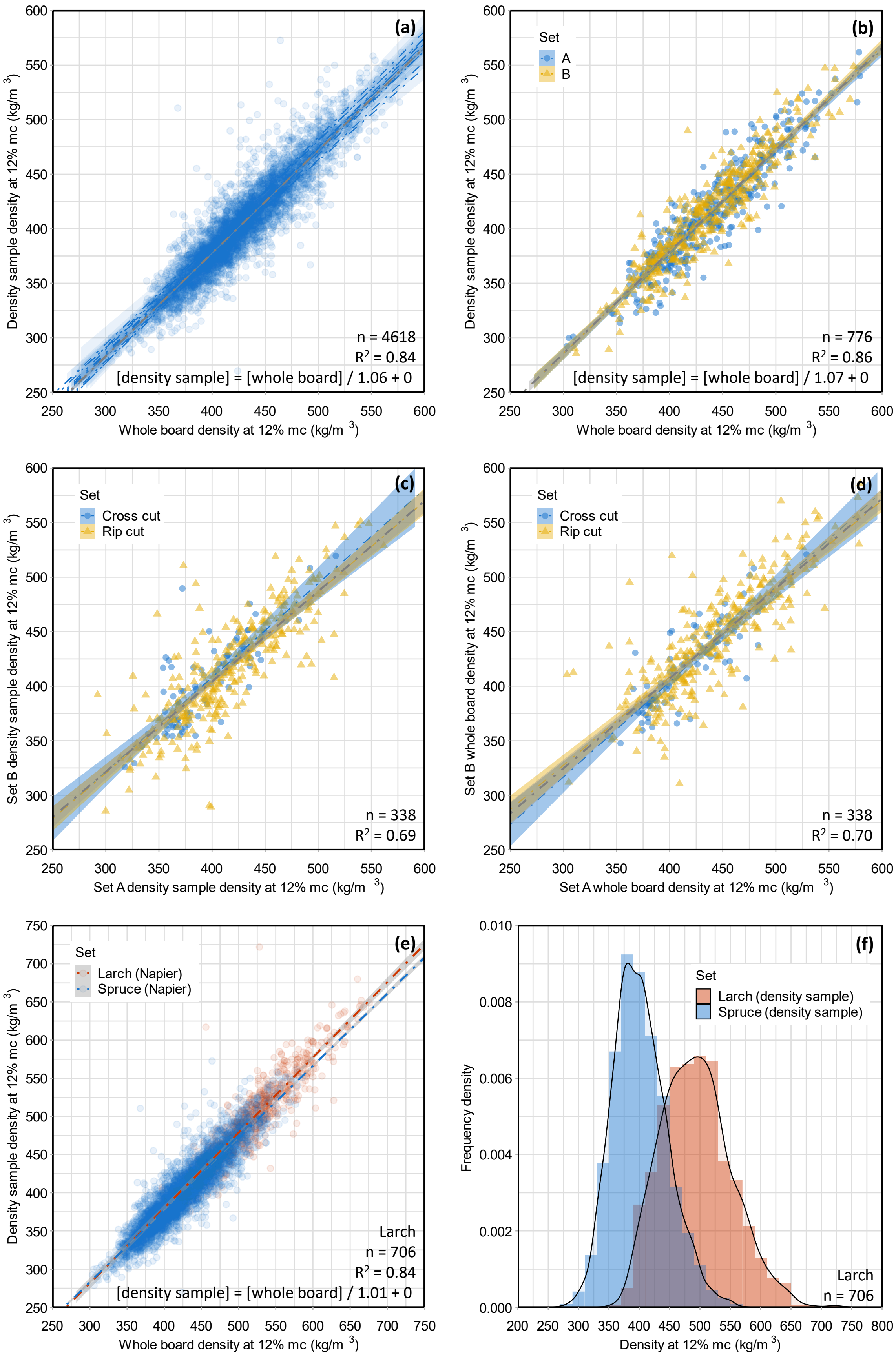

Figure 2: Spruce whole board density and density sample density: (a) Edinburgh Napier University data; (b) for split boards;(c) split board comparison for density sample density; (d) for whole board density; (e) with larch data; (f) histograms.

