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THE UNIFORMITY FACTOR—A PROPOSED METHOD FOR EXPRESSING VARIATIONS IN SPECIFIC GRAVITY

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ABSTRACT

Existing measures of uniformity of specific gravity, as obtained by X-ray densitometry, are examined in light of how well they fulfill the requirements thought to be necessary for a uniformity indicator. Based upon an examination of mass and volume specific gravity distributions, a new indicator is proposed. This indicator, the uniformity factor, relates the volume distribution of specific gravity within an increment of wood to a selected reference base. The suitability of the uniformity factor for estimating wood uniformity is shown using data from two species of different uniformities. This approach appears to have potential as a new tool in predicting wood quality.

Keywords: *Pseudotsuga menziesii*, *Abies concolor*, specific gravity, X-ray densitometry, densitometry, wood quality, physical properties.

INTRODUCTION

Wood is a highly variable material. Physical and chemical characteristics may differ widely within annual rings, from pith to bark, from one side of a tree to the other, up and down the stem, from tree to tree, from stand to stand, within species, or between species. Larson (1969) considered this general lack of uniformity of wood's physical and chemical properties as one of the greatest problems facing the wood industry. For example, lack of uniformity in one physical property, growth rate, is highly undesirable with respect to dimensional stability as well as machining and finishing characteristics (Mitchell 1961).

Uniformity can be defined as a measure of variability in a particular physical or chemical property within a piece of wood. Appropriate numerical indices that relate to a property's degree of variability can be used to estimate wood uniformity. One such indicator, a density distribution index developed by Echols (1972a, 1973), determines uniformity of variations in incremental specific gravity[2] of increment cores taken at breast height from X-ray densitometric output. Other uniformity indicators, for such properties as growth rate, latewood percentage, shrinkage, grain angle, treatability, etc., may be used depending upon the wood's intended use. Each, however, may indicate only one aspect of the uniformity within a piece of wood.

Generally there are many properties that are relevant to each type of processing or end use. Specific gravity has been, however, accepted as the best single wood quality indicator without considering specific end uses (Mitchell 1961). The measure of specific gravity normally used is the average or gross specific gravity, disregarding within-sample variations. Consequently, wood may have a very high aver-

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[2] Incremental specific gravity is the quantity of material for a given sample, either on a volume or mass basis, that is found within an arbitrarily specified range of specific gravity, e.g., from 0.30–0.35.

age specific gravity, while at the same time possessing low specific gravity uniformity. The quality of this wood could perhaps be better evaluated by determining uniformity of specific gravity as well as average specific gravity.

OBJECTIVES

The objectives of this study were:

1. To evaluate present methods for measuring uniformity of specific gravity as determined from incremental specific gravity data obtained by X-ray densitometry.
2. To investigate variations and distributions of incremental specific gravity.
3. Using the above results, to determine if a new measure of specific gravity uniformity is necessary and if so to propose a new method.

EXISTING UNIFORMITY EXPRESSIONS

Since the development of X-ray densitometry for evaluation of density from increment cores (Polge 1965), numerous X-ray densitometric units have been installed throughout the world (Parker and Kennedy 1973). Their primary function is to investigate intraring specific gravity variations. In addition, other properties such as latewood percentage, ring width, growth rate and earlywood-latewood-sample minimum, maximum and mean specific gravities can be readily determined. In evaluating such X-ray data, an extreme variation in the distribution of specific gravity values may be found within a given annual ring or from ring to ring or from core to core. Thus, it seems appropriate to try to quantify this variation in order to estimate the uniformity or lack of uniformity in specific gravity of the particular increment of wood in question.

A numerical value of specific gravity uniformity should satisfy at least five major requirements. First, the indicator should show sufficient variation from sample to sample. Second, a reference or base point should be included in the calculation of the indicator to simplify comparisons between different samples. Four such comparisons are possible including 1) between species, 2) between trees of the same species, 3) within individual trees, and 4) within annual rings. A third requirement is that the distribution of variations in incremental specific gravity should be included in the calculational procedure. Fourth, the indicator should be adaptable to both types of existing X-ray systems, i.e., direct readout (Megraw and Munk 1974) and film-densitometer-integrator type (Echols 1973). Finally, to avoid possible confusion in interpretation of results, a higher index value should indicate greater specific gravity uniformity.

