Transforming
Timber

Material Compatibility and Optimisation for Home-Grown Mass Timber Systems

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Contents

List of figures

List of tables

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The grading settings information is based on data compiled for a journal paper:

Dan Ridley-Ellis, David Gil-Moreno and Annette M. Harte, "*Strength grading of timber in the UK and Ireland in 2021*", under review for the International Wood Products Journal. (Ridley-Ellis, et al., (under review))

Dan Ridley-Ellis is task group leader of the CEN/TC124/WG2/TG1 "task group for machine grading settings & visual grading assignments for EN1912" and David Gil-Moreno is the secretary.

Caveat

This report covers the position as of December 2021 and information repeated from standards and grading approvals is for guidance only. When grading, the primary references should be consulted, noting that new assignments and settings can be added, existing ones can be changed, and even the definition of EN 338 (CEN, 2016a) strength classes may change.

A note on reference to countries

The United Kingdom of Great Britain and Northern Ireland is officially GB in ISO 3166-1 (ISO, 2020), but sometimes appears in standards and settings tables as UK. In this report, UK is used, as the more familiar abbreviation. The report uses "Great Britain" to specifically refer to England, Scotland and Wales (i.e. UK without Northern Ireland). Ireland (and IE) is used to refer to the Republic of Ireland.

1. Introduction

There is currently no commercial mass timber manufacturer in the UK, and the current home-grown sawn timber supply is focussed on production of sawn timber for general construction, fencing, and wood packaging materials. There is therefore a need to adapt the existing supply chain to make it suitable for scaled-up volume production beyond the pilot project.

Further to this, and in order to compete with imported laminated products and graded timber, the value return from the UK timber resource will have to be maximised via appropriate selection, sawing, drying, grading and handling.

The properties of timber lamellas used for the manufacture of mass timber products, such as Cross-Laminated Timber (CLT) and glulam, determine the performance of the end-product. For this reason, a number of key properties of this raw material must be carefully considered to ensure that the in-service performance of the end-product meets expectations, while also being commercially viable.

Wood properties and production parameters interact, so both must be considered together. Each CLT manufacturer has their own approach to selection of boards for panel manufacture (standard thicknesses and strength classes). This is usually dictated by the type, and availability, of raw material in their supply chain, as well as the end-product requirements of the markets they serve. Similarly, the cross-section and the make-up of the layers differ from manufacturer to manufacturer.

The purpose of this report is to provide guidance and outline best practice for utilising UK-grown softwood for mass timber manufacture. Opportunities for a manufacturer to optimise are outlined, but since this depends on their individual priorities, and target markets, no single optimised solution can be given here. Instead, the potential for manufacturers to optimise to their own situation is presented. This includes possibilities, within the standardisation framework, that are not typically considered.

Included in this document are:

- An overview of the home-grown timber resource, now and in the future;
- A review of UK timber strength grades, along with appropriate grading equipment, grading settings and expected yields for UK species;
- Recommendations for a best practice strength grading procedure that could be implemented for mass timber production;
- Recommendations for appearance grading for UK timber species, with respect to mass timber manufacture;
- A review of the available data on drying, moisture movement and distortion, and consequences for production.

This report draws on extensive mechanical properties data from previous research by Edinburgh Napier University, Forest Research, National University of Ireland Galway, and the Building Research Establishment. This data has been considered with particular reference to Cross-Laminated Timber production, and so what is described here may differ from other reports and research papers.

2. Key aspects of the standardisation framework

For UKCA and/or CE marking, it will be necessary to follow the relevant production standards. One particularly important aspect is reaction to fire, which is normally dealt with by reference to the mean density of the wood. The mean density requirements for classification without need for further testing (CWFT) are specified for wood conditioned according to EN 13238 (CEN, 2010), which requires a different temperature and relative humidity (23±2 °C and 50±5 % RH) to the one usually used for measuring the density of construction timber (EN 384, 20 °C and 65 % RH (CEN, 2018b)). This consequently corresponds to a density of the wood at around 9% moisture content, rather than at around 12%. The approximate equivalent minimum mean densities for 12% moisture content reference are summarised in Table 1, together with the implied minimum 5th percentile density for a strength class that meets that requirement (as calculated by the EN 384 equations for secondary properties).

Table 1 Density and reaction to fire classification without need for further testing (CWFT)

	Required mean density conditioned according to		Implied required 5th percentile density (kg/m^3)
	EN 13238	EN 384 (approximately)	
EN 14081-1 structural timber	≥ 350	≥ 355	≥ 296
EN 15497 finger jointed timber	≥ 350	≥ 355	≥ 296
EN 16351 cross-laminated timber			
Walls and ceilings	≥ 350	≥ 355	≥ 296
Floors (surface pine)	≥ 430	≥ 436	≥ 364
Floors (surface spruce)	≥ 400	≥ 406	≥ 338
EN 14080 glulam	≥ 380	≥ 386	≥ 321

2.1. Structural timber and EN 14081-1 (harmonised/designated)

For structural timber, certain key properties need to be assessed in order to ensure building safety, and economic use of the material. The means by which this is achieved is known as “strength grading”, and sometimes by the old terminology “stress grading”.

In Europe (including the UK), structural timber is graded under the system set out by the harmonised European standard EN 14081-1. It sorts rectangular cross-section timber into grades based on requirements for three primary grade determining properties. For normal construction timber those are bending strength, bending stiffness and density. The reference moisture content for these properties is 12%, irrespective of the moisture content at which grading is carried out. Strength and density are specified as fifth percentiles and stiffness by the mean. These are known as the characteristic properties, and are probabilistic descriptions rather than properties of any single piece of timber.

Instead of bending, grading can also be based on tension strength and stiffness. No tension grading has yet been established for UK- and Irish-grown timber. Grading based on tension testing is most commonly done for glulam production, since tension strength is more important for the design. The high cost of tension testing, and the lack of home-grown glulam manufacture, means there has been no priority for developing tension-based grading for this resource.

In the case of grading established on the basis of bending testing, the tension strength is one of the secondary properties, calculated from equations in EN 384. In the case of grading on the basis of tension testing, the bending strength is a secondary property (See Section 4.4).

There are two parallel systems for grading: visual and machine, both of which follow the same fundamental basis: timber is sorted into grades according to a non-destructive assessment that is predictive of the grade determining properties. The collective characteristic properties of the timber sorted into those grades determines the strength class. A strength class is simply a grade with associated numbers for strength, stiffness and density that can be used in design. Strength class is usually specified with reference to EN 338 (CEN, 2016a), but properties can be declared directly, or by means of a user-defined strength class.

Machine grading can be by machine control or output control. Output control requires the producer to periodically test batches of graded timber and, if necessary (by statistical procedures), adjust the grading machine settings to ensure grading proceeds correctly and efficiently. This method is not common in Europe, because of the high cost of testing and the relative uniformity of the timber resource. The much more common method is machine control, where settings are determined by previous testing and the grading machines of a certain model are expected to have identical performance. These settings are examined and approved by European Committee for Standardization (CEN) committee TC124/WG2/TG1 (“TG1”), which consists of a panel of experts with sufficient experience to be able to identify potential problems separate from simple compliance with the standards. See http://blogs.napier.ac.uk/cwst/tg1/ for the latest additional rules and guidelines from TG1.

A number of additional “visual override” checks are needed to cover things like drying distortion and fissures. It is whether those are carried out after drying that determines whether timber can be described as “dry-graded”. The rest of the grading need not be carried out dry, if using machine settings specifically for green timber, or a machine that can adjust for high moisture content. A more detailed explanation of strength grading can be found in (Ridley-Ellis, et al., 2016) (although it is now little out of date on some detail).

It is also under EN 14081-1 that visual strength grading can be carried out according to grading rules that are usually (but do not have to be) national standards. Assignment to a strength class is specific to a combination of grading standard and timber source.

Due to ongoing problems with citation of construction product standards in the Official Journal of the European Union, the version of EN 14081-1 that is regarded as the harmonised / designated one, is the withdrawn 2005 version (CEN, 2011).

In the 2005 version, Annex C gives a required minimum mean density of 350 kg/m^3 (conditioned according to EN 13238) for reaction to fire classification without need for further testing (This is the same as in clause 5.2 of the 2016 version (CEN, 2019)).

In the 2005 version, Clause 5.1.2 specifies the maximum allowable change in cross-section (e.g. by planing) that maintains the strength grading assignment. This is no more than 5 mm for dimensions less than or equal to 100 mm, and no more than 10 mm for dimensions greater than 100 mm. This is the same as in Clause 5.1.1 of the 2016 version, except that this also specifies that dimensions lower than 22 mm cannot be reduced (an edit following reduction of the minimum size in EN 336 (CEN, 2013b)). The reason for this limitation is that changes in cross-section change the relative size and position of defects in the wood, which can reduce its strength.

The standard also specifies that structural timber that has previously been graded shall not be re-graded to the same or different grades unless the method of determining characteristic values has made allowances for changes to the timber population caused by the previous grading. This does not prevent already graded timber having a second grading process applied for manufacture of laminated products, but it means the original grading process must be controlled to ensure it does not change in a significant way (e.g. as a result of change of machine, strength class combination or settings table).

2.2. Cross-laminated timber and EN 16351

Clause 4.1.3.1 of EN 16351 (CEN, 2021) limits the grading of timber for CLT to the process in EN 14081-1, as well as stating that the timber within layers must be of same strength class. This prevents the formal grading of higher density timber to the parts of a CLT panel where connections would be made.

Layers are restricted to single species as per a given list (Table 2). It is stated that Norway spruce and silver fir may be considered single species, as may different cultivars of poplar. Of note here is that Sitka and Norway spruce are listed separately and there is no entry for Japanese or hybrid larch. A strict reading of this clause means that Sitka and Norway spruce cannot be mixed within a layer, but this issue could perhaps be resolved in a National Annex for the UK, until EN 16351 can be revised. There is no technical issue, it is simply an oversight in code writing. There is also a restrictive list of species in the finger jointing standard EN 15497 (CEN, 2014).

Clause 4.4 gives a required minimum mean density of 350 kg/m^3 (conditioned according to EN 13238) for reaction to fire classification of CLT panels for walls and ceilings without need for further testing. This is the same as the requirement set by EN 14081-1. For floors with surface made of pine, there is a further requirement of at least 430 kg/m^3, and for floors with surface made of spruce, a requirement of at least 400 kg/m^3. These are new to the 2021 version of EN 16351, but they were set out in EU regulation 2017/2293 of 3.8.2017
http://data.europa.eu/eli/reg_del/2017/2293/oj

The mean density of home-grown spruce is very close to 400 kg/m^3 (varying from batch to batch) so care would be needed to ensure compliance across production.

Table 2 List of permitted species according to EN 16351, EN 14080 and EN 15497

Species	Name	Code (CEN, 2003)
Abies alba	Silver fir	ABAL
Populus x euramericana *	Poplar	POER
Chamaecyparis nootkatensis	Yellow cedar	CHNT
Larix decidua	European larch	LADC
Larix gmelinii	Dahurian larch	
Larix sibirica	Siberian larch	LASI
Picea abies	Norway spruce	PCAB
Picea sitchensis	Sitka spruce	PCST
Pinus nigra spp. **	Black pine	PNNG
Pinus palustris	Southern yellow pine	PNPL
Pinus pinaster	Maritime pine	PNPN
Pinus radiata	Radiata pine	PNRD
Pinus sylvestris	Scots pine	PNSY
Pseudotsuga menziesii	Douglas-fir	PSMN
Thuja plicata	Western red cedar	THPL
Tsuga heterophylla	Western hemlock	TSHT

* EN 14080 (glulam) and EN 15497 (finger jointing) restrict poplar to the specific clones cv "Robusta", "Dorskamp", "I214" and "I4551". EN 16351 (CLT) changed to a general entry in the 2021 revision.

** EN 14080 (glulam) and EN 15497 (finger jointing) restrict *Pinus nigra* specifically to Corsican pine and Austrian pine, but EN 14080 groups them together as one entry. EN 16351 (CLT) changed to a general entry in the 2021 revision.

2.3. Glue laminated timber and EN 14080 (harmonised/designated)

Clause 5.1.2 of EN 14080 (CEN, 2013a) limits the grading of timber for glulam to the process in EN 14081-1. Clause 5.5.2 states that layers must be of a single species as per a given list (Table 2). It is stated that Norway spruce and silver fir may be considered single species. Of note here is that, again, Sitka and Norway spruce are listed separately and there is no entry for Japanese or hybrid larch. A strict reading of this clause means that Sitka and Norway spruce cannot be mixed within a layer, but this issue could perhaps be resolved in the National Annex for the UK, until EN 14080 can be revised. Again, this is a code writing oversight, not a technical issue. The UK National Annex already introduces a route for a wider range of species, including hardwoods, (via PD 6693-1 (BSI, 2019)), but notes that "In general UK practice there is no experience of testing or performance in service for British-grown coniferous species used to manufacture glued solid timber".

Clause 4.4 gives a required minimum mean density of 380 kg/m^3 (conditioned according to EN 13238) for reaction to fire classification without need for further testing. This is higher than the requirement set by EN 14081-1.

3. Summary of the UK timber resource

Sitka spruce is by far the most commonly produced commercial softwood species available in the UK, accounting for approximately 50% of the standing softwood resource and almost 60% within Scotland (Forestry Commission, 2014b). Together with Norway spruce, its availability, good strength to weight ratio, and ease of processing means that that Sitka spruce would be the primary species considered for mass timber production in the UK. Other mainstream home-grown species that could provide suitable material include Scots pine, larch and Douglas-fir, for which stocked areas are listed in Table 3. These species are more briefly covered below. Hardwoods are not covered due to their current low timber volumes produced, but they may provide a future resource for smaller scale production.

Table 3 Stocked area of the main softwood species (Forestry Commission, 2014b)

	Stocked woodland area (thousand hectares)			
	England	Wales	Scotland	Great Britain
Sitka spruce	80	77	507	665
Norway spruce	27	8	25	61
Scots pine	61	3	154	218
Corsican pine	40	2	3	46
Larches	40	20	66	126
Douglas-fir	25	9	12	46

For the main softwood species, the UK and Ireland are usually considered as a common growth area. This is due to the similarity of the timber resource, forest practices, and the long-standing log trade across the border. For this reason, wood properties data is presented here from research in both the UK and Ireland.

Since the timber processing industry is active across the border, in normal circumstances, it would be expected that any new grading work covers both countries, but EN 14081-2 (CEN, 2018a) does not prevent grading work based on timber from only one country, or indeed from only part of one country. That said, there is (in this case) no wood properties advantage to be obtained from a tight geographical focus, and while it may suit a particular commercial situation, it must be borne in mind that grading work is difficult to extend to a wider settings area afterwards. This is another reason why Ireland is included with UK in this report. It does not necessarily mean that new grading work can also be used by Irish producers, since this can be controlled by intellectual property restrictions. It also does not mean that Irish-grown timber needs to be part of the raw material mix.

The properties of the main home-grown softwood species are summarised in Table 4. Since mean density is a key property in regard to reaction to fire classification, the species densities are compared to the CWFT requirements (Table 1) in Table 5.