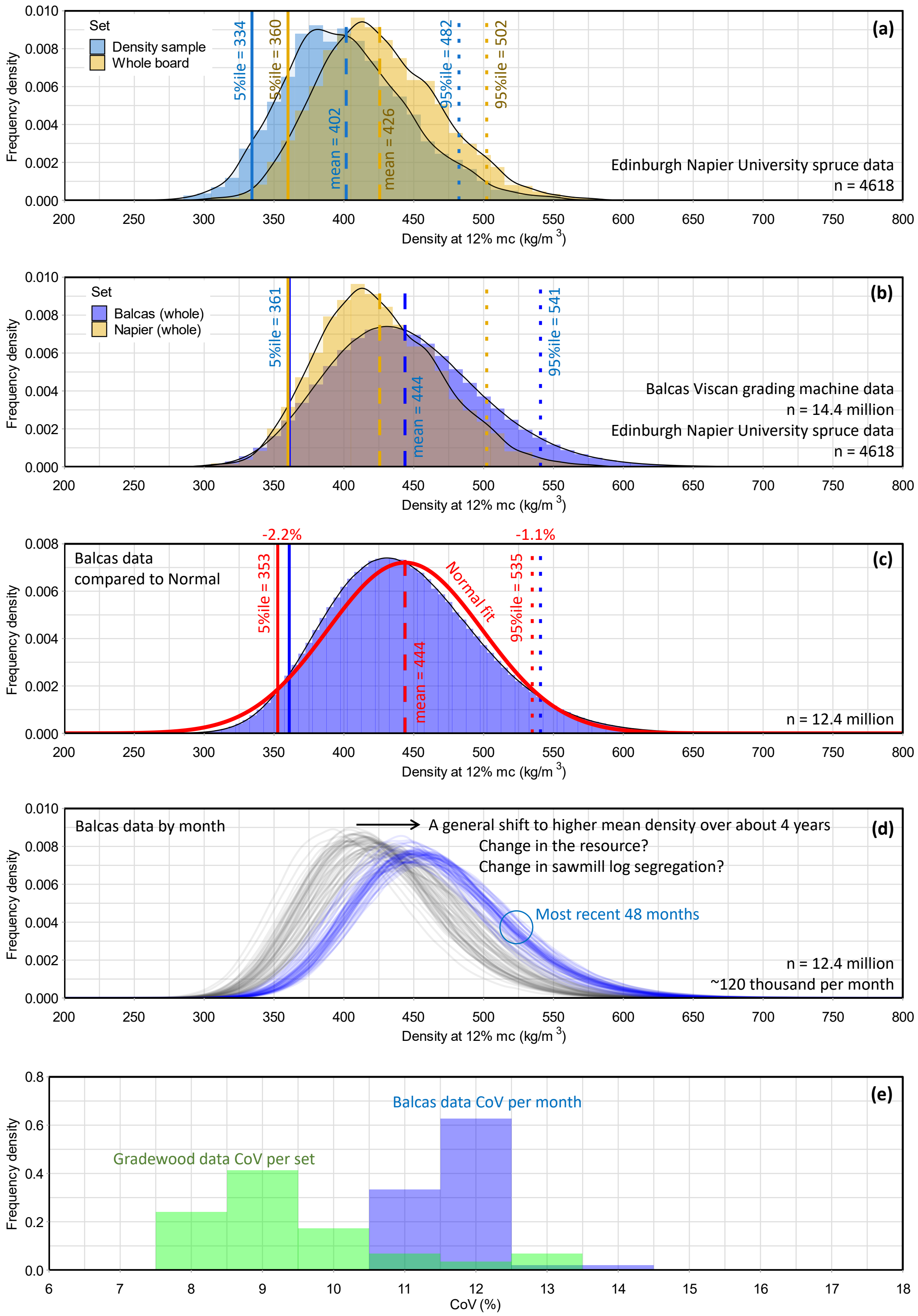

Figure 3: Spruce whole board density and density sample density: (a) Edinburgh Napier University data histograms; (b) Balcas grading data for whole board density;(c) Balcas grading data compared to normal distribution; (d) by month; (e) Balcas data coefficient of variation by month compared to Gradewood project spruce datasets

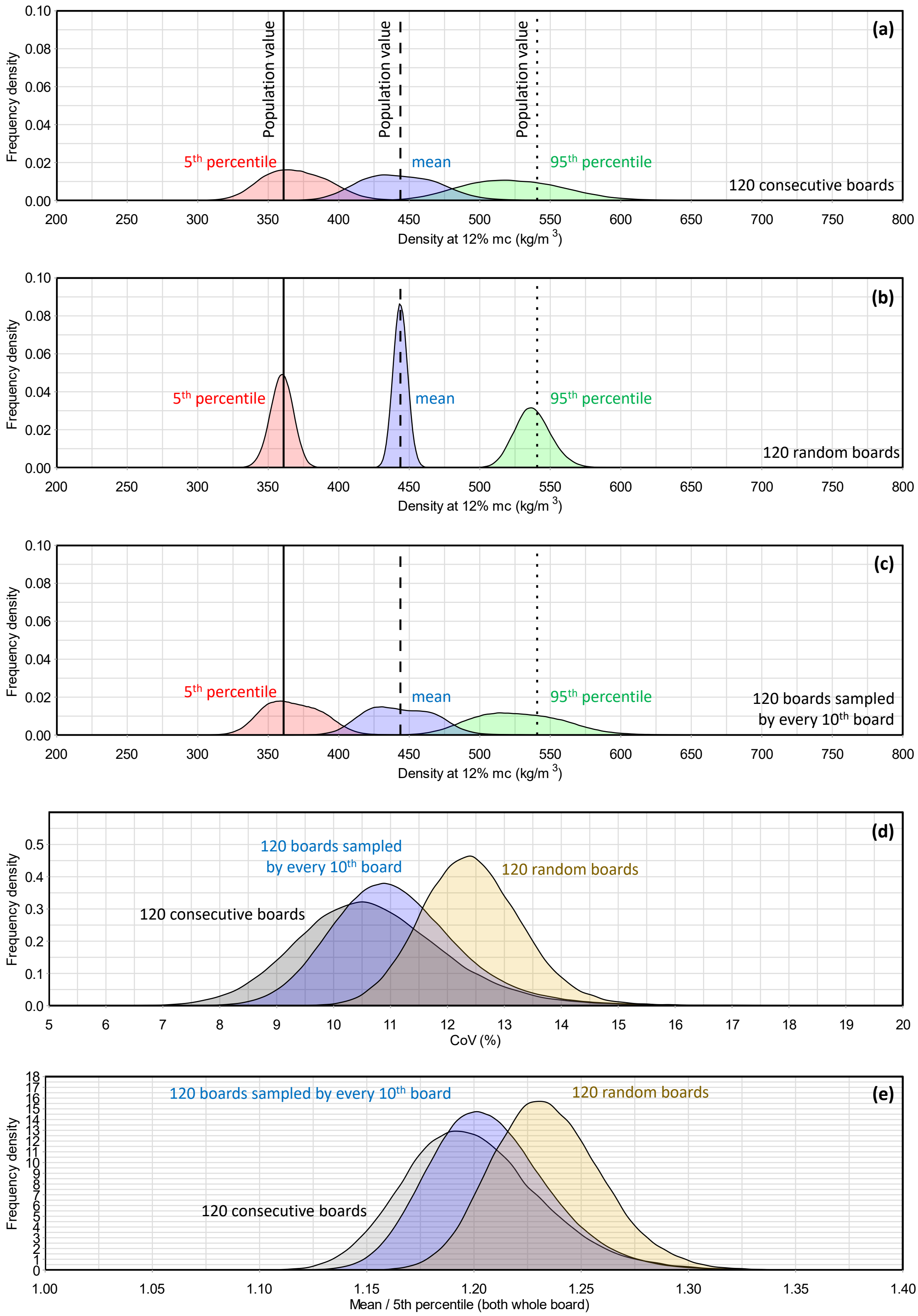

Figure 4: Histograms of spruce whole board density results when sampling 120 boards from the Balcas grading data: (a) 120 consecutive boards all chosen at a random time; (b) boards each chosen separately at random times; (c) every 10th board chosen at a random time; (d) coefficient of variation for the above; (e) ratio of mean to 5th percentile for the above. (Percentiles evaluated by simple ranking).