Table 4 Summary of main home-grown species properties (before grading)

	Mean bending strength (N/mm^2)	Mean bending stiffness (kN/mm^2)	Mean density (kg/m^3)	Heartwood durability EN 350 (CEN, 2016b)	Janka hardness (N) (Lavers, 1983)
Sitka and Norway spruce	30 to 33 (CoV 30%)	7.5 to 8.5 (CoV 30%)	380 to 410 (CoV 10%)	Slightly durable to not durable	~2200
Scots pine	36 to 46 (CoV 30%)	8.5 to 10.0 (CoV 30%)	480 to 550 (CoV 10%)	Moderately durable to slightly durable	~3000
European, Japanese and hybrid larch	37 to 44 (CoV 30%)	9.5 to 10 (CoV 25%)	480 to 530 (CoV 12%)	Moderately durable to slightly durable	~3200
Douglas-fir	28 to 50 (CoV 35%)	8.5 to 13 (CoV 25%)	450 to 550 (CoV 10%)	Moderately durable to slightly durable	~3400

Note 1: A range is given to reflect the variation within the resource and from batch to batch
Note 2: CoV is coefficient of variation (standard deviation / mean)

The figures below showing forecast availability (Figure 1 to Figure 4) draw on data from Forestry Commissions “50-year forecast of softwood timber availability” (Forestry Commission, 2014b) and “50-year forecast of hardwood timber availability” (Forestry Commission, 2014a). These were published in 2014 and an update is due in 2022. These are included for broad comparison, and are not necessarily accurate, especially for the disease impacted species larch and ash. The forecast is shown up to 2050, which is the supply already growing in the forest. The supply after that date will depend on new planting now.

Spruce is expected to remain the main component of the commercial softwood resource, but the relative amount is decreasing over time and in the decades to come it will be important to transfer the UK timber industry over to using a more diverse range of species.

Production of 10,000 m^3 of CLT per year would represent 1.1% of the current sawn construction timber output of the UK.

Table 5 Estimated minimum reject rates (grading by density) to achieve minimum mean density for reaction to fire performance without the need for further testing

Species (home-grown)	Structural timber EN 14081-1 Finger jointed timber EN 15497 CLT walls & ceilings EN 16351	Glulam EN 14080	CLT floors with spruce surface EN 16351	CLT floors with pine surface EN 16351
Mean density, conditioned to EN 13238	≥ 350 kg/m^3	≥ 380 kg/m^3	≥ 400 kg/m^3	≥ 430 kg/m^3
Confident estimates from grading work				
Sitka & Norway spruce	0%	0%	6%	50%
Scots & Corsican pine	0%	0%	0%	0%
European, Japanese & hybrid larch	0%	0%	0%	0%
Douglas-fir	0%	0%	0%	0%
Reasonable estimates from research work				
Noble fir	0%	10%	47%	82%
Western hemlock	0%	0%	0%	0%
Western red cedar	0%	45%	71%	92%
Rough estimates from limited research work				
European silver fir	0%	0%	22%	82%
Grand fir	0%	29%	59%	88%
Pacific silver fir	0%	8%	38%	72%
Japanese red cedar	73%	96%	NA	NA
Serbian spruce	0%	0%	0%	33%

Note: Grading by any other IP than density will require a higher reject rate (unless the rate is zero)

3.1. Spruce

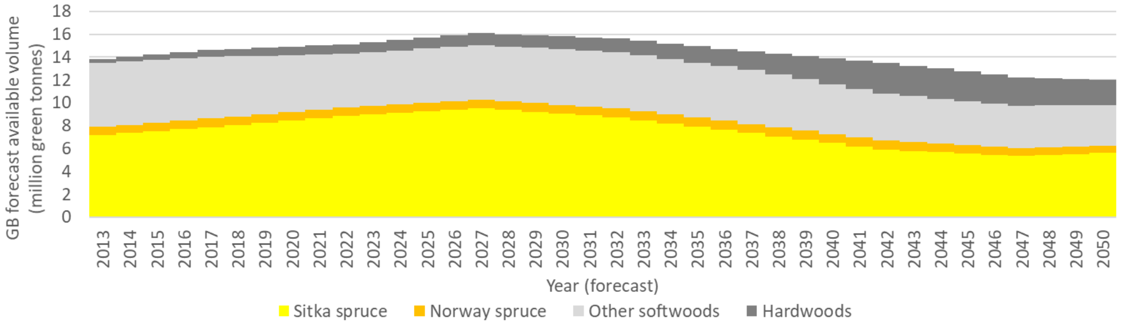

Figure 1 Forecast availability of spruce (Great Britain)

The combination of Sitka spruce (*Picea sitchensis*, PCST) and Norway spruce (*P. abies*, PCAB) is the main commercial timber species group in UK and Ireland. It is in long=standing use, and recognised in EN 14081-1 where it is given the species code WPCS. In that standard, it is referred to as "British spruce" but since the 2016 version there is no implied growth area for this combination, despite this name. This mixture is problematic for a strict reading of EN 16351 and EN 14080 since the standards list them separately (Table 2) and do not say they can be treated as the same species for the layup of CLT or glulam.

UK and Irish sawmills do not differentiate between the two species, and they are processed and sold together. In both countries the resource is, overall, approximately 90% Sitka spruce so it is often referred to simply as "Sitka", including in research reports. Despite this, there is no implied requirement in the species mix "British spruce" that it should be mostly Sitka, and it is very possible that individual packages of timber may be entirely Norway spruce, or contain no Norway spruce at all.

Once the timber is sawn is not practically possible to tell the two apart since the wood of Norway spruce and Sitka spruce is effectively indistinguishable. For practical purposes (when grown in Ireland or UK) they can be considered to have the same mechanical properties, and grade in the same way. There has been no extensive research to properly compare, but what little has been done is enough to confirm the similarity we expect from long-standing industry experience (Gil-Moreno, et al., 2016). What little difference there is between the species is small compared to the variation within the species (see Section 4).

The characteristic density of ungraded UK-grown spruce ranges from about 310 to 350 kg/m^3. Characteristic strength ranges from about 13 to 18 N/mm^2, and mean stiffness ranges from about 7 to 9 kN/mm^2. It is therefore the stiffness that tends to limit the structural grading to the EN 338 strength classes, but when grading to C16 alone (as is current practice) the machine reject is minimal anyway.

For this C16 graded timber, strength is higher than the C16 requirement (more than C18 requires) and density is actually the least critical property (sufficient for C20), but still low enough to make spruce's high strength to weight ratio another one of its practical advantages. This extra strength and density can be made use of by using Edinburgh Napier University's bespoke timber grade for UK spruce, "C16+" (See section 5.2.2).

With the right grading machine, yields of about 25% C24 with 75% C16 and minimal machine reject are achievable (See Section 5.2). Grades of up to C27 and TR26 can be achieved in small amounts.

Spruce is generally creamy white in colour and with little or no difference between sapwood and heartwood. The wood is non-resinous and has very little extractives content. There is a gradual transition from earlywood to latewood and the contrast between them is medium. Spruce has good sawing, machining, nailing, screwing, gluing, drilling and finishing characteristics.

Over the typical range of values of density in home-grown spruce, the thermal conductivity ranges from about 0.09 to 0.12 W/mK (Moore, 2011).

More information about UK-grown Sitka spruce is available in (Moore, 2011) and the sources it draws on, and also in (Moore, et al., 2013). Information about UK- and Irish-grown Sitka and Norway spruce can be found in (Gil-Moreno, et al., 2016), (Krajnc, et al., 2018), and (Simic, et al., 2017).

3.2. Pine

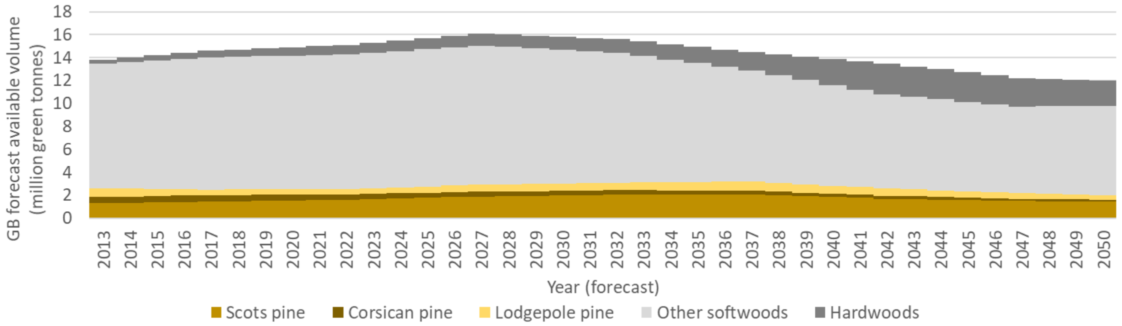

Figure 2 Forecast availability of pine (Great Britain)

In the grading standards, "British pine" is a mixture of Scots pine (*Pinus sylvestris*) and Corsican pine (the listing is *P. nigra*, but it is assumed to mean Corsican pine specifically, due to the relatively large amount in the UK). This mixture is problematic for a strict reading of EN 16351 and EN 14080 since the standards list them separately (Table 2) and do not say they can be treated as the same species for the layup of CLT or glulam.

Around 17% of conifer forest area in Great Britain comprises of Scots pine, with an additional 4% of Corsican pine (Forestry Commission, 2014b). The available timber volume of these species will increase slightly over the next 30 years, and by 2040 around 20% of softwood production in Great Britain could be British pine.

Ungraded British pine has a characteristic density of 420 to 450 kg/m^3, characteristic strength of 17 to 23 N/mm^2. Stiffness tends to be the grade limiting property, reaching C16 or C18 in ungraded populations with mean values of 8.5 to 10 kN/mm^2. Density, again, tends to be the least critical property and can meet C40 requirements. Machine grading to C16 can be done with low reject rates, and smaller yields of C24 in combination with C16 are possible. With the available machine settings this is not possible without increase in reject, but new settings for modern grading machines would be expected to grade both in combination with minimal reject.

Pine has a higher permeability than spruce, but the higher extractive content in the heartwood might affect permeability negatively (Mclean, 2019), which could limit the suitability of pine wood for glue laminated products. The extractive content, on the other hand, increases the natural durability of pine heartwood, and it can achieve EN 350 durability class 3-4 (CEN, 2016b).

The sapwood is creamy white to yellowish in colour and the heartwood is usually pale yellowish brown to reddish brown. The earlywood to latewood transition is fairly abrupt and the colour contrast is medium. Pine is prone to blue-stain which disfigures the wood but does not damage it.

Pine has good sawing, machining, nailing, screwing, gluing, drilling and finishing characteristics, but care is needed when nailing and screwing to avoid splitting the timber. The density, size and number of knots is particularly affected by the growth conditions.

More information about UK-grown Scots pine is given in (Mclean, 2019) and the sources it draws on.

3.3. Larch

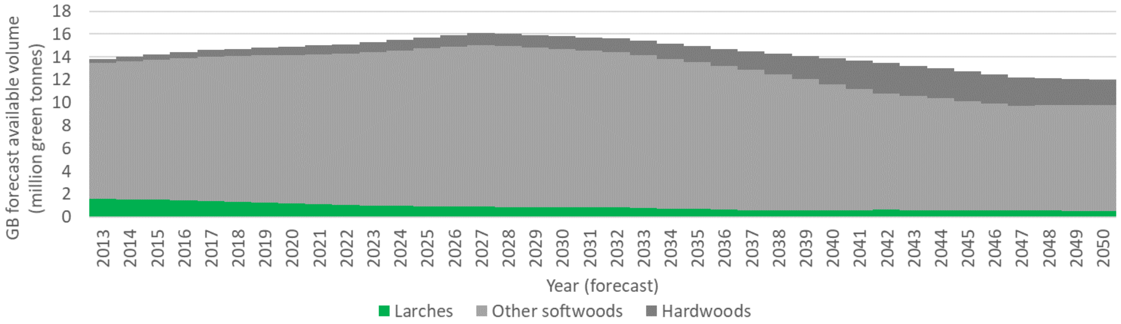

Figure 3 Forecast availability of larch (Great Britain)

Larch in the UK (WLAD) is a mixture of European larch (*Larix decidua*) (LADC), Japanese larch *(L. kaempferi*) (LAKM) and hybrid larch (*L. x eurolepis*) (LAER). This mixture is problematic for EN 16351, EN 14080 and EN 15497 since the standards do not list Japanese or hybrid larch (Table 2).

Larches are an important commercial timber source in the UK, but Ramorum disease (*Phytophthora ramorum*) devastates existing stands, especially in Wales, South-West England and South-West Scotland, and impacts the uptake of new plantings. Between 2009 and 2016 the larch woodland area in the UK declined by 28% (Forest Research, n.d.). Over the next 30 years, the share of larch among the softwood harvest in Great Britain will decrease from around 10% to 5% (Forestry Commission, 2014b).

The characteristic density of ungraded UK-grown larch ranges from about 400 to 420 kg/m^3. Characteristic strength ranges from about 19 to 22 N/mm^2, and mean stiffness ranges from about 9 to 11 kN/mm^2. It is therefore, again, the stiffness that tends to limit the strength grading, but larch can achieve C20 or C22 as a single grade with minimal machine reject. With the right grading machine, yields of about 30% C27 with 70% C16 and minimal machine reject are achievable. Grades of up to C35 can be achieved in small amounts. Density is, again, the least critical property and even ungraded it is higher than the C40 requirement.

Larch heartwood is pale red-brown colour, and distinct from lighter-coloured sapwood. It is a resinous wood. The big difference in density between earlywood and latewood, and the sharp transition from earlywood to latewood makes very prominent growth rings. Larch has fair sawing, machining, nailing, screwing, gluing, drilling and finishing characteristics, but care is needed when nailing and screwing to avoid splitting the timber.

A Forest Research note on larch is in press and expected to be published when the updated timber forecast is available.

3.4. Douglas-fir

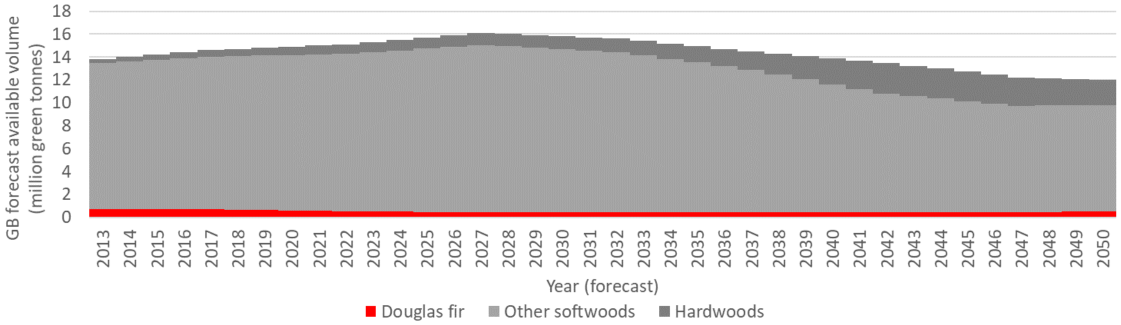

Figure 4 Forecast availability of Douglas-fir (Great Britain)

Home-grown Douglas-fir (*Pseudotsuga menziesii*) (PSMN) is quite similar to UK larch, in mechanical properties, availability and durability. However, Douglas-fir is much more variable from stand to stand, and this variability requires the grading to be more conservative. This variability also causes the characteristic properties of the ungraded timber to be very low, although they are quickly improved by grading.