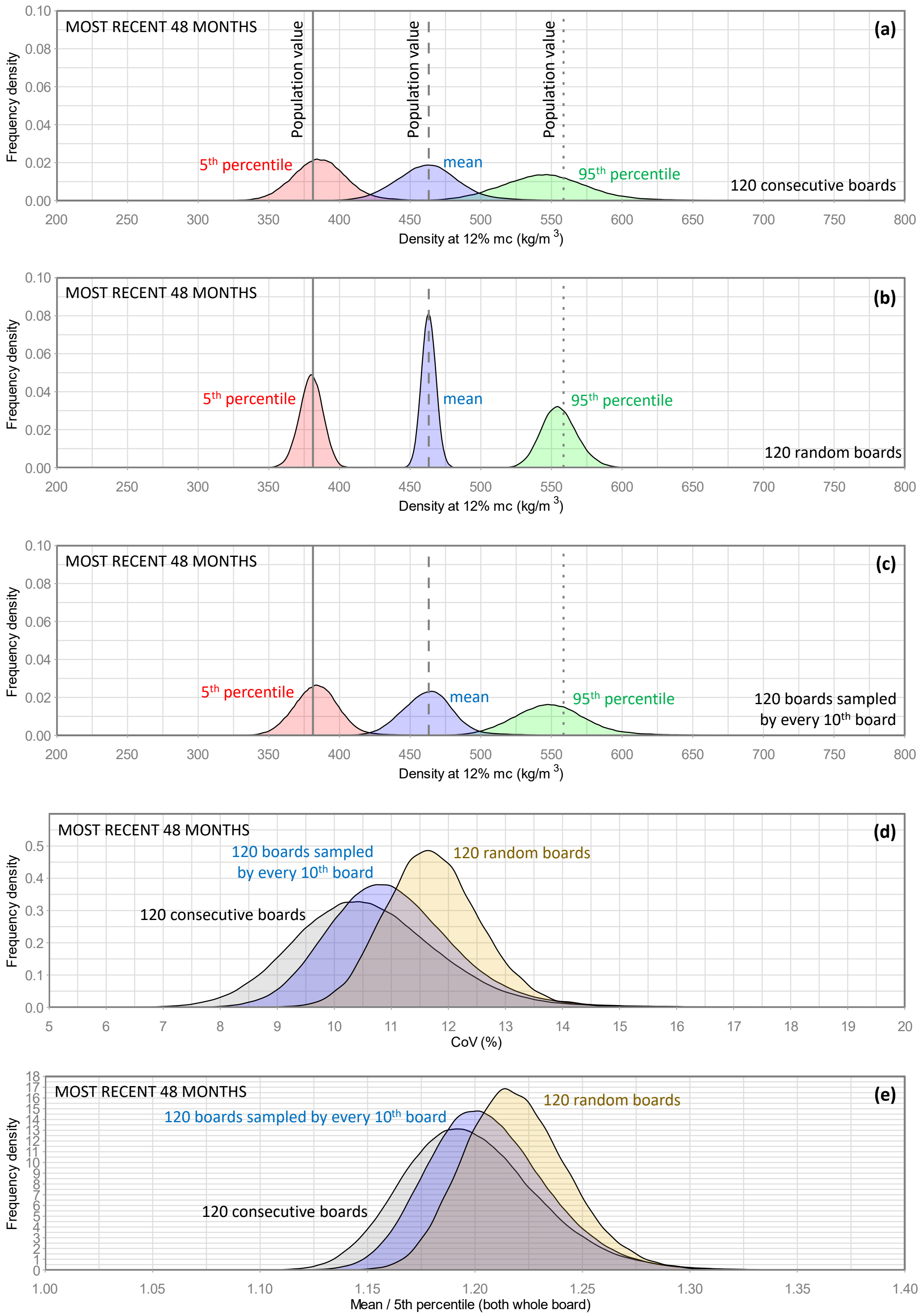

Figure 5: Histograms of spruce whole board density results when sampling 120 boards from Balcas grading data for the <u>most recent 48 months</u>: (a) 120 consecutive boards all chosen at a random time; (b) boards each chosen separately at random times; (c) every 10th board chosen at a random time; (d) coefficient of variation for the above; (e) ratio of mean to 5th percentile for the above. (as Figure 4, but last 4 years' data).