The characteristic density of ungraded UK-grown Douglas-fir ranges from about 360 to 450 kg/m^3. Characteristic strength ranges from about 10 to 25 N/mm^2, and mean stiffness ranges from about 8 to 13 kN/mm^2. For Douglas-fir it is the strength that tends to limit the grading and, ungraded, it does not meet the requirements even for C16. However, because the characteristic strength can be quickly increased through grading, the machine yield of C18 as a single grade is about 95%. With the right grading machine, yields of about 65% C24 with about 25% C16 and about 10% machine reject are possible. Grades of up to C40 can be achieved in small amounts. Once again, density is the least critical property, and while lower than Douglas-fir grown in Europe it is, when ungraded, at worst, higher than the C27 requirement.

The heartwood is light reddish-brown in colour, and usually distinct from the lighter coloured sapwood. The big difference in density between earlywood and latewood, and the sharp transition from earlywood to latewood makes very prominent growth rings. Douglas-fir has fair sawing, machining, nailing, screwing, gluing, drilling and finishing characteristics, but care is needed when nailing and screwing to avoid splitting the timber. The density, and size and number of knots is particularly affected by the growth conditions.

More information about UK-grown Douglas-fir properties can be found in (Gil-Moreno, et al., 2019), (Drewett, 2015), and (Bawcombe, 2012). Information about Irish-grown Douglas-fir can be found in (Krajnc, et al., 2018).

3.5. Other species

A wider range of species are being considered for new planting, in order to build resilience of the forest resource to climate change, pests and diseases. This new planting will begin to reach harvest age around 2050 – a time for which important promises have been made about net zero carbon and use of renewable resources in place of carbon intensive and fossil-based materials. For the long-term resilience and sustainability of the UK timber industry, the development of any new product value chain should plan ahead for this (with research and standards improvement work).

There are also a number of tree species that are currently under-managed for the production of wood, but which could potentially be brought into the supply chain in the near future. However, data is currently sparse for properties of these species when home-grown, and it is uncertain how suitable they would be for processing in mills that have optimised their operation for the relatively small list of current species.

A study by the Strategic Integrated Research into Timber (SIRT) project took a preliminary look at certain potential alternative species, to gauge what properties could be expected from growth in UK forests, and how they might complement the existing commercial species for the wood processing industries. It requires a large amount of testing across several sites to properly characterise a timber species for commercial production, so the data that follows can only be an indication of potential, pending more comprehensive study.

UK-grown Japanese red cedar would likely struggle even to make C14, due to low stiffness and a remarkably low mean density of just 310 kg/m^3. This does not mean that it does not have its uses, where its low weight could come in handy for use as, for example, the core of lightweight cross-laminated timber. It is an attractive wood, but also rather soft.

If grown in the UK, four of the North American species, grand fir, western red cedar, noble fir and Nordmann fir, also look like they might not be able to achieve the usual UK market strength class, C16, with high grading yields, the first two due to low stiffness and the second two due to low strength. This, however, might well be due to the limited testing, particularly for grand fir and Nordmann fir. The other properties measured for grand fir showed more promise, with strength suitable for C16 and density suitable for C18, and similarly with Nordmann fir, where stiffness was equivalent to C18 and density C30.

The other two North American species look like they would be able to achieve viable C16 yield for grading, if grown in the UK. Pacific silver fir is limited by its density and western hemlock by its stiffness. However, western hemlock, being rather similar to Sitka but with higher density, is a good candidate for blending in with existing British spruce supplies. Pacific silver fir, with strength and stiffness both looking to be around the C18 mark, might have potential for lightweight construction, even compared to Sitka spruce, which was historically favoured for building aircraft.

Three UK-grown European species of conifer were included. Of these, European silver fir looks limited to C16 by stiffness, but strength and density again far exceeded this grade (C20 and C27 respectively). Serbian spruce looks to be limited to C16 by strength, but had good stiffness (C18) and density (C40).

Many of these conifer species look like they could have potential to be blended in to the existing C16 ‘British spruce’ market, ideally by mixed processing, subject to adequate grading approaches. This is encouraging, as relatively small amounts of these species could start entering the mainstream markets with little disruption. Western hemlock is a prime example, with the further advantage of being listed in the laminated timber product standards (Table 2).

Additionally, two hardwood species, sycamore and birch, were looked at to see if they could be the equivalent of and be graded along with the conifers. Both species were found to have good properties; with sycamore, stiffness is the limiting factor and would fit the ‘softwood’ grade of C18.

For birch, both the stiffness and strength are limiting factors, but fit the high grade C40. However, it proved difficult to get enough birch of the dimensions required, which not only meant that only limited testing could be carried out but also that it may be difficult to find enough suitable material for processing. Density for both these species is, unsurprisingly, much higher than the softwood grades require, but it is also not enough to grade well into the hardwood D-classes where it would become the limiting property, reducing the declarable design strength and stiffness. Hardwoods are permitted to be graded to softwood strength classes, and there are recent examples of European grading work for lesser-used hardwoods. However, there are also current concerns about the correctness of the EN 384 secondary properties equations for this case, and a therefore a need to rethink the temperate hardwood grading system in Europe.

3.6. Recovered wood

Timber recovered from existing buildings, during deconstruction or renovation, is a potential additional resource in the UK. With the increased focus on circular economy, and increasing strain on mainstream timber supplies, there is growing interest in timber reuse. Cross-laminated timber is a product that has potential, but significant challenges exist with regards to standards, grading and detection and removal of metal for cutting, planing and, particularly, finger jointing.

Rose et al. proposed the concept of secondary CLT in 2018 (Rose, et al., 2018) and manufactured two CLT panels, one with three and one with five lamellas, from secondary timber collected from construction and demolition sites in London. They compared the compression and bending properties of primary and secondary CLT panels and found that the secondary CLT has comparable compression properties and a higher bending stiffness compared to primary CLT, but lower bending strength. When modelling the effect of defects using finite elements method, the authors saw only a small negative impact of man-made defects on modulus of elasticity in bending and compression. The authors also modelled the effect of diminished modulus of elasticity of the feed material and concluded that it has little effect when secondary timber is used in the crosswise lamellas of elements with large span-to-depth ratios.

The idea of using secondary material in the middle layer of CLT, where the mechanical and aesthetic requirements are less demanding, has since become more widespread. The Build-in-Wood Project recently demonstrated the production of 3-ply CLT, using wood recovered from a recycling plant in Norway or sawmill rejects in the middle layer (Stenstad, et al., 2021). The demonstration, using nine panels with different lay-ups, concluded that the transverse layer had a minimal effect on the stiffness of the end-product, so that secondary timber and sawmill rejects could be used in the middle lamella. They confirmed that even large, man-made holes in the middle lamella had no effect on stiffness or rolling shear behaviour of the panels.

The ongoing InFutUReWood project (partly in collaboration with the CIRCuIT project) has manufactured and/or tested CLT and glulam from recovered timber. In Spain and Slovenia secondary CLT from unusually old wood sources has been manufactured. The feedstock included 60-year-old spruce from a roof structure and 100-year-old oak wood from a bridge, as well as virgin timber for comparison. In Ireland and the UK, softwood timber from different demolition sites was used for manufacturing CLT and glulam. It was found that the older timber showed much lower mechanical properties than new wood, but CLT panels made from a combination of recovered and virgin timber showed satisfying bending strength and stiffness. The timber, recovered from demolition sites in

Ireland and the UK, was younger and CLT manufactured from this feed material showed comparable properties to primary CLT.

The secondary timber in the latter example is likely to be a more representative sample of secondary timber in the UK, which suggest that this resource could be used for the manufacturing of CLT. Around 4.5 million tonnes of wood waste are generated in the UK annually, and around 30% of this is “grade A”, clean solid wood (Cramer & Ridley-Ellis, 2020), which might be suitable as feed material. Even though apparently man-made defects do not have a big impact on the suitability of secondary timber for CLT production, the viability of this business is dependent on the condition of the timber upon recovery. The presence of metal fasteners complicates the planning and finger-jointing of feed material, as metal in the timber poses a risk to machinery and removing metal contamination can be time-consuming and costly. In addition, recovered timber elements should preferably be more than 1.5 metres long, so that the cost of finger-jointing is not increased prohibitively. Timber from demolitions could be recovered in a suitable condition for CLT production, if this was encouraged by a monetary incentive.

Currently, this would not be feasible under EN 16351 or EN 14080 requirements. The standards required CLT feed material to be graded to EN 14081-1 (which is incompatible with recovered wood) and EN 16351 explicitly does not cover CLT made from recovered timber. Standards will likely take a decade or more to revise, but the possibility may be worth planning ahead for now.

4. The properties of UK-grown spruce

4.1. Variation within the resource

Extensive research on UK-grown Sitka spruce has revealed that the variation in wood properties between sites is much smaller than the variation within trees from the same site. This conclusion can be assumed to apply also to Norway spruce. The main practical consequences of this are:

1. There is a limited opportunity to improve timber quality through resource segregation at forest or tree level, or for developing grading settings for a tightly defined region.

2. While we would expect some differences in resource quality (and therefore also grading yields) from sawmill to sawmill, the relatively large amount of within-tree -variation helps ensure that the grading is reliable (because there are not big changes between shifts; the resource stays quite consistent).

This means that different sawmills in the UK would provide more or less equivalent timber, if processing that timber with the same cutting patterns and similar grading methods.

Table 6 shows percentage of total variation in stiffness, density and strength attributable to each stratum (repeated from (Moore, et al., 2013)). The within-log variation has implications for grading because of cutting patterns.

Table 6 Sources of variation in the home-grown spruce resource

	Stiffness	Density	Strength
Site	26%	23%	18%
Tree within site	36%	51%	25%
Log within tree	2%	2%	5%
Within log	35%	25%	52

That said, there are still differences in timber quality from site to site, with the best stands having the required properties of C20 to C24, and the worse stands having the required properties of C14 (Moore, et al., 2013). This does not mean that the timber could be graded that way with real grading machines, but it does mean there is some potential for resource segregation to improve yield when aiming to grade higher grades.

Site factors such as elevation, latitude, spacing, thinning, rotation length, and seed provenance do have a meaningful effect on the wood properties, and also on the grading indicators (e.g. (Moore, 2011), (Treacy, et al., 2000), (Vihermaa, 2010), (Mclean, 2007), (Moore, et al., 2012) and (Moore, et al., 2009)), but for grading of the current resource these are of minor practical importance, and their effect is covered in the sampling used to establish the grading parameters. These site factors (and tree breeding programmes) do, however, have a bearing on future resource quality and continued correctness of grading. For C16 reject grading any changes are unlikely to be very problematic (although a decline in the stiffness is a concern), but for more sophisticated grading it will be necessary to more closely monitor these issues and adjust the grading accordingly.

In home-grown spruce, the wood density, stiffness and strength vary considerably within the tree in both the radial and longitudinal directions. The radial variation (Figure 5) has implications for timber grading linked to cutting patterns. Stiffness and strength tend to increase from the pith outwards, with the lowest values in the so-called juvenile core (the first 12-16 years of growth). Density is high near the pith, reduces, and then increases again (partly explaining the poor correlation between density and strength and stiffness in home-grown spruce). In the UK, the structural product is normally cut from the centre of the log, while the side-boards would be better quality timber with less juvenile wood.

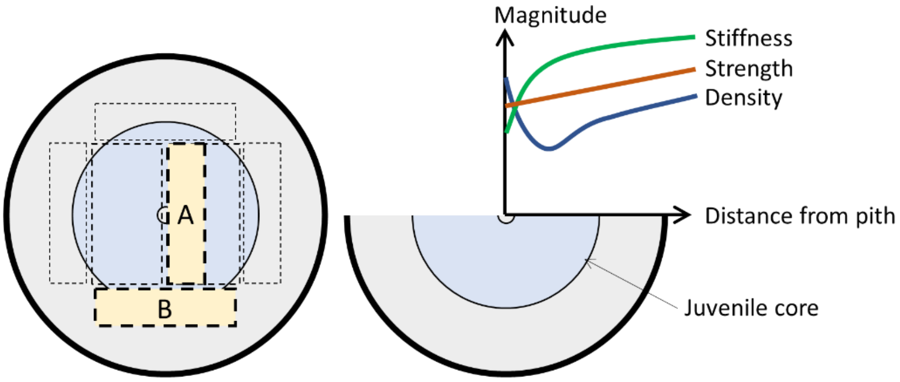

Figure 5 Radial trends in home-grown spruce

Grading settings work that has been done so far, as is required by the standards, is representative of normal production. It therefore includes a large proportion of juvenile wood, and little work has been done on lamella-sized cross-sections. This is especially true of product cut from the outer part of the log. Note that lamellas resawn from normal core product (e.g. A in Figure 5) would have quite different properties from lamellas cut from side-boards (e.g. B in Figure 5). This is not just as a result of radial position, but also the orientation of the growth rings and knots.

4.2. Grade determining properties

The characteristic density of ungraded structural-sized sawn Sitka and Norway spruce from Ireland and UK ranges from about 310 to 350 kg/m^3. Characteristic strength ranges from about 13 to 18 N/mm^2, and mean stiffness ranges from about 7 to 9 kN/mm^2 (Ridley-Ellis, 2019). These are vaguely described figures because of the variation within the resource, and because results vary according to the way the sampling and testing is done. Those figures are based on the data used to establish grading settings and so are the most representative data available for summarising grading of structural timber to current European standards. Further details on properties and correlations between them can also be found in the SIRT project species information sheet on British spruce (SIRT project, 2020).

These properties correspond to an almost 100% machine grading yield for C16/reject, which is the usual industrial practice, with stiffness being the most limiting property. That the resource fits quite well to C16 is no accident, since the EN 338 grades were fitted to the quality of the main commercial timber at the time the standards were developed, and spruce from the UK was considered one of these.

Sitka spruce is grown in other European countries but the growth conditions (climate, forest management, seed provenance and tree improvement) are such that the timber is far too different to be (safely or economically) considered a common growth area with Ireland and/or UK. Norway spruce is widely grown in Europe but is also quite different and therefore unsuitable for making a combined growth area. The European-grown spruce tends to be strength limited for grading to EN 338 strength classes, but UK- and Irish grown spruce tends to be limited by the stiffness. This difference can lead to issues with the way standards are written if there is not sufficient input from the Irish or UK industry, and underpinning research work. Small (usually inadvertent) things in standards can lead to big implications for grading yields (such as the EN 384 conversion of global modulus of elasticity to shear-free stiffness), although most of the current issues have been addressed in recent years.

Pack weights, relevant to handling and transportation, are summarised in Table 7. Correlations between properties, which may be useful for modelling, are summarised in Table 8.

Table 7 Pack weights for handling considerations

Condition	Average kg per 1 m^3 of timber (volume at moisture content)		
	Low estimate	Middle estimate	High estimate
Fresh sawn, green	600 (heartwood)	850	1100 (sapwood)
40% moisture content	430 (less dense)	455	480 (more dense)
20% moisture content	395 (less dense)	415	435 (more dense)
12% moisture content	380 (less dense)	400	420 (more dense)

Table 8 Correlation matrix (R & [R-squared]) for structural sized home-grown spruce timber

From → With ↓	Bending strength	Bending stiffness	Density	Resonance dynamic MOE	Statistics Mean	CoV
Bending strength	1.00 [1.00]				33.4 N/mm^2	30 %
Bending stiffness	0.69 [0.48]	1.00 [1.00]			8.40 kN/mm^2	27 %
Density	0.39 [0.16]	0.46 [0.22]	1.00 [1.00]		400 kg/m^3	11 %
Resonance dynamic MOE	0.61 [0.38]	0.86 [0.73]	0.57 [0.33]	1.00 [1.00]	9.56 kN/mm^2	21 %

At reference 12% moisture content, adjusted to EN 384 but without modification factor for size (k_h)
Ungraded, but visual override removed
Data from testing of 724 timbers from UK & Ireland, ranging from 38×100 to 75×150

4.3. Indicating properties

The properties and features assessed in grading, which are correlated with the grade determining properties, can be called “Indicating Properties” (IPs).

Density is commonly considered to be an important indicator of the wood strength and stiffness, but in truth the coefficient of determination (R-squared) between strength and density in home-grown Sitka is only about 0.2, due partly to this species growing relatively dense, but less strong, wood in the early years of growth (Section 4.1).

Stiffness assessed by mechanical minor axis bending is the operating principle of the classic bending grading machines. Stiffness is a good indicator of strength, but the correlation is compromised by inaccuracies caused by the speed at which the timber goes through the machine.

X-rays measuring density, and size and position of knots is a common method used in UK sawmills (with a Goldeneye702). The method is very fast for grading, but knots and density do not correlate so well with stiffness (which is normally the grade-limiting property for home-grown spruce). However, when grading C16 there is very little reject needed and correlation matters much less than the speed of the machine. One other advantage of x-ray-based machines is that they can grade boards before they are split.

Longitudinal resonance is a measure of the speed of sound in the wood, which is a function of the stiffness and density. Since there is a low correlation between density and stiffness in home-grown spruce (Table 8 of about 0.2), this method is less good without the addition of density measurement.

Longitudinal resonance with density allows calculation of the stiffness (dynamic modulus of elasticity) which is the single best correlator for grade-determining properties, strength and stiffness (Table 8 of about 0.4 and 0.7). Density has, obviously, a good correlation with density, although the whole board density is not the same as the density sample density used as the grade determining property (Ridley-Ellis & Cramer, 2020).

Grain angle / camera scanning machines are less useful for home-grown spruce, since grain angle and knots are poorly correlated with stiffness (the normally grade-limiting property). They do, however, have advantages for possible appearance and hardwood grading.

For normal home-grown spruce, there is not a lot of data available about the correlations of visual grading parameters; knots, slope of grain and ring width. However, it can be observed that there is little slope of grain (usually) and that knots and ring width generally have quite low correlation with grade-determining properties (R-squared in the order of 0.3 at most).

British-grown Sitka spruce typically has ring widths of 5 to 8 mm, decreasing to less than 2 mm after ring 20. Ring widths of more than 10 mm are occasionally found near the pith (Moore, 2011). There is a slight correlation with density in the sawn timber (R-squared about 0.3), but ring width does not correspond to tree growth rate and mechanical properties as is commonly thought in the trade.

Some of these correlations are not completely causal, and can change with tree improvement and forest management. It is therefore important to monitor this aspect of grading to confirm correctness of grading continues over the next decades. This is less of an issue when grading C16/reject, but is very important if grading higher grades and bespoke grades.

The improvement in grade determining properties, when using whole board density or dynamic modulus of elasticity (frequency and density) for grading is illustrated with real data in Figure 6, Figure 7 and Figure 8. The yield (percentage passing the IP threshold) is plotted against the grade-determining property. Lines for 5th percentile and mean are shown. It can be seen that density-based grading hardly improves characteristic strength (Figure 7).

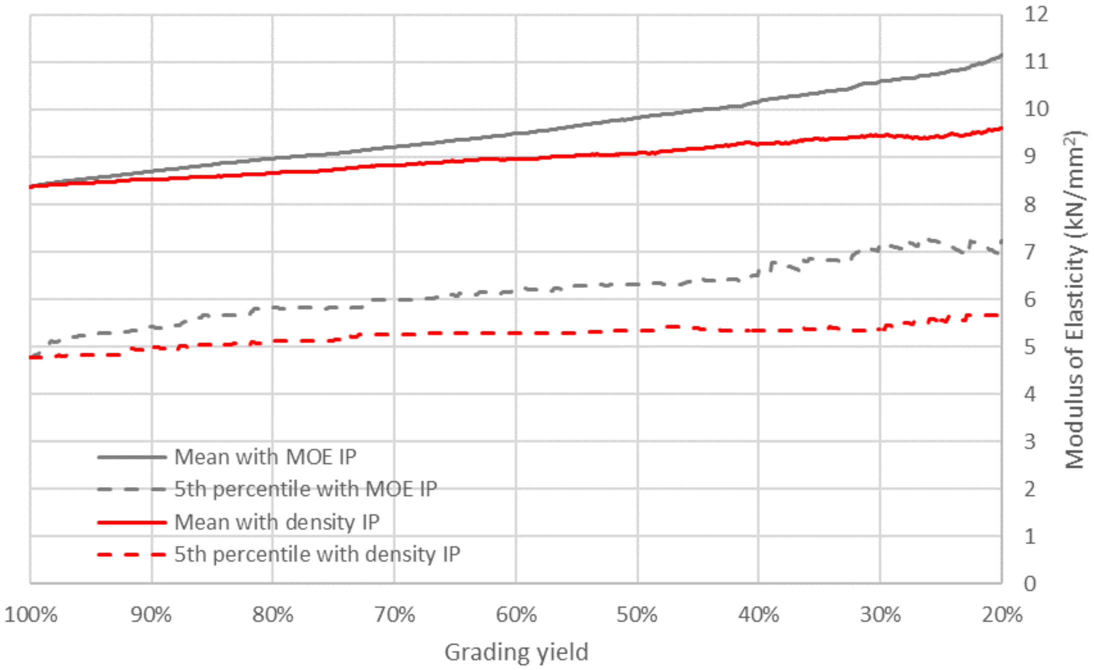

Figure 6 Simplified grading example for home-grown spruce stiffness

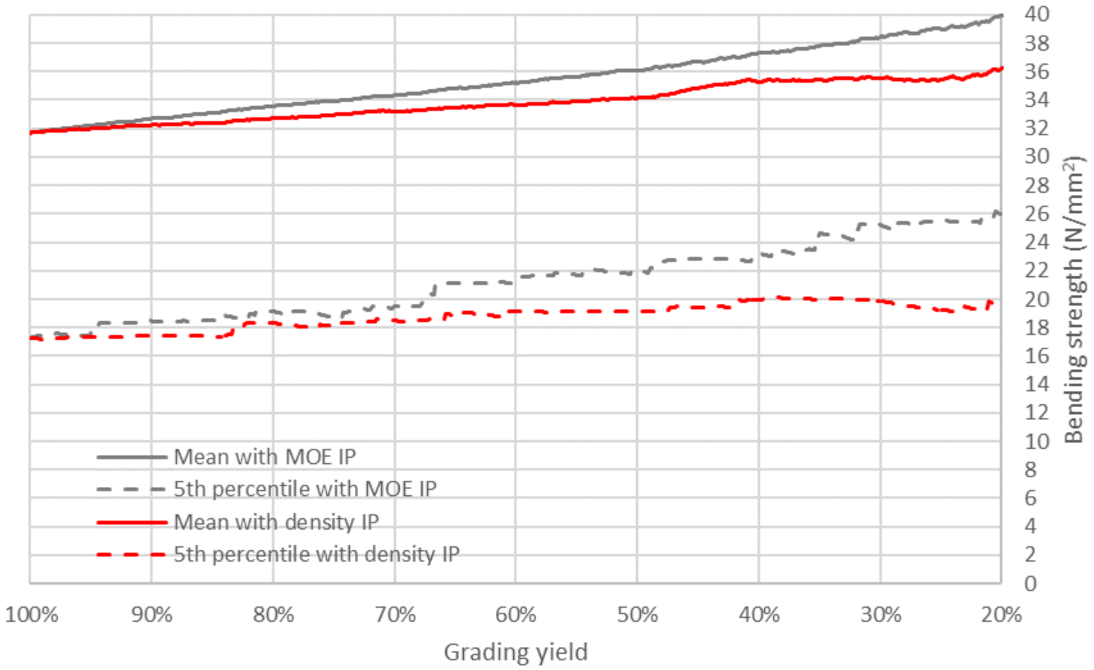

Figure 7 Simplified grading example for home-grown spruce strength

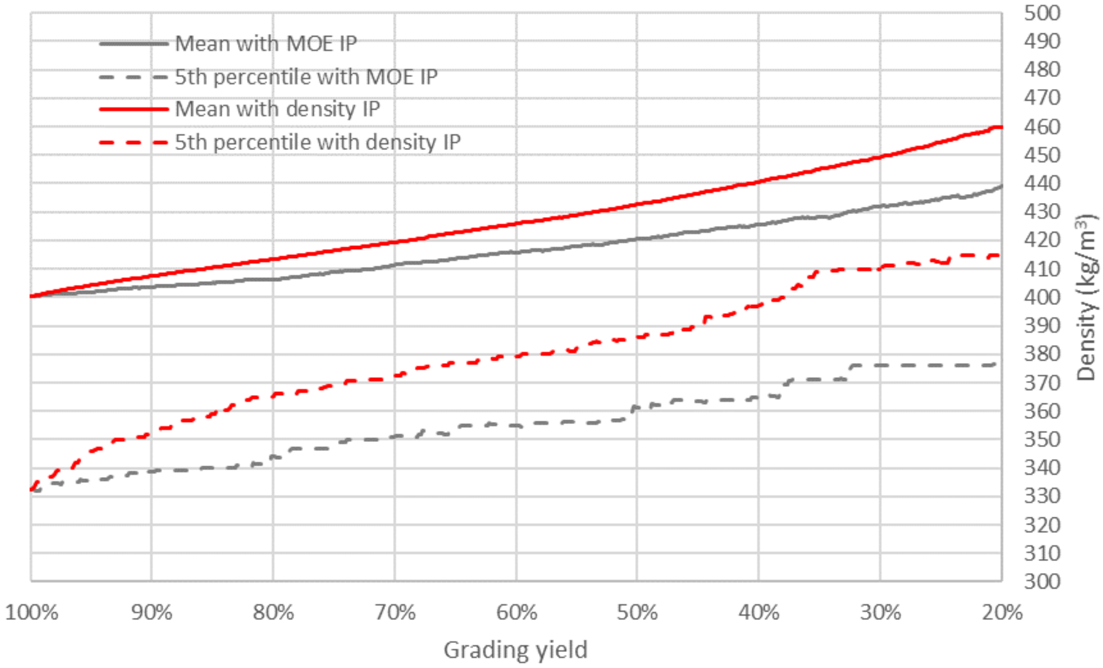

Figure 8 Simplified grading example for home-grown spruce density

4.4. Secondary properties

Secondary design properties are usually conservatively estimated from the three primary properties (usually bending stiffness, bending strength and density) used to establish the grading. This is done via the equations in EN 384. It would be too expensive to undertake the large number of tests necessary to routinely treat secondary properties to the same level of confidence as the three grade determining properties, but they can be declared based on testing, if desired.

Since these properties vary considerably between species and growth area, the conservative relationships in EN 384 are limited by the least good species in common usage, and often do not fit well to the real properties of the graded timber. Since these limits are usually based on European data they often do not match well to timber from Ireland or UK. So this is one of the easy, and potentially very useful, things that can be done when grading a known resource for a particular manufactured product (Ridley-Ellis, et al., 2016). It is also not guaranteed that the properties are indeed conservative and important values should be confirmed to ensure product quality.

The measurement of secondary properties by testing is on the research agenda at Edinburgh Napier University (SIRT project) and NUI Galway (WoodProps project), but nothing substantial has been published so far. However, if there is a particular cutting pattern and grading process it would, anyway, make most sense to test the key secondary properties for CLT or glulam with those in mind.

The secondary properties would include mean density (in relation to the reaction to fire requirements), tension strength, compression strength perpendicular to grain, and shear strength and stiffness.

For home-grown spruce the mean density of the whole board (not the clear wood density sample) is about 420 kg/m^3, while the average clear wood density (the one used in grading) is about 400 kg/m^3 (Ridley-Ellis & Cramer, 2020). Mean density is important for the reaction to fire, and the design self weight, so reasonable correct figures are an advantage. Since density can be graded accurately, the assumption inherent in the EN 384 equation breaks down, and the ratio between mean density and 5th percentile density can change, depending on the grading yield and IP R-squared, as shown in Figure 9.

Tension testing at National University of Ireland, Galway, suggests home-grown spruce could be graded to tension class T11 with high yield, although there is far from enough data available to allow this at present. Characteristic tension strength might be in the order of 15 N/mm^2 (Gil-Moreno, et al., In press).

Limited, unpublished, testing of compression strength perpendicular to grain at Edinburgh Napier University suggests the 5th percentile value may be slightly less than the EN 384 calculated design value.

Shear properties have also not been extensively researched, but average shear strength is in the order of 7 to 8 N/mm^2 and shear modulus in the order of 520 N/mm^2 (Khokhar, 2011), which is the same as the C16 value.

Note that the actual 5th percentile modulus of elasticity perpendicular to grain might be slightly less than the EN 384 calculated design value.

The potential for secondary properties improvement is summarised in Table 9.

Table 9 How secondary properties might be improved by direct measurement

Property	C16 EN338	C16+ See Section 5.2.2	Potential from direct testing
Strength (N/mm^2)			
5%ile bending	16	18.5	NA
5%ile tension parallel	8.5	10.4	15.0?
5%ile tension perpendicular	0.4	0.4	?
5%ile compression parallel	17	18	?
5%ile compression perpendicular	2.2	2.3	2.0?
Shear	3.2	3.5	4.0?
Stiffness (kN/mm^2)			
Mean MOE parallel	8.0	8.0	NA
5%ile MOE parallel	5.4	5.4	5.1?
Mean MOE perpendicular	0.27	0.27	?
Mean shear modulus	0.50	0.50	0.50
Density (kg/m^3)			
5%ile density	310	330	NA
Mean density	370	400	400