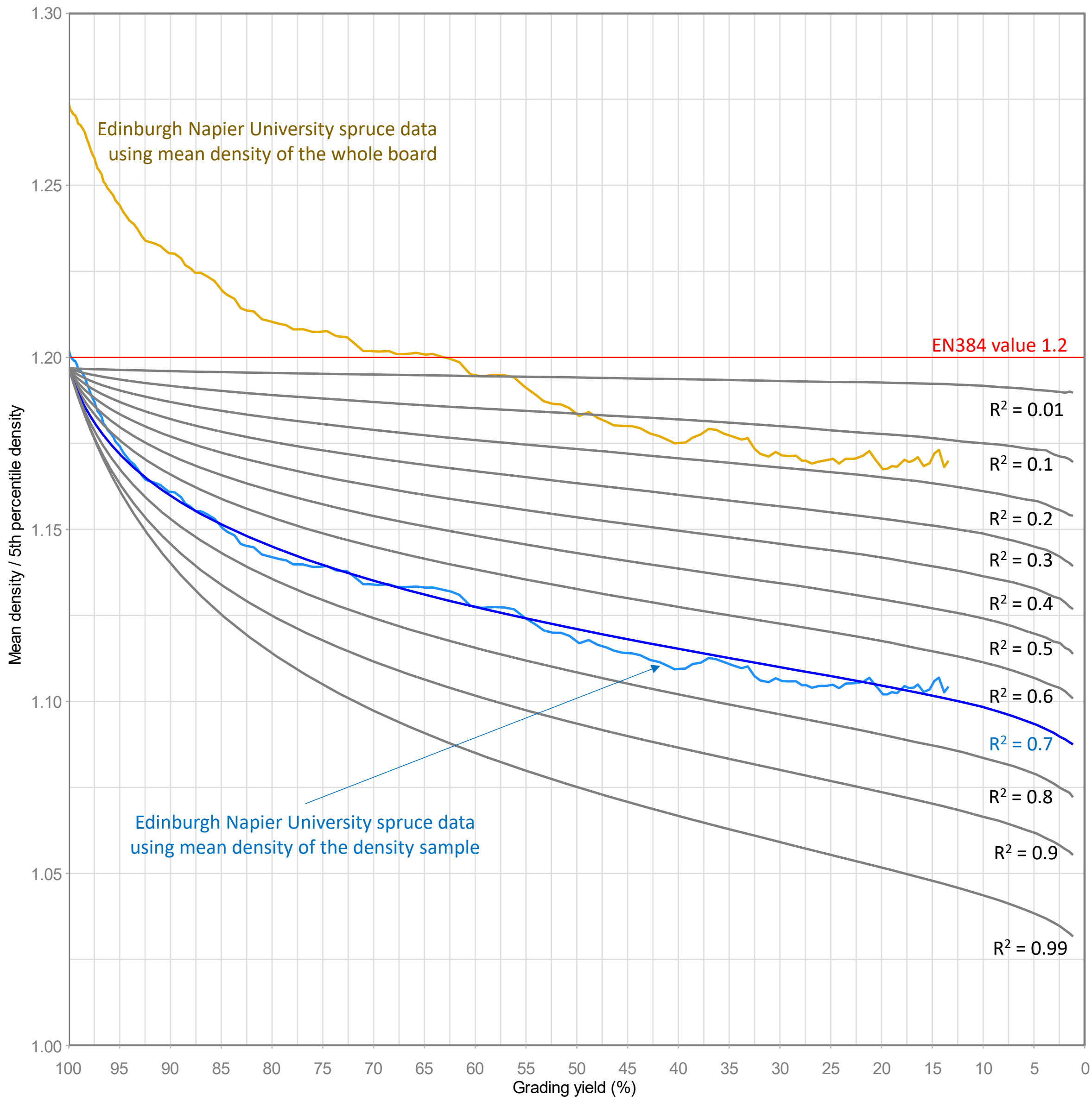

Figure 6: How grading can affect the ratio of mean density to fifth percentile density, depending on both the yield, and the correlation between the density and the grading parameter. Based on a simulation with a population with density that is normally distributed and has coefficient of variation 10%. Depending on the strength of the correlation between the grading parameter (IP) and density, the ratio of mean density to 5th percentile density (evaluated by simple ranking) decreases as grading yield decreases (resulting in increased density of the graded population). Also shows the results when grading the Edinburgh Napier University spruce dataset (which begins with a slightly higher coefficient of variation (11%) and non-normal distribution. For this real dataset the IP is whole board density (R^2 = 0.84) and the fifth percentile is calculated from density sample density. Curves are shown for the ratio based on mean whole board density and mean density sample density.