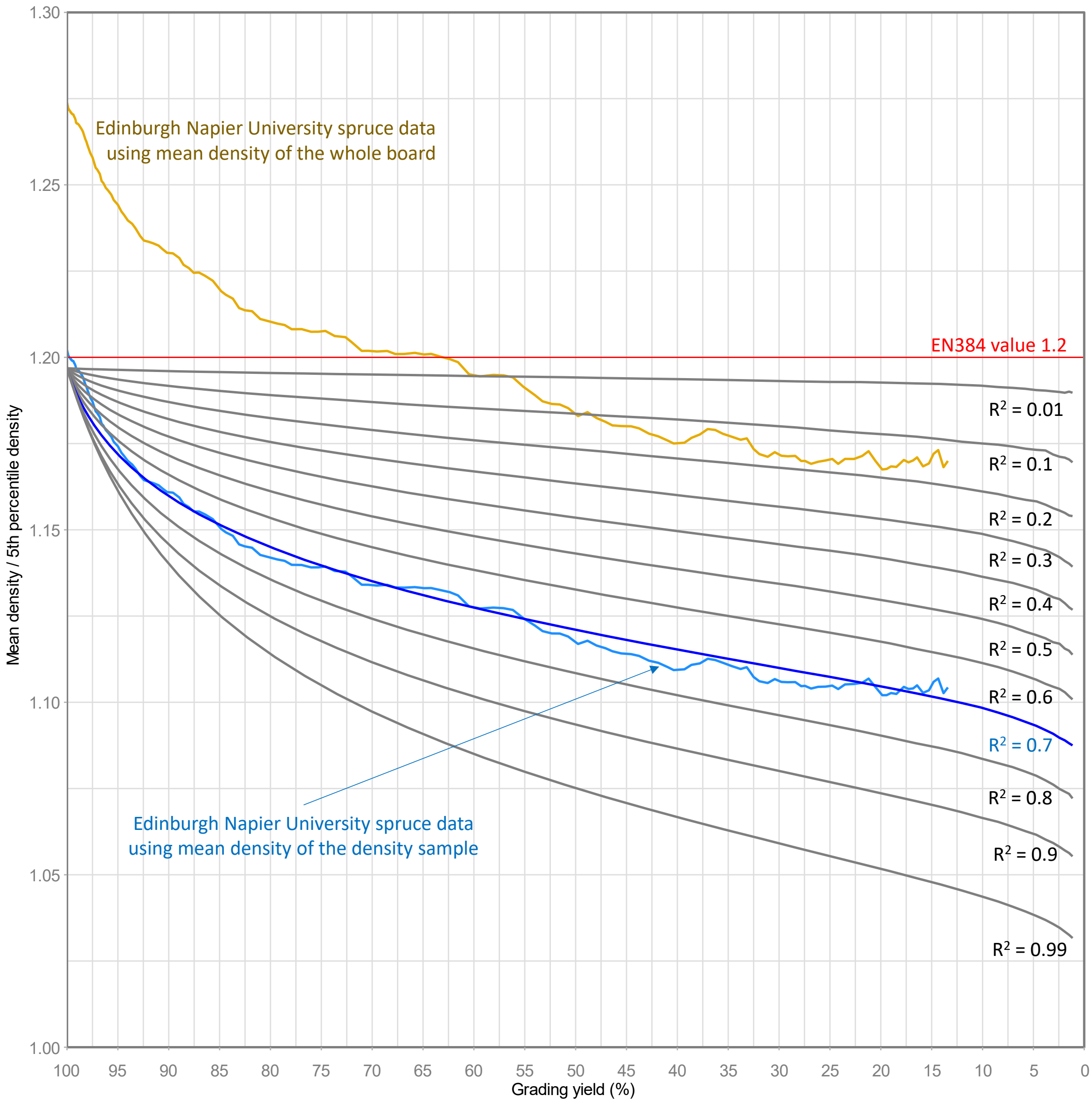

Figure 9 How grading can affect the ratio of mean density to fifth percentile density for an upper grade (Ridley-Ellis & Cramer, 2020)

4.5. Market perception

The general perception of Irish and UK-grown spruce is that it "grows too quickly" and is "therefore of low density" and "therefore of low strength". This is an incorrect understanding of the wood quality and the drivers of wood properties (see also Sections 4.1 and 4.3). Research has shown this for several years, but the perception is hard to shift. In particular, there remains a perceived link between wide growth rings and low wood quality that is largely unsupported in reality. The misconception is partly fed by the "slow-grown timber" marketing message used by importers for many years.

This has implications for the market perception for CLT made form Irish- and UK-grown spruce, especially compared to imported CLT. That it is home-grown may be seen as a negative, and it is worth noting that much of the sawn graded spruce found in merchants is not marketed as home-grown. Since this is perception rather than a reflection of actual wood quality this can perhaps be corrected by education and marketing, but our experience of correcting these misconceptions has been that it is a very slow process.

4.6. Drying, distortion, moisture movement and creep

In home-grown spruce, the typical amount of radial and tangential shrinkage from green to 12% moisture content is 3.0% and 5.0%, respectively (Harding, 1988). These values describe the change in dimension as a percentage of the original green dimension. For practical purposes, the standard softwood equations in EN 336 (CEN, 2013b) work well:

- Increase in thickness and width of 0.25% for every 1.0% moisture content above 20%, up to 30% moisture content
- Decrease in thickness and width of 0.25% for every 1.0% moisture content below 20% moisture content

As well as shrinkage, the drying of timber introduces distortion and other defects, which limit its usefulness if too extreme. Twist is especially problematic in home-grown spruce, leading to up to 6% reject after drying (Canavan, 2017). Unlike bow and spring, twist distortion cannot be balanced by turning the piece.

Typically, UK structural timber is dried to 20% moisture content and continues to dry (increasing distortion effects) during transport, storage and service, depending on the climatic conditions.

Feed material for CLT and glulam should be dried to roughly 12±3 % mc, which is closer to service conditions and optimised for gluing and pressing (Borgström & Fröbel, 2019) (Karacabeyli, 2013). Drying to low moisture content is expected to lead to even higher reject rates after drying, but the occurrence of twist can be mitigated both at the procurement and at the drying stage.

When buying feed material for CLT or glulam, it is possible to exclude timber that is likely prone to twist. Contrary to traditional beliefs, the twist behaviour of home-grown spruce does not seem to be related to under-bark slope of grain (Reynolds, 2010), but other predictors can be used. Canavan describes that spruce timber members which include the pith are more prone to twisting. According to Reynolds, up to 70% of twist in spruce can be attributed to the radial position in the stem, with twist decreasing with increasing distance to the pith. Since the core of the log is less stiff (Section

4.1) pieces with lower stiffness correlate with radial position and can be excluded during grading (prior to drying) or pre-sorting. Cutting patterns could also restrict the used material to the outer part of the log.

In addition, if timber is bought at 20% moisture content (or a similar mc below fibre saturation point) it will already have started distorting. Canavan found that the twist at 20% mc is indicative of total twist at 15 or 8% mc. Roughly, a 1% decrease in moisture content leads to a 5% increase in twist. This already distorting material could be removed prior to further drying down to 12%.

If sawing, grading and drying is not under the control of the CLT / glulam manufacturer, an agreement with the seller of the feed material should be reached that specifies dry-grading requirements, which would be stricter than normal C16 requirements regarding stiffness, presence of pith and/or degree of twist at 20% mc. The stricter requirements are likely to increase the cost of the feed material, and minimum requirements should be determined in trials. The well-known link between distortion and cutting pattern (described in timber textbooks) should also be taken advantage of where possible.

Furthermore, it should be ensured that optimal drying schedules are used, both when drying to 20% mc and when drying to lower moisture contents. This should follow best practice, and be executed and monitored by trained personnel (Riddiough, 2000).

Deformation of timber during drying can, to a certain degree, be avoided by drying at higher temperatures than commonly used in the UK. When the wood temperature reaches the glass transitioning temperature of lignin, the wood matrix begins to soften, and drying stresses are released. In combination with top weights that fixate the timber in a flat position, drying temperatures of above 90°C can mitigate twist (Riddiough, 2000). This might be an alternative to excluding twist-prone timbers. When drying to 12% different timbers could be pre-sorted and dried in different drying schedule. Examples of different drying groups include:

1. High requirement surface lamellas: Selected timber members of appearance grade (see 5.3), which are unlikely to twist. Dried slowly to avoid defects.

2. Lower requirement inner lamellas: Timber member with lesser appearance. Dried more quickly. Surface checks and discolorations are permitted.

3. Timber members prone to twist: Dried at high temperature with top weights to avoid deformation.

It is to be established which combination of procurement and drying strategies is linked to minimal costs.

Creep is the deformation of materials under long-term load. The long-term creep behaviour of Glulam manufactured from Irish-grown Sitka is under investigation by a research group at the National University of Ireland Galway. It was found that the long-term deformation of glulam mostly depends on the initial deflection, governed by the stiffness of the material (O’Ceallaigh, et al., 2018). The principal viscoelastic creep behaviour on the other hand is not influenced by stiffness. The same research group finds that the mechano-sorptive creep behaviour can be reduced by limiting swelling and shrinking effects, achieving this by reinforcing the glulam with fibre-reinforced polymer rods, which increase the stiffness in the tension zone (O'Ceallaigh, et al., 2019). In the production of CLT, various approaches could be trialled to limit creep behaviour in different use scenarios:

Service Class 1:

- Using stiffer material in the tension zone (one or both outer lamellas). Stiffer species or higher strength classes can be used. Bespoke strength classes are possible.

Service Class 2 or higher:

- Using thin, modified timbers as outside lamellas or as covers to limit moisture uptake
- Reinforcing tension zone with high-stiffness inlays to limit moisture deformation
- Using protective coatings to limit moisture uptake

5. Current grading options for UK-grown timber

Grading is based on the species combinations listed in Table 10.

Table 10 Standard species combinations

Group	Common name	Botanical name	Reference
Spruce WPCS	Sitka spruce PCST	*Picea sitchensis*	EN 14081-1:2016 (§B2)
	Norway spruce PCAB	*Picea abies*	
Pine WPNN	Scots pine PNSY	*Pinus sylvestris*	EN 14081-1:2016 (§B2)
	Corsican pine PNNL	*Pinus nigra* subsp. *laricio*	
Larch WLAD	European larch LADC	*Larix decidua*	EN 14081-1:2016 (§B2)
	Hybrid larch LAER	*Larix × marschlinsii (syn. L. × eurolepsis)*	
	Japanese larch LAKM	*Larix kaempferi*	
Douglas-fir	Douglas-fir PSMN	*Pseudotsuga menziesii*	EN 13556:2003 (Tab2)
Oak	European oak QCXE	*Quercus petraea*	EN 13556:2003 (Tab1)
		Quercus robur	
Sweet chestnut	Sweet chestnut CTST	*Castanea sativa*	EN 13556:2003 (Tab1)

Note: EN 14081-1, EN 1912 and the settings tables for UK grown pine are not specific about the exact subspecies of *Pinus nigra*. The National Forest Inventory methodology does, however, specify *Pinus nigra v. maritima* for the only main entry of a *Pinus nigra*, which is a synonym for *Pinus nigra subsp. laricio.*

5.1. Visual grading

Visual grading assignments for home-grown timber, according to EN 1912 (CEN, 2012) and PD 6693-1 (BSI, 2019), are summarised in Table 11.

Table 11 Current visual grading assignments for home-grown timber

Species	Source	Visual grade	Strength class	Reference
To BS 4978 (BSI, 2017a)				
Spruce *Picea sitchensis* *Picea abies*	UK	GS	C14	EN 1912:2012 (§6)
		SS	C18	EN 1912:2012 (§6)
Pine *Pinus sylvestris* *Pinus nigra*	UK	GS	C14	EN 1912:2012 (§6)
		SS	C22	EN 1912:2012 (§6)
Larch *Larix decidua* *Larix × marschlinsii* *Larix kaempferi*	UK	GS	C16	EN 1912:2012 (§6)
		SS	C24	EN 1912:2012 (§6)
Douglas-fir *Pseudotsuga menziesii*	UK	GS	C14	EN 1912:2012 (§6)
		SS	C18	EN 1912:2012 (§6)
		SS (* large)	C24	PD 6693-1:2019 (§7.2)
To IS 127 (NSAI, 2015)				
Spruce *Picea sitchensis* *Picea abies*	IE	GS	C14	EN 1912:2012 (§6)
		SS	C18	EN 1912:2012 (§6)
To BS 5756 (BSI, 2017b)				
Oak *Quercus petraea* *Quercus robur*	UK	TH2	D24	PD 6693-1:2019 (§7.1)
		TH1	D30	PD 6693-1:2019 (§7.1)
		THB (* large)	D30	PD 6693-1:2019 (§7.1)
		THA (* large)	D40	PD 6693-1:2019 (§7.1)
Sweet chestnut *Castanea sativa*	UK	TH1	D24	PD 6693-1:2019 (§7.1)

* These are for cross-section area > 20,000 mm^2, width and thickness ≥ 100 mm

Note 1: Assignment via BSI Published Document PD 6693-1 is possible when used with the UK National Annex to BS EN 1995-1-1 (BSI, 2014)

Note 2: It is expected the ongoing revision of EN 1912 will extend the assignments of BS 4978 to apply to also to IS 127 and to change the source of spruce for both standards to UK and IE

5.2. Machine grading

Most mills, being set up for C16/reject grading of spruce, lack the capacity to physically sort a second or third grade (having bins only for the grade pass and the grade reject). However, depending on the set-up, the mills may still have the capability to piece mark different grades in a grade combination. This would allow grades to be separated manually at a later stage, such as the appearance grading or during the layup.

Indicative yields when grading spruce are listed in Table 12 (for machines using dynamic MOE or x-ray IP). The situation for individual mills will vary from batch to batch due to variation in the resource. For higher grades, this variation can be significant. For Douglas-fir, see (Gil-Moreno, et al., 2019).

Table 12 Indicative yields for home-grown spruce (frequency with mass, and/or x-ray)

Strength class combination	Perfect yield	Expected yield	Notes
C27/C16/R	15%/80%/5%	10%/90%/1%	
NapierSA/SC/R		25%/75%/1%	
C24/C16/R	25%/65%/10%	10%/90%/1% to 25%/70%/5%	
NapierSB/SD/R		50%/50%/1%	Fits 5-ply lay-up
C22/C14/R	50%/50%/1%	20%/80%/1% to 40%/60%/1%	Fits 5-ply lay-up
C20/C14/R	70%/20%/10%	40%/60%/1% to 65%/25%/10%	
C18/R	85%/15%	75%/25% to 85%/15%	
C16+/R	100%/0%	100%/1%	
C16/R	100%/0%	100%/1%	

Note 1: Numbers do not add to 100% due to rounding
Note 2: A two grade 50%/50% yield would suit a 5-ply layup with best grade in the outer layer (allowing some excess to be downgraded to maintain a consistent 2 and 3 ratio)
Note 3: A two grade 75%/25% yield would suit a 3-ply layup with best grade in the outer layer (allowing some excess to be downgraded to maintain a consistent 2 and 1 ratio). No grading option currently fits this because the lower grade would be below C14, but a bespoke system could be developed.

When using the current grading options and C16/reject, the technology of the grading machine does not matter much for yield, since the pass rates are nearly 100%. If aiming for the higher grades, the machines which grade based on longitudinal resonance (i.e. dynamic modulus of elasticity) and density are the ones that perform best. Since there is only a low correlation between density and strength or stiffness in this resource, the machines that work on resonance frequency (i.e. acoustic velocity) alone do not perform so well. Machines that measure knots and density (x-ray or optical) are better for targeting strength than they are for stiffness, but they do not perform as well as the resonance machines (except on small cross-section timber). Combined use of frequency, density and knots is marginally better than combined frequency and density, which can improve yields for the higher, strength-limited, grades.

5.2.1. Machines and datasets

The vast majority of the available spruce grading machine settings are based on a testing by Edinburgh Napier University. This is data on about 2000 pieces (not counting batten sizes). A little less than half of this is owned by grading machine manufacturer Microtec, and is specific to their machines (This does not include the WoodEye or Finscan machines, for which there is currently no data on home-grown timber). While this dataset does cover the full size range for lamellas, it does not cover their actual dimensions well, as shown in Figure 10. The smaller thicknesses are biased conservatively towards small widths.

The vast majority of the available larch grading machine settings are based on testing by Edinburgh Napier University and National University of Ireland, Galway. This is data on about 1000 boards.

The vast majority of the available Douglas-fir grading machine settings are based on testing by National University of Ireland, Galway and Edinburgh Napier University. This covers data on about 700 boards.

The grading settings for pine are based on testing by BRE of about 1000 boards. This data is not fully available for new analysis, and anyway only covers the old bending type machines. The properties data presented in this report is based on a dataset of about 500 boards (unpublished data from BRE, Forest Research, Edinburgh Napier University, and the National University of Ireland, Galway).

The bending machine settings for spruce are based on testing by BRE of about 1700 boards. This data is partly available for new analysis, but only covers these old bending machines.

There is a separate dataset on home-grown spruce. Testing by Holzforschung Munich provided data for the Goldeneye 702/802.

All home-grown timber data for the Precigrader machine was from testing outside the UK: FCBA and RISE for spruce; RISE for larch and Douglas-fir.

Of the machines that currently do not have settings for the UK, the ones that are technically different (the grain angle, camera scanning ones) do not have great additional merit for UK-grown spruce because slope of grain and knots are poorly correlated with the most critical property, stiffness. They do, however, have possible uses in applying appearance grading rules and for future hardwood grading. The WoodEye likely has most potential, since it also measures longitudinal resonance and density.

Table 13 Strength grading machines approved for machine-controlled grading in Europe

Manufacturer	Name	ID*	Description
Machines which have settings for UK-grown timber are **highlighted in bold**			
Tecmach Ltd	***Cook Bolinders***	**1**	**Mechanical bending**
Measuring and Process Control Ltd	***Computermatic Micromatic***	**2**	**Mechanical bending**
VTT	*Raute Timbergrader*	3	Mechanical bending
Microtec s.r.l. – GmbH	*EuroGrecomat-702*	4	X-ray
	Goldeneye 702/802	**5**	**X-ray**
	EuroGrecomat-704	6	X-ray & mechanical bending
	Viscan	**8**	**Longitudinal resonance**
	EuroGrecomat-706	9	X-ray & longitudinal resonance

	Goldeneye 706/806	**10**	**X-ray & longitudinal resonance**
	Viscan Plus	**20**	**Longitudinal resonance & x-ray density**
	Viscan Compact	**22**	**Longitudinal resonance & density**
	Viscan portable with balance	**29**	**Portable, longitudinal resonance & density**
	Viscan portable without balance	**30**	**Portable, longitudinal resonance**
Microtec Linköping	*WoodEye Strength Grader*	31	Longitudinal resonance, density & laser tracheid grain angle
Microtec Espoo	*Finscan Nova*	36	Camera scanning (visual & near infrared)
	Finscan HD	37	Camera scanning (visual)
Dynalyse AB	*Dynagrade*	7	Longitudinal resonance
	Precigrader	**12**	**Longitudinal resonance & density**
Brookhuis Applied Technologies BV	***MTG 960***	**11**	**Portable, longitudinal resonance & density**
	mtgESCAN 962/966	**14**	**Longitudinal resonance & density**
	MTG 920	**19**	**Portable, longitudinal resonance**
	MTGbatch 962/966	**23**	**Longitudinal resonance & density**
	MTGbatch 922/926	**24**	**Longitudinal resonance**
	mtgESCAN 922/926	**26**	**Longitudinal resonance**
Dimter GmbH	*Grademaster*	13	Longitudinal resonance, density & knots
Luxscan technologies	***EScan FWM/FW***	**14**	**Longitudinal resonance & density**
	EScan FM/F	**26**	**Longitudinal resonance**
	OptiStrength XE	33	X-ray & longitudinal resonance
	OptiStrength X	34	X-ray
Concept Bois Structure SARL	*Triomatic*	15	Ultrasonic time of flight & pin indentation density
Automatisation J.R.T Inc	*CRP*	16	Mechanical bending
XYLOMECA	*Xyloclass T*	17	Longitudinal resonance & density
	Xyloclass F	21	Flexural resonance & density
SARL Esteves	*Noesys*	18	Flexural resonance & density
Rosén & Co Maskin	*Rosgrade*	25	Longitudinal resonance
	Rosgrade plus	28	Longitudinal resonance & density
Innodura	*E-CONTROL model AC*	27	Longitudinal resonance & density
RemaSawco AB	*RS Strength Grader*	32	Laser tracheid grain angle
	RS Strength Grader Density	39	Laser tracheid grain angle & density
Ilkon	*STIG*	35	Portable, longitudinal resonance
M. Manfred Hudel	*MODULO*	38	Mechanical bending

Note: See also https://blogs.napier.ac.uk/cwst/grading-machines-speeds/

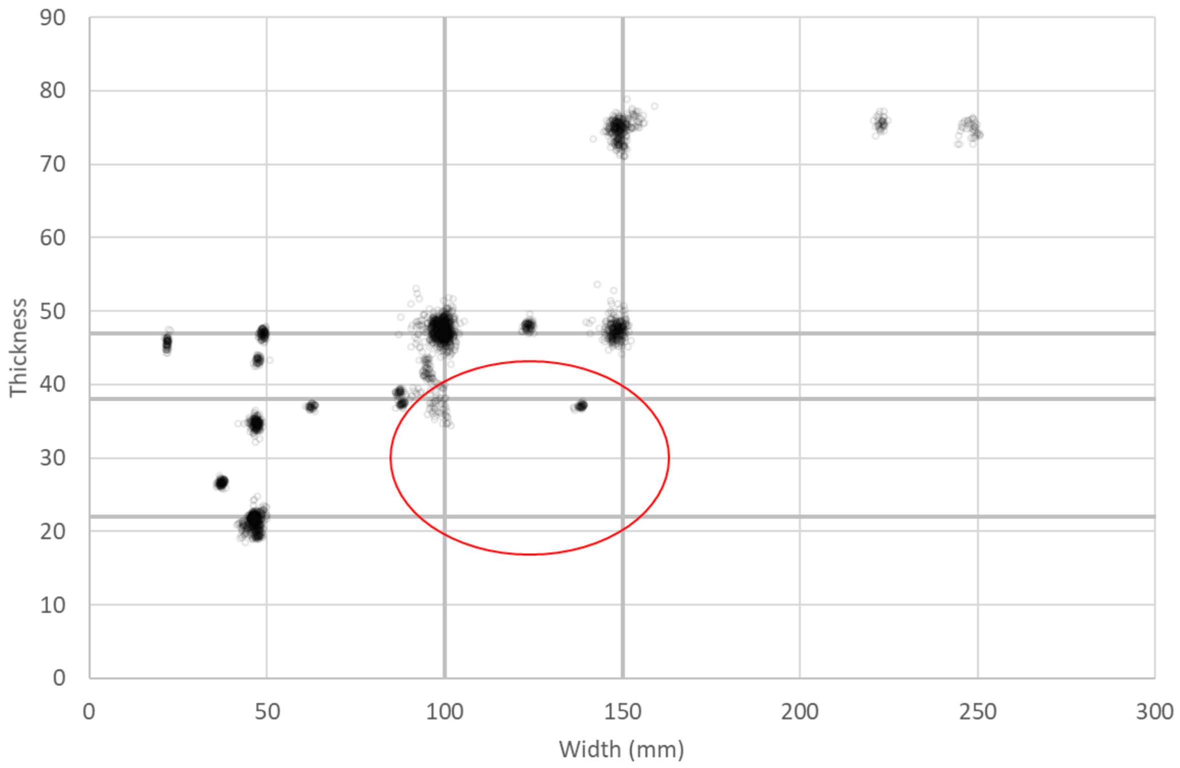

Figure 10 Poor coverage of lamella dimensions in the Edinburgh Napier University home-grown spruce grading dataset

5.2.2. Existing bespoke grades

Existing “user-defined” strength classes for home-grown timber are summarised in Table 14.

C16+ is intended to be used as replacement for C16 when grading to a single grade, and has the same (almost 100%) machine grading pass rate as C16. It allows to take advantage of the extra strength and density (Ridley-Ellis, et al., 2016). One other advantage of C16+ is that (via the equations in EN 384) it has mean density sufficient to meet the glulam mean density requirement for reaction to fire classification without need for further testing (Section 2.3). C16 does not meet this requirement.

NapierSA, NapierSB, NapierSC and NapierSD are user defined grades developed on the basis of target yields when grading to two strength classes. They are for use in pairs aiming for minimal reject and, roughly, grading yields of 25%/75% (NapierSA & NapierSC) and 50%/50% (Napier SB and NapierSD) (Ridley-Ellis, et al., 2018). The grades NapierL_ and NapierD_ follow the same concept, for home-grown larch and Douglas-fir respectively.

The grades batten10, batten12 and batten14 were developed for grading small cross-section timber (tiling battens) and are not relevant to CLT.

Table 14 Existing bespoke grades for home-grown timber

Class	Better than EN 338	5th percentile strength (N/mm^2)	Mean stiffness (kN/mm^2)	5th percentile density (kg/m^3)	Date of first report
		Bending			
Intended to be used with spruce					
C16+	>C16	18.5 (+16%)	8.0	330 (+6%) ❷	2014
NapierSA	>C24	25.0 (+4%)	11.0	375 (+7%) ❹	2017
NapierSB	>C22	22.0	10.0	360 (+6%) ❸	
NapierSC	>C16	16.0	8.0	320 (+3%) ❶	
NapierSD	>C14	15.0 (+7%)	7.0	310 (+7%) ❶	
batten14	>C14	14.0	7.5 (+7%)	330 (+14%) ❷	2018 (Tiling and cladding batten dimensions)
batten12	-	12.0	7.5	330 ❷	
batten10	-	10.0	7.0	330 ❷	
Intended to be used with larch					
NapierLA	>C30	30.0	13.0 (+8%)	480 (+26%) ❹	2017
NapierLB	>C27	28.0 (+4%)	12.0 (+4%)	440 (+22%) ❹	
NapierLC	>C18	21.0 (+17%)	9.0	400 (+25%) ❹	
NapierLD	>C16	20.0 (+25%)	8.0	390 (+26%) ❹	
Intended to be used with Douglas-fir					
NapierDA	>C35	35.0	13.0	460 (+18%) ❹	2018
NapierDB	>C30	30.0	12.0	460 (+21%) ❹	
NapierDC	>C16	16.0	10.0 (+25%)	400 (+29%) ❹	
NapierDD	>C14	14.0	9.0 (+29%)	400 (+38%) ❹	
EN 338 classes for comparison					
C14		14	7.0	290	
C16		16	8.0	310 ❶	
C18		18	9.0	320 ❶	
C20		20	9.5	330 ❷	
C22		22	10.0	340 ❸	
C24		24	11.0	350 ❸	
C27		27	11.5	360 ❸	
C30		30	12.0	380 ❹	
C35		35	13.0	390 ❹	
C40		40	14.0	400 ❹	
C45		45	15.0	410 ❹	
C50		50	16.0	430 ❹	

Expected to meet the CWFT density requirement for:
❶ Sawn timber in EN 14081-1 & CLT walls & ceilings in EN 16351
❷ and also glulam in EN 14080
❸ and also CLT floors with surface of spruce in EN 16351
❹ and also CLT floors with surface of pine in EN 16351

5.2.3. Spruce

Approved machine grading settings for home-grown spruce are listed in Table 15. More information about the settings can be found in the “AGR/ITT” tables and from the machine manufacturers. The existence of grading settings for a species and strength class does not mean that the grades will be easily available on the market.

EN 14081-2 includes fixed settings to grade two of the most important species in Europe: Norway spruce (*Picea abies*) and Silver fir (*Abies alba*) (the combination “spruce and fir whitewood”,WPCA), for the grade combinations C24/C18 and T14/T11 as well as for C24, C18, T14 and T11 as single grades. This means any approved grading machines measuring longitudinal resonant frequency can grade these two species within the specified limitations for timber size and additional requirements for operation and environment. The settings cover most of the European countries, and therefore will typically result in lower yields than settings developed for the specific characteristics of a particular timber source. All longitudinal resonance-based machines listed in Table 13 are able to use the EN 14081-2 fixed settings tables. They do not have to be repeated in the machine’s settings tables, although in some cases they are. Grading is not, however, particularly useful for the UK and yields would be very low.

Table 15 Current machine settings for home-grown spruce (Sitka and Norway)

Source	Size (mm × mm)	Combinations	[Machine] & *table*	Report by
Cook Bolinders				
UK IE	35-75 x 60-300	[C24/C16] [C18] [C16]	[1]-*1*	UKTGC & Timbersolve
Computermatic Micromatic				
UK IE	35-75 x 60-300	[C24/C16] [C18] [C16]	[2]-*1*	UKTGC & Timbersolve
Goldeneye 702/802				
UK IE	35-80 x 70-260	[C24/C16] [C16]	[5]-*1a* also [10]	Holzforschung Munich
UK IE	35-82 x 57-275	[C24/C16] [C22/C14] [C18] [C16]	[5]-*17* also [10]	Edinburgh Napier University
UK IE	20-83 x 47-275 ≥ 1600 mm^2	[C24/C16] [C22/C14] [C18] [C16] [C16+]	[5]-*34* also [10]	Edinburgh Napier University
UK IE	34-83 x 57-275	[C24/C16] [C22/C14] [C20/C14] [C18] [C16] [C24/C16+] [C16+]	[5]-*48* also [10]	Edinburgh Napier University
UK IE	20-52 x 35-67 ≥ 900 mm^2	[C14] [batten14] [batten12] [batten10]	[5]-*54* also [10]	Edinburgh Napier University
Viscan				
UK IE	35-82 x 57-275	[C22/C14] [C18] [C16]	[8]-*18* also [10] [20] [22]	Edinburgh Napier University
UK IE	20-83 x 47-275 ≥ 1600 mm^2	[C22/C14] [C18] [C16] [C16+]	[8]-*32* also [10] [20] [22]	Edinburgh Napier University
UK IE	34-83 x 57-275	[C24/C16] [C22/C14] [C20/C14] [C18] [C16] [C24/C16+] [C16+]	[8]-*45*	Edinburgh Napier University

			also [10] [20] [22]	
Goldeneye 706/806				
UK IE	35-82 x 57-275	[C27/C16] [C24/C16] [C22/C14] [C18] [C16] [TR26/C16]	[10]-*22*	Edinburgh Napier University
UK IE	20-83 x 47-275 ≥ 1600 mm^2	[C27/C16] [C24/C16] [C22/C14] [C18] [C16] [TR26/C16] [C16+]	[10]-*43*	Edinburgh Napier University
UK IE	34-83 x 57-275	[C27/C16] [C24/C16] [C22/C14] [C20/C14] [C18] [C16] [C27/C16+] [TR26/C16] [TR26/C16+] [C24/C16+] [C16+]	[10]-*58*	Edinburgh Napier University
MTG 960				
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C24/C16] [C22/C14] [C20] [C18] [C16]	[11]-*13*	Edinburgh Napier University
UK IE	34-84 x 84-168	[C27/C16] [C24/C16] [C22/C14] [C20] [C18] [C16] [NapierSA/NapierSC] [NapierSB/NapierSD]	[11]-*18*	Edinburgh Napier University
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C18] [C16] for grading while green	[11]-*22*	Edinburgh Napier University
UK IE	20-52 x 35-54 ≥ 900 mm^2	[C14]	[11]-33	Edinburgh Napier University
Precigrader				
UK IE	34-82 x 69-247	[C27/C18] [C27/C16] [C24/C16] [C24] [C18] [C16] [TR26/C16] [TR26]	[12]-*9*	Institut Technologique FCBA
UK IE	34-83 x 57-247 ≥ 2155 mm^2	[TR26/C16] [C27/C18] [C27/C16] [C24/C16] [TR26] [C24] [C18] [C16]	[12]-*20*	RISE Research Institutes of Sweden
mtgESCAN 962/966 and Escan FWM/FW				
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C24/C16] [C24/C14] [C22/C14] [C22] [C20] [C18] [C16] [C16+]	[14]-*14*	Edinburgh Napier University
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C22] [C20] [C18] [C16] for grading while green	[14]-*26*	Edinburgh Napier University
MTG920				
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C20] [C18] [C16]	[19]-*10*	Edinburgh Napier University
Viscan Plus				
UK IE	35-82 x 57-275	[C24/C16] [C22/C14] [C18] [C16]	[20]-*6* also [10]	Edinburgh Napier University
UK IE	20-83 x 47-275 ≥ 1600 mm^2	[C24/C16] [C22/C14] [C18] [C16] [C16+]	[20]-*25* also [10]	Edinburgh Napier University
UK IE	34-83 x 57-275	[C27/C16] [C24/C16] [C22/C14] [C20/C14] [C18] [C16] [C27/C16+] [TR26/C16] [TR26/C16+] [C24/C16+] [C16+]	[20]-*39* also [10]	Edinburgh Napier University
Viscan Compact				
UK IE	35-82 x 57-275	[C24/C16] [C22/C14] [C18] [C16]	[22]-*4* also [10]	Edinburgh Napier University