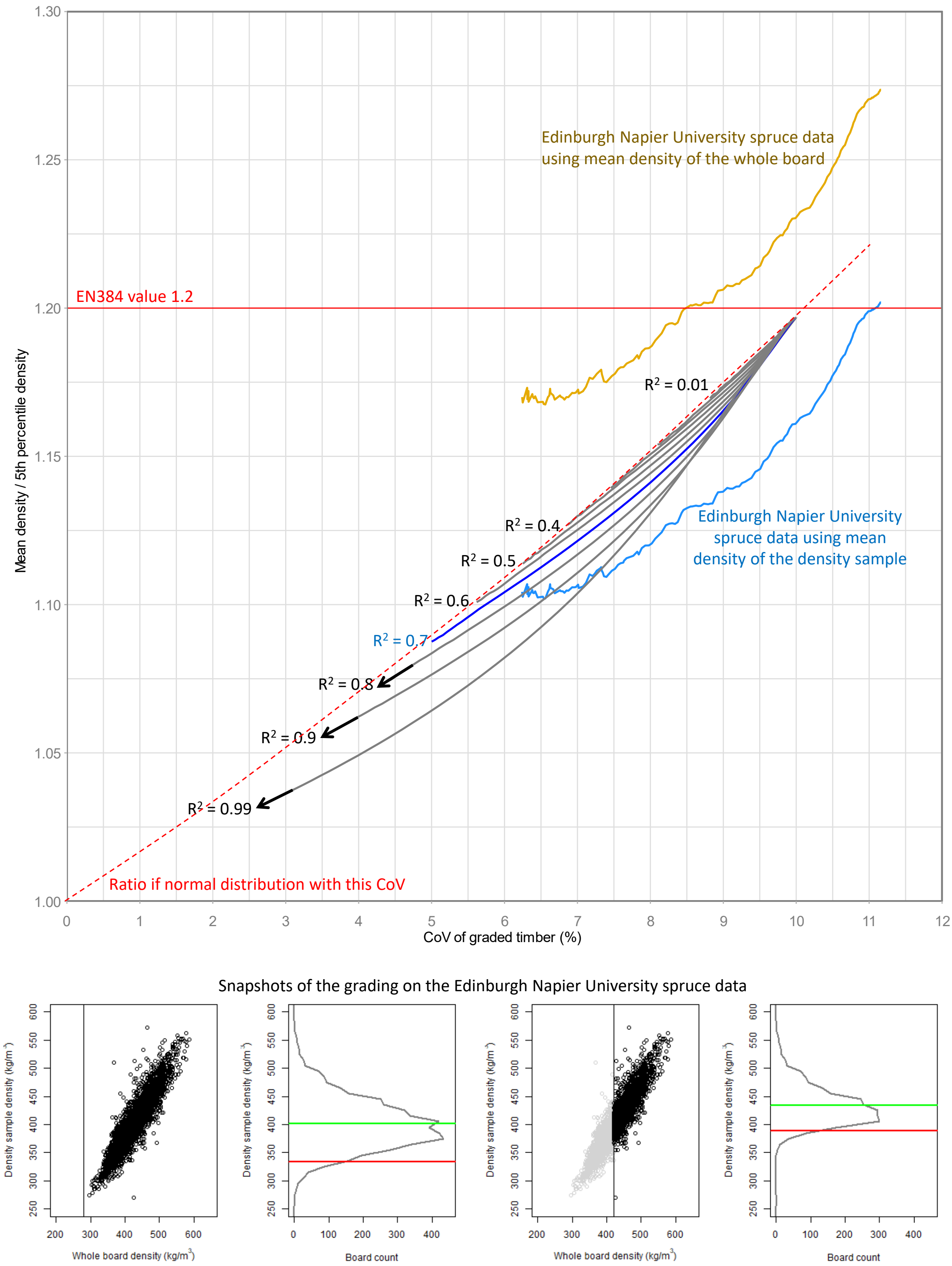

Figure 7: The same simulation as Figure 6, but plotting the ratio of mean density to fifth percentile density against the coefficient of variation of the graded timber. A grading parameter (IP) that is well correlated to density can reduce the coefficient of variation, but the distribution of density in the graded population also becomes less normal. This effect is most pronounced when yield is around 50%.

SUMMARY

Is coefficient of variation about 10%?