UK IE	20-83 x 47-275 ≥ 1600 mm^2	[C24/C16] [C22/C14] [C18] [C16] [C16+]	[22]-*24* also [10]	Edinburgh Napier University
UK IE	34-83 x 57-275	[C27/C16] [C24/C16] [C22/C14] [C20/C14] [C18] [C16] [C27/C16+] [TR26/C16] [TR26/C16+] [C24/C16+] [C16+]	[22]-*37* also [10]	Edinburgh Napier University
MTGbatch 962/966				
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C24/C16] [C24/C14] [C22/C14] [C22] [C20] [C18] [C16] [C16+]	[23]-*13*	Edinburgh Napier University
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C22] [C20] [C18] [C16] for grading while green	[23]-*25*	Edinburgh Napier University
MTGbatch 922/926				
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C22/C14] [C20] [C18] [C16]	[24]-*10*	Edinburgh Napier University
mtgESCAN 922/926 and EScan FM/F				
UK IE	20-83 x 47-165 ≥ 1600 mm^2	[C22/C14] [C20] [C18] [C16]	[26]-*10*	Edinburgh Napier University
Viscan portable with balance				
UK IE	34-83 x 57-275	[C24/C16] [C22/C14] [C18] [C16] [TR26/C16] [TR26/C16+] [C24/C16+]	[29]-*20* also [10] [22]	Edinburgh Napier University
Viscan portable without balance				
UK IE	34-83 x 57-275	[C22/C14] [C18] [C16]	[30]-*18* also [8] [10] [20] [22]	Edinburgh Napier University

5.2.4. Pine

Approved machine grading settings for home-grown pine are listed in Table 16. More information about the settings can be found in the "AGR/ITT" tables and from the machine manufacturers. The existence of grading settings for a species and strength class does not mean that the grades will be easily available on the market.

Table 16 Current machine settings for home-grown pine (Scots and Corsican)

Source	Size (mm × mm)	Combinations	[Machine] & *table*	Report by
Cook Bolinders				
UK IE	35-75 x 60-300	[C24/C16] [C16]	[1]-*1*	UKTGC
Computermatic Micromatic				
UK IE	35-75 x 60-300	[C24/C16] [C16]	[2]-*1*	UKTGC

5.2.5. Larch

Approved machine grading settings for home-grown larch are listed in Table 17. More information about the settings can be found in the "AGR/ITT" tables and from the machine manufacturers. The existence of grading settings for a species and strength class does not mean that the grades will be easily available on the market.

Table 17 Current machine settings for home-grown larch (European, Japanese and hybrid)

Source	Size (mm × mm)	Combinations	[Machine] & *table*	Report by
Cook Bolinders				
UK	43-82 x 92-250	[C27/C16] [C18] [C16]	[1]-*4*	Timbersolve
Computermatic Micromatic				
UK	43-82 x 92-250	[C27/C16] [C18] [C16]	[2]-*5*	Timbersolve
Goldeneye 702/802				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[5]-*31* also [10]	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C16] [TR26/C14]	[5]-*73* also [10]	National University of Ireland, Galway and Edinburgh Napier University
Viscan				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[8]-*29* also [10] [20] [22]	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C16] [TR26/C14]	[8]-*61* also [10] [20] [22]	National University of Ireland, Galway and Edinburgh Napier University
Goldeneye 706/806				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[10]-*39*	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C16] [TR26/C14]	[10]-*84*	National University of Ireland, Galway and Edinburgh Napier University
MTG 960				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [C20] [TR26/C16]	[11]-*12*	Edinburgh Napier University
UK	42-112 x 88-307	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [C20] [NapierLA/NapierLC] [NapierLB/NapierLD]	[11]-*19*	Edinburgh Napier University

UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C30/C18] [C27/C16] [C24/C16] [C24/C14] [C22] [C20] [NapierLA/NapierLC] [NapierLB/NapierLD] [TR26/C14]	[11]-*29*	National University of Ireland, Galway and Edinburgh Napier University
Precigrader				
UK	32-110 x 60-248	[C24/C16] [C18] [C16]	[12]-*18*	RISE Research Institutes of Sweden
mtgESCAN 962/966 and Escan FWM/FW				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[14]-*16*	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C30/C18] [C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22] [NapierLA/NapierLC] [NapierLB/NapierLD] [TR26/C14]	[14]-*35*	National University of Ireland, Galway and Edinburgh Napier University
MTG920				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [C20] [TR26/C16]	[19]-*9*	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22] [C20] [NapierLB/NapierLD] [TR26/C16]	[19]-*14*	National University of Ireland, Galway and Edinburgh Napier University
Viscan Plus				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[20]-*22* also [10]	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C16] [TR26/C14]	[20]-*61* also [10]	National University of Ireland, Galway and Edinburgh Napier University
Viscan Compact				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[22]-*21* also [10]	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C16] [TR26/C14]	[22]-*61* also [10]	National University of Ireland, Galway and Edinburgh Napier University
MTGbatch 962/966				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[23]-*15*	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C30/C18] [C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22] [NapierLA/NapierLC] [NapierLB/NapierLD] [TR26/C14]	[23]-*34*	National University of Ireland, Galway and Edinburgh Napier University
MTGbatch 922/926				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[24]-*9*	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22]	[24]-*14*	National University of Ireland, Galway and

		[NapierLB/NapierLD] [TR26/C16] [TR26/C14]		Edinburgh Napier University
mtgESCAN 922/926 and EScan FM/F				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [TR26/C14]	[26]-*9*	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22] [NapierLB/NapierLD] [TR26/C16] [TR26/C14]	[26]-*14*	National University of Ireland, Galway and Edinburgh Napier University
Viscan portable with balance				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C20] [TR26/C16]	[29]-*11* also [10] [22]	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C35/C18] [C30/C16] [C27/C16] [C24/C14] [C22] [C20] [TR26/C16] [TR26/C14]	[29]-*37* also [10] [22]	National University of Ireland, Galway and Edinburgh Napier University
Viscan portable without balance				
UK	20-110 x 47-303 ≥ 2000 mm^2	[C30/C16] [C27/C16] [C24/C14] [C20] [TR26/C16]	[30]-*9* also [8] [10] [20] [22]	Edinburgh Napier University
UK-IE	20-110 x 42-303 ≥ 1600 mm^2	[C30/C16] [C27/C16] [C24/C14] [C22] [C20] [TR26/C16] [TR26/C14]	[30]-*29* also [8] [10] [20] [22]	National University of Ireland, Galway and Edinburgh Napier University

5.2.6. Douglas-fir

Approved machine grading settings for home-grown Douglas-fir are listed in Table 18. More information about the settings can be found in the "AGR/ITT" tables and from the machine manufacturers. The existence of grading settings for a species and strength class does not mean that the grades will be easily available on the market.

Table 18 Current machine settings for home-grown Douglas-fir

Source	Size (mm × mm)	Combinations	[Machine] & *table*	Report by
Goldeneye 702/802				
UK IE	33-84 x 68-248	[C35/C18] [C35/C16] [C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22/C14] [C20/C14] [C20] [C18] [C16] [TR26/C16]	[5]-*53* also [10]	Edinburgh Napier University and National University of Ireland, Galway
Viscan				
UK IE	33-84 x 68-248	[C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22/C14] [C20/C14] [C20] [C18] [C16] [TR26/C16]	[8]-*47* also [10] [20] [22]	Edinburgh Napier University and National University of Ireland, Galway
Goldeneye 706/806				
UK IE	33-84 x 68-248	[C40/C30/C16] [C40/C27/C16] [C40/C24/C16] [C35/C18] [C35/C16] [C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22/C14] [C20/C14] [C20] [C18] [C16] [TR26/C16]	[10]-*63 & 64*	Edinburgh Napier University and National University of Ireland, Galway
MTG 960				
UK IE	33-84 x 68-248	[C35/C16] [C24/C14] [TR26/C14] [NapierDA/NapierDC] [NapierDB/NapierDD]	[11]-*24*	Edinburgh Napier University and National University of Ireland, Galway
Precigrader				
UK Belgium	32-110 x 60-247 ≥ 2840 mm^2	[TR26/C16] [C24/C18] [C24] [C18] [C16]	[12]-19	RISE Research Institutes of Sweden
mtgESCAN 962/966 and Escan FWM/FW				
UK IE	33-84 x 68-248	[C35/C16] [C24/C16] [C24/C14] [TR26/C14] [NapierDA/NapierDC] [NapierDB/NapierDD]	[14]-*28*	Edinburgh Napier University and National University of Ireland, Galway
MTG920				
UK IE	33-84 x 68-248	[C27/C16] [C24/C14] [TR26/C16]	[19]-*11*	Edinburgh Napier University and National University of Ireland, Galway

Viscan Plus				
UK IE	33-84 x 68-248	[C40/C30/C16] [C40/C27/C16] [C40/C24/C16] [C35/C18] [C35/C16] [C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22/C14] [C20] [C18] [C16] [TR26/C16]	[20]-*42* also [10]	Edinburgh Napier University and National University of Ireland, Galway
Viscan Compact				
UK IE	33-84 x 68-248	[C40/C30/C16] [C40/C27/C16] [C40/C24/C16] [C35/C18] [C35/C16] [C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22/C14] [C20] [C18] [C16] [TR26/C16]	[22]-*40* also [10]	Edinburgh Napier University and National University of Ireland, Galway
MTGbatch 962/966				
UK IE	33-84 x 68-248	[C35/C16] [C24/C16] [C24/C14] [TR26/C14] [NapierDA/NapierDC] [NapierDB/NapierDD]	[23]-*27*	Edinburgh Napier University and National University of Ireland, Galway
MTGbatch 922/926				
UK IE	33-84 x 68-248	[C27/C16] [C24/C16] [TR26/C16]	[24]-*11*	Edinburgh Napier University and National University of Ireland, Galway
mtgESCAN 922/926 and EScan FM/F				
UK IE	33-84 x 68-248	[C27/C16] [C24/C16] [TR26/C16]	[26]-*11*	Edinburgh Napier University and National University of Ireland, Galway
Viscan portable with balance				
UK IE	33-84 x 68-248	[C40/C30/C18] [C40/C27/C16] [C40/C24/C16] [C35/C18] [C35/C16] [C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22/C14] [C20/C14] [C20] [C18] [C16] [C14] [TR26/C16]	[29]-*21&22* also [10] [22]	Edinburgh Napier University and National University of Ireland, Galway
Viscan portable without balance				
UK IE	33-84 x 68-248	[C30/C16] [C27/C16] [C24/C16] [C24/C14] [C22/C14] [C20/C14] [C20] [C18] [C16] [C14] [TR26/C16]	[30]-*19* also [8] [10] [20] [22]	Edinburgh Napier University and National University of Ireland, Galway

5.3. Appearance grading

As the name suggests, appearance grading focuses on the appearance of timber. As opposed to visual strength grading, appearance grading does not aim at characterising the structural properties of timber, but sorts it into different appearance classes that might be used for different purposes. Appearance classes can be defined freely by timber processors, manufacturers or merchants, and should be aligned with customer expectations. As well as aesthetics, appearance grading can cover useability aspects such as dead knots that might cause problems in processing.

Even though appearance grading is separate from strength grading, it can function also in a strength grading role if the undesired features are also correlated with mechanical properties.

Appearance grading can be a step in the manufacturing of CLT, but the grading strategy needs to be adapted to the market requirements. The following considerations need to be taken into account:

1. Market demand for exposed (“appearance grade”) CLT

In theory, appearance of CLT is mainly of relevance where it will be visible in the finished structure. Current timber building practices in the UK are typically conscious of fire safety, leaving little timber exposed. In high-rise buildings, combustible materials, including CLT, need to be covered with non-combustible materials and this is common practice in low-rise buildings as well. However, trends like using more natural materials and biophilic design in buildings might increase the demand in appearance grade CLT. The current and future demand for visible CLT could be estimated in a customer survey.

2. Market value of appearance grade CLT

It should be determined how the market value of CLT is influenced by its appearance grade and whether the additional time needed for an extra grading step can be reflected in the sale price. It should be studies which defects in particular influence the customer’s valuation of the product, if any at all. Grading to three or more appearance grades instead of only two might prove to be beneficial for marketing.

3. Misconceptions around appearance

Even though appearance grading does not have the goal to increase the structural performance of a timber population, it does reduce the amount and/or severity of defects. CLT with many defects might be perceived as weaker than a similar product with fewer defects, even when the structural performance of both is declared the same. Appearance grade CLT might therefore be perceived as having superior structural properties compared to non-appearance grade CLT, so that appearance is of importance for sale, even when in the final application it is not. A careful market analysis studying customer perceptions and motives for buying appearance grade CLT would be beneficial. This should also include a comparison of the appearance of CLT available on the market and potential UK-made CLT of similar strength.

The market analyses should result in requirements to the appearance grading schedule, if one is required. This includes:

- Number of appearance grades
- Name of the grades for marketing

- Which defect types to consider
- Desired yields of each grade (or target amounts of CLT panels with certain appearance grade faces on one or both sides, which determines required yields)
- Person-hours that can be taken for appearance grading to be financially viable (or cost of employing machine methods of appearance grading, if not incorporated into the strength grading rule)

When the desired outcomes of the appearance grading are well defined, bespoke grading rules can be derived for sorting the timber into appearance grades. This could be oriented on existing appearance grading standards, but should be adapted to specific customer expectations and required yields. Such rules can cover manufacturing defects as well as timber defects.

Ideally, the appearance grading rule can be incorporated into the strength grading rule to take advantage of the increase in quality. If this can be done automatically by the grading machine this would count as normal machine strength grading. If the appearance grading rule is applied manually, the framework instead would be visual strength grading (assisted by machine).

The frequency, size and condition of knots is probably the most important growth-related feature. This is related to branching habit of the tree, radial and vertical position within the stem, and forest management. There is some influence, therefore, on aesthetic qualities on resource selection and cutting pattern.

Home-grown spruce is quite simple to appearance grade, as it does not have a wide range of defect types, knots are quite consistent, and colour is very uniform.

6. Possible bespoke grading approaches

6.1. Using existing datasets

Grading development can be more optimised to the actual end use rather than defaulting to the standard EN 338 strength classes. It is worth noting that grading can be used to optimise differently from the normal approach; such as sorting timber with high stiffness but low density (for better performance to weight ratio).

With the exception of the bending type machines (for which data is not available in suitable form), the grading datasets for all machines can be used to create settings for new user-defined strength classes. This could include some new testing to extend the size range where it currently does not cover the smaller thicknesses.

It is also possible to calculate a large array of user-defined strength classes to allow flexibility in production. This way grading can be continually adjusted to fit the raw material to the production requirement.

A second grading process can be applied on top of bought-in, already graded, C16 timber and settings for this second grading can potentially be developed from existing datasets (depending on the machines involved).

6.2. Using new datasets

Since the existing grading datasets are not well matched (in cutting pattern or cross-section sizes) to lamellas, new testing work on a more representative resource for CLT/glulam production would likely bring:

- Ability to grade with better yields and/or grade design properties
- Other grading machine options (if included in the grading settings work)

Grading datasets need to be at least 450 boards (CEN, 2018a), but 700 to 1300 is recommended if high grades or multiple grade combinations are needed (to avoid statistical adjustments from small subsets of the data). For machines that already have UK-data this need not be a new full dataset as some of this existing data could be used. New testing should cover the full geographic range of spruce in UK and Ireland to be sure to be representative. Grading development work typically takes a year and a half to get to the approval stage (CEN TC124 WG2 TG1 meets twice a year).

6.3. Single grade

For a single grading scheme, the idea of C16+ can be extended. This might be worth doing if density needs to be increased to meet the CWFT requirement for CLT floors (Section 2.2), or new testing can be done to make a settings dataset that is more representative of the size and cutting patterns that would be used in practice, or higher stiffness or strength is required by the product end use. Otherwise, C16+ already suits well, especially if the secondary properties can be increased by testing (Section 4.4).

6.4. Multiple grade

For a multiple grading situation, making use of all the material (i.e. no grading going to another product), the classes could be based on the proportion going in the lay-up. For example, in a 5-ply CLT a high grade could be made for the outer lamellas, favouring high stiffness and high density (and by correlation, high strength). Outer lamellas are 40% of the product, but if the yield for this was about 50%, it would allow for variation in yield in practice. Excess material can be downgraded, for use in the other layers. A low grade, with the lower density and lower stiffness pieces can be made for the core lamella, and a middle grade of what remains (high stiffness, low density and high density, low stiffness) can be used for the second and fourth layers. A simplified illustration of this concept is given in Figure 11 and Table 19. In practice, the calculation procedure in EN 14081-2 will produce different results, but it would, anyway, be ideal to base this bespoke grading on new testing that is more representative of the size and cutting patterns that would be used in practice (Figure 10). Appearance grading rules could be incorporated into the grade for the outer layers.

This is slightly different to the standard method of grading, in favouring high density for the outer layers to improve hardness and fastener performance (and possibly fire performance).

For this system to work for a single CLT panel type, the lamellas need to be of the same thickness. However, the idea can be extended to balance grade and lamella type over the full range of laminated products being produced.

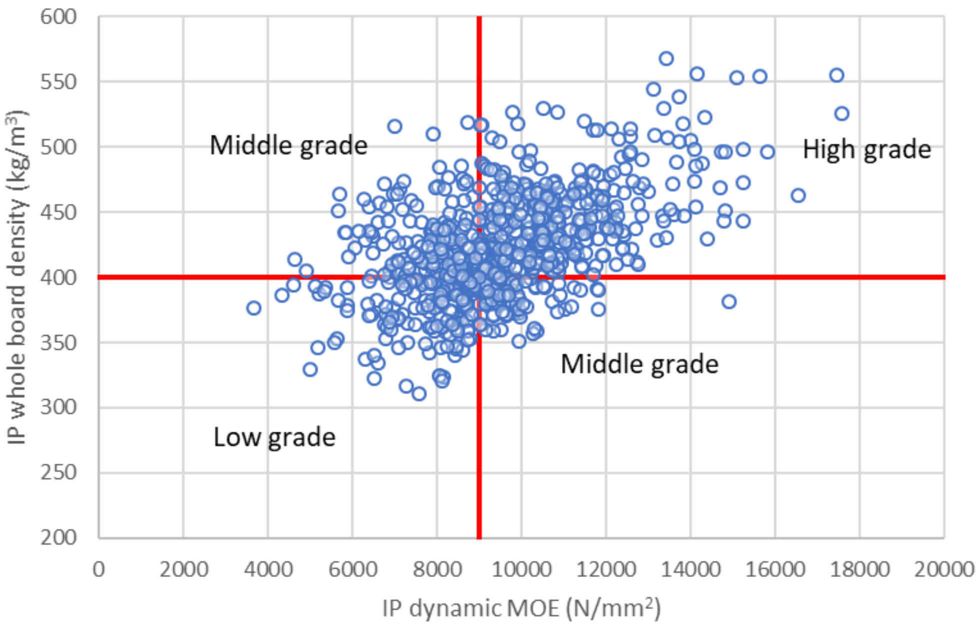

Figure 11 Simplified grading example for home-grown spruce, dual density and stiffness grading into three grades, balanced for 5-ply layup

Table 19 Simplified example, potential strength class properties

Grade	Yield	Strength (N/mm^2)		Stiffness (kN/mm^2)		Density (kg/m^3)	
		5%ile	Mean	5%ile	Mean	5%ile	Mean
Low (>C14)	20%	15	26	4.0	7.0	300	350
Middle (>C14)	30%	16	29	4.8	7.6	340	390
High (>C22)	50%	22	36	6.6	10.0	380	420
Overall	100%					330	400

Note: It may be necessary to reject about 7% for low density to raise the mean density overall beyond the CWFT limit for CLT floors with spruce surface (See Section 2.2)

7. Production considerations (focus on spruce)

7.1. Log segregation

Since stiffness is the property of most concern, the quality of the feedstock can be improved by acoustic segregation of the logs (Searles, 2012), as is already the practice in some sawmills. Since there is a wide variation of wood stiffness within a log, this cannot raise the quality by much, but it can usefully reduce the reject rate, especially when aiming for grades higher than C16.

7.2. Cutting patterns

The current cutting patterns in use in Irish and UK sawmills tend to take the structural product (carcassing dimensions) from the centre of the log, aiming for maximum volume recovery for the sawn timber overall. The centre is sometimes considered to be the better-quality timber, but in truth this is the juvenile core, which tends to have inferior stiffness and strength, compared to the wood on the outer part of the log (Section 4.1). Research has shown that timber from the outer part of the log would be expected to grade better, and so long as the sawmills have suitable equipment, alternative cutting patterns may result in better grading (Ridley-Ellis, et al., 2009). This has most potential for the dimensions of lamellas used for CLT and glulam manufacture, but the research has not yet specifically looked at this so far.

There is a supposed size effect in timber grading, but it is not really known to what extent this is real and what is an artifact of the cutting patterns (Ridley-Ellis, et al., 2016). This is a potential topic of research to optimise cutting patterns, resource and grading potential for CLT manufacture, but not one that can really be answered by the testing done so far. There are indications that a cutting pattern aimed at CLT lamellas from the outer part of a log of typical rotation length could raise the general grade from C16 to C18 or even C20 thanks to the trend for increasing stiffness with radial position (Moore, et al., 2012). This would require new grading settings work aimed specifically at this process (current grading settings are for the most general cases and reflect current industrial practice and products).

7.3. Grading

If the CLT/glulam manufacturer is not in control of the sawing and grading process, then it is likely most important that the grading requirement does not restrict the options for supply of the timber. Any special requirements for grading will need to consider the sawn timber products that the sawmiller makes from the rest of the log.

If the grading is for a specific set of cross-sections from specific cutting patterns, there is considerable scope for improving both the yields and the performance by concentrating the grading development on this specific resource. This would require new testing.

If the grading is done as part of the manufacturing process, rather than by the sawmills, there is more scope for improvement for a number of reasons:

1. There is possibility to relax some of the criteria that are there for timber placed on the open market, without knowing the final use. (Full advantage of this would require some modification of the standards, which still refer to the whole process under EN 14081-1).

2. There can be a greater number of strength classes, and they can be continually adjusted to fit the raw material to the production requirement.

3. The grading development can be more optimised to the actual end use.

4. Grading is much less limited by the capability of the sawmills to adapt their existing processes and equipment.

A second grading process can be applied on top of already graded C16 timber, but this will require some control over the original sawing and grading to ensure there are no significant changes that affect the correctness of the second grading.

One advantage for home-grown spruce is that the simplest, cheapest and most compact technology (longitudinal resonance) works the best.

The main grading options are:

- Purchase graded timber and use this in manufacture, sorting only for appearance
    - C16 graded sawn timber (standard market grade)
    - C16+ graded sawn timber
    - Other grades by special arrangement with the sawmill
- Purchase C16 graded timber and apply a second strength grading
    - 2 grades (face and inner)
    - 3 grades (face, inner and intermediate)
- Purchase ungraded timber and apply strength grading
    - 2 grades (face and inner)
    - 3 grades (face, inner and intermediate)
- Saw and grade timber within the manufacturing process
    - 2 grades (face and inner)
    - 3 grades (face, inner and intermediate)

It will not be possible to grade more than 3 grades in one operation, due to how the EN 14081-2 calculation works, but there can be more than 3 grades produced across options for the grading operation.

7.4. Drying

It is common practice in the UK to kiln dry the spruce only to the 20% moisture content, the limit for dry-graded timber in EN 14081-1. Drying down to lower moisture content takes considerably more time and energy, and also results in the potential for significantly more reject due to drying distortion and other kilning problems. What is best in a production process will depend very much on the kiln size and technology, as well as the cutting pattern used to make the timber, and any sorting of the kiln load. There has been little academic research on this topic in the UK, but the drying parameters are so specific to the sawmiller’s production process that the parameter optimisation is best done in the company anyway. The starting point is documented best practice (Riddiough, 2000).

The typical moisture content in the heartwood of the standing trees is in the order of 50% to 100%, but in the sapwood it is typically 100% to 250%, varying by season (Yerbury, 2017).

The spruce planes well, but drying distortion can cause significant practical problems and/or wastage for the CLT layup. Twist is usually considered to be the most problematic type of distortion. It can be minimised by good kilning, stacking and storage practice, but usually gets worse once the timber dries past 20% so the problem of distortion usually manifests after the timber has left the sawmill, especially if it is not properly stacked and stored. Avoiding unnecessary reject from distortion due to poor kilning, stacking and storage practice will be paramount, since it cannot really be avoided by resource segregation at the green stage, although cutting pattern producing CLT lamellas from the outer part of the log probably would help (see Section 4.6).

7.5. Defect cutting and finger-jointing

Home-grown spruce normally produces one distinct whorl of branches in a growing season, along with a number of much smaller inter-whorl branches. On low yield class sites the average distance between whorls can be 0.3 m, whereas on more productive sites it can be up to 0.7 m (Moore, 2011). The consequence of this is that the sawn timber has knots, typically, every half metre and that each cluster of knots is quite similar in severity. Defect cutting would therefore result in short lengths to finger-joint and is not likely to result in a big increase in quality, aside from the aesthetics.

8. Summary and recommendations (focus on spruce)

8.1. Recommendations for CLT production parameters

Table 20 summarises the recommended production parameters for a UK-based mass timber (CLT) production facility. The data, such as, recommended volume output, timber species, timber and panel dimensions is based on the previous research undertaken by Edinburgh Napier University.

Table 20 Recommended production parameters for UK-based CLT production facility

Production parameters	
Capacity (initial)	≈10,000 m^3/shift/annum
Capacity (target)	≈20,000 m^3/shift/annum
Wood parameters	
Species	Sitka spruce & Norway spruce mix (initial) Plus mixture of minor species (target)
Density	370-420 kg/m^3
Grade	C16 or C16+ Or C22/C14 or NapierSB/NapierSD Or C24/C16 or NapierSA/NapierSC Or a bespoke grading scheme
Moisture content	12±3%
Pre-planed board dimensions	
Thickness	22 mm | 38 mm | 47 mm
Width	100 mm | 150 mm
Length	2,400 mm | 3,600 mm | 4,800 mm
Planed board dimensions*	
Thickness	20 mm | 33 mm | 42 mm
Width	95 mm | 145 mm
Length	2,400 mm | 3,600 mm | 4,800 mm
Finished CLT dimensions**	
Thickness	100 mm | 150 mm | 180 mm | 210 mm
Width	Up to 3,000 mm
Length	Up to 13,000 mm (Up to 4,700 mm)
Lay-up	3-ply | 5-ply
Finger jointing***	
Type of finger joint	Vertical (structural)
Piece length	Long (end jointed, not defect cut)
Mass timber products****	
Cross Laminated Timber (primary product)	Initial
Glue Laminated Timber (secondary product)	Initial
Nail Laminated Timber (NLT)	Target
Dowel Laminated Timber (DLT)	Target

* Noting the maximum reprocessing allowance in EN 14081-1 (see Section 2.1)

** 13 m panel length is only possible if boards are finger jointed, or if used for fully supported walls. Otherwise panel length is restricted to 4.7 m.

*** Recommended but not essential, without finger joints panel length will be restricted (see above).

**** Both CLT and Glulam can be produced on vacuum press. Relatively inexpensive with small footprint, DLT and NLT presses could be added to the existing manufacturing plant at later date.

8.2. Recommendations for strength grading method

If the ambition is to use only C16, then the timber properties have little importance to grading machine choice, as there is almost no machine reject.

If the ambition is to use only C16+, then any modern machine is capable, even if it currently does not have settings (they could be calculated from the grading dataset). However, it is easier with the machines that currently have settings. Note, however, that not all mills will have the settings, even if they have the machines that can run them.

The grading machine should ideally be "in-line" (not portable) to take advantage of the kv factor that increases characteristic strength (CEN, 2018a). However, since stiffness is usually the limiting property, portable machines can often grade just as well as the in-line ones.

If higher grades or grading to multiple grades is desired, the machines that work on dynamic modulus of elasticity (frequency and density) are the most useful.

If strength grading is combined with knot-based appearance grading of the surface layer, a machine also with capability to measure knots is useful. Of these, the x-ray technology is most convenient.

If appearance of the surface layer is very important for the product, grading could instead be on a visual grading basis, assisted by machine. Portable machines based on dynamic MOE would be most useful for this. Enabling this would, however, require new testing and grading development work.

8.3. Recommendations for appearance grading

If different strength grades are used in the outer layers, the appearance grading rules are ideally incorporated into the strength grading (whatever the required aesthetic considerations are). The selection of strength grading machine is relevant, as some are able to automatically sense relevant qualities, while others cannot.

There is no point in fully adopting an existing appearance grading standard, but they may provide inspiration for in-company bespoke appearance grading rules. Certain issues, such as dead knots, may be possible to avoid earlier in the processing chain via log selection and cutting patterns.

Depending on the production methods, it may be sufficient to grade only the 'best face' of the timber since only one face will be visible in the made-up lamination.

8.4. Recommendations for kiln drying

Unfortunately, the potential to reduce drying degrade through current methods of tree or log segregation has shown to be minimal, so the recommended approach is to follow established best practice, especially correct stacking, stickering and storage (Riddiough, 2000). If practically possible, segregation of kiln load by moisture content would help. Kiln schedules and top weighting can be adjusted based on the experienced issues in practice.

If drying is done in a two-stage process, with received timber at about 20% moisture content, being kilned down to 12%, the removal of distorted pieces before the second kilning would target the pieces most likely to distort further. In a two-stage process, the correct stacking, storage and handling of the timber between stages is important.

Removal of low-stiffness pieces, by acoustic resonance grading prior to drying, may also help reduce the amount of distortion.

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