This seems to be a reasonable assumption for ungraded softwood timber, but grading works by reducing the coefficient of variation so it can be much less when yield to a grade is around 50% ore more. Since timber could be graded by any method with any yield it is not possible to say that higher strength classes, *per se*, have lower CoV and in some circumstances it would be sensible to assume 10% as an upper bound, and in others to assume ~5% as a reasonable lower bound. A typical value of 10% reported in literature does suggest the true value in production is higher, at about 12%, because sampling is unable to capture variation over time.

Is density normally distributed?

No, but it seems like it is not too bad of an assumption for ungraded softwood timber when considering means and 5th percentiles. However, caution is advised when considering other percentiles, particularly the high ones. A beta distribution may work better, but a vast quantity of data is required to properly establish the true distribution. In the absence of better information, the assumption of normality is a good one (for ungraded timber).

Given that grading, when working well, removes only the worst pieces, how well does the distribution stay like a normal distribution after grading?

Since grading changes the shape of the distribution, the relationship between mean, fifth percentile and CoV moves further way from the assumption of normality. In practical real-world situations the consequences of this are mitigated by the extra density in the resource (compared to the requirement), but it could be a problem when grading of a particular resource is limited by density rather than strength or stiffness.

Since density varies along the length of the board, and there is a choice where the density sample is cut, how well do we characterise the density of that piece of timber, and how does this relate to the mean whole board density of the graded timber that would be relevant to self-weight?

The assumptions in current use seem to be OK for softwood, but this does vary by species and it is sensible to check by measuring both density sample density and whole board density, and using the most appropriate value in calculations (especially for longitudinal resonance).

How does density vary in the resource, and how well can we characterise it by sampling boards to test?

Density varies over timescales that are hard to capture in practical sampling. The way sawmills cut and pack timber means that sampling boards from individual packs will result in underestimating the variation. Sampling by drawing from several packs does help, but the best method is sampling over a long time period (or numerous mills). The statistical methods in, for example EN14358, do not really account for this effect, and when sampling from a single pack the effective sample size is smaller than the actual sample size. It may therefore be prudent to increase the measured CoV for calculation if the sampling is known to be from only a few trees from the same stand. Classical statistical methods cannot adequately compensate for unrepresentative sampling because the data is not truly random.

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REFERENCES

Articles:

Bowers W (2008) Variation of wood properties with moisture content, Nuffield Science Bursary report, Edinburgh Napier University.

Ho H. (2008) Distortion of Sitka spruce with moisture content, Nuffield Science Bursary report, Edinburgh Napier University.

Moore J.R., Lyon A.J., Searles G.J., Lehneke S.A. and Ridley-Ellis D. (2013) Within- and between stand variation in selected properties of Sitka spruce sawn timber in the UK: implications for segregation and grade recovery. Annals of Forest Science **70:** 403-415. https://doi.org/10.1007/s13595-013-0275-y

Ranta-Maunus A., Denzler J.K. and Stapel P. (2011) Strength of European Timber. Part 2. Properties of spruce and pine tested in Gradewood project. VTT working papers 179. https://www.vttresearch.com/sites/default/files/pdf/workingpapers/2011/W179.pdf

Ridley-Ellis D. (2014): TG1/201410/34rev: Derivation of MTG 960, mtgBATCH 962 and mtgBATCH 966 grading machine settings for British spruce (confidential report).

Ridley-Ellis D., Stapel P. and Baño V. (2016): Strength grading of sawn timber in Europe: an explanation for engineers and researchers. European Journal of Wood and Wood Products, **74** (3): 291-306. https://doi.org/10.1007/s00107-016-1034-1

Standards (note that all the ENs are also British Standards):

EN338:2016: Structural timber. Strength classes. European Committee for Standardization, Brussels.

EN384:2016+A1:2018: Structural timber – determination of characteristic values of mechanical properties and density. European Committee for Standardization, Brussels.

EN408:2010+A1:2012: Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties. European Committee for Standardization, Brussels.

EN1995-1-1:2004+A2:2014: Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings. European Committee for Standardization, Brussels.

EN14081-1:2016+A1:2019: Timber structures – Strength graded structural timber with rectangular cross section. Part 1: General requirements. European Committee for Standardization, Brussels.

EN14358:2016: Timber structures. Calculation and verification of characteristic values. European Committee for Standardization, Brussels.