Uniformity of specific gravity has up to this time been measured primarily by two methods, the previously mentioned density distribution index (Echols 1972a, 1973) or the arbitrary breakdown of the material into broad specific gravity classes (Megraw personal communication 1975). The former will be evaluated first. Echols (1973) defined the density distribution index as a measure of the variation of specific gravity within a given wood sample, or the extent and magnitude of departure from the *mean* specific gravity. He incorrectly calculated the mean specific gravity, however, and had acually determined the *median* specific gravity, or that specific gravity value at which half the volume (or counts in the X-ray film-densitometer-integrator method) of incremental specific gravity values are above and half below. As will be seen shortly in the discussion on specific gravity distributions, since the mean and median specific gravity values can be very different for a given increment of wood, a significant error is introduced by referring to or using one in place of the other. This confusion in the initial calculation of the density distribution index probably resulted because the film-densitometer-integrator output is based upon the *volume* of material per specific gravity class rather than total *mass* per class as is needed to determine a mean specific gravity. The past calculations of the density distribution index can be considered correct and valid only by redefining this uniformity indicator as being the extent and departure from the *median* specific gravity. If this is done, the count or percent volume output can be correctly used in its calculation. However, all references to the mean specific gravity in these studies (Echols 1972a, 1972b, 1973) should be changed to the median specific gravity. The true mean specific gravity of an increment core or growth increment can be determined from the X-ray film-densitometer-integrator count output using a weighted-class count method (Olson 1974). This method will be described later in the discussion on specific gravity distributions.

The density distribution index, when properly redefined and calculated using the median specific gravity, does not satisfy two of the desired uniformity indicator requirements. One problem is the inverse relationship between density distribution index and specific gravity uniformity, i.e., a lower index value represents greater uniformity. This results in confusion when interpreting this uniformity indicator. However, more importantly, a valid reference or base point is not used. This can be clearly seen in an evaluation of within-tree variation of specific gravity uniformity. For example, it is possible to calculate with this approach a density distribution index value of 100, signifying an ideally uniform tree, at all heights in a tree, which would appear to indicate that this tree is highly uniform in incremental specific gravity. However, this may not be the case, as the median or mean specific gravity may vary considerably between different heights in the tree. Thus, there is no basis for a comparison of values within a given tree, as the index has been simply weighted from the median specific gravity for *each* respective height. The density distribution index, therefore, cannot completely express the actual uniformity of specific gravity within a tree. The same problem is encountered when making between-tree comparisons. For example, the index values obtained from breast height increment cores of various trees may show a high degree of uniformity. If the objective of the program utilizing the data is to make a species more uniform, then these index values are not comparable since the trees may at the same time have vastly different median or mean specific gravities. For these reasons, this uniformity indicator is not thought to be a completely suitable measure of specific gravity uniformity.

An arbitrary breakdown of a sample into broad specific gravity classes provides a second means of expressing specific gravity uniformity (Megraw personal communication 1975). This indicator, while easily calculated, neither considers the total variation in incremental specific gravity nor uses a base or reference point. With this approach two classification systems can be used. The first considers the percentage of materal contained in a number of broad specific gravity classes, e.g., the percentage of material having a specific gravity less than 0.3, that between 0.3 to 0.6, and that greater than 0.6. The other system separates the material into a given range around a median or mean specific gravity value, e.g., the percentage of material within the range of the mean specific gravity ± 0.25 times the mean value. While such indicators give an indication of the macro-uniformity of a piece of wood, they can be misleading since they do not consider the actual distribution of material within the broad classifications.

Other possible indicators of specific gravity uniformity might include statistical measures of dispersion, such as the standard deviation or coefficient of variation (standard deviation divided by mean). Unfortunately, these statistical methods do not include an established reference point and thus are not totally appropriate.

SPECIFIC GRAVITY DISTRIBUTIONS—DEVELOPMENT OF THE UNIFORMITY FACTOR

As noted earlier the total variation in incremental specific gravity values should be considered in the calculation of specific gravity uniformity. The material within any given specific gravity increment can be expressed on either a volume or mass basis. This is perhaps best seen in Table 1,

TABLE 1. *Typicial data for volume and mass specific gravity distributions within a single increment core (weight and volume on a 12 percent moisture content basis)*

	VOLUME DISTRIBUTION			MASS DISTRIBUTION			
Specific Gravity Class	Counts in Class	% Total Volume in Each Class	Cumulative % Volume	Midpoint of Class	Specific Gravity Increments	% Total Mass in Each Class	Cumulative % Mass
0.85-0.90	16	0.30	100.00	0.875	0.0026	0.63	100.00
0.80-0.85	122	2.40	99.70	0.825	0.0198	4.79	99.37
0.75-0.80	180	3.55	97.30	0.775	0.0275	6.65	94.58
0.70-0.75	177	3.49	93.75	0.725	0.0253	6.12	87.93
0.65-0.70	232	4.57	90.26	0.675	0.0308	7.45	81.81
0.60-0.65	206	4.06	85.69	0.625	0.0253	6.12	74.36
0.55-0.60	280	5.52	81.63	0.575	0.0317	7.66	68.24
0.50-0.55	320	6.31	76.11	0.525	0.0331	8.00	60.58
0.45-0.50	319	6.29	69.80	0.475	0.0298	7.20	52.58
0.40-0.45	362	7.14	63.51	0.425	0.0303	7.33	45.38
0.35-0.40	288	5.68	56.37	0.375	0.0213	5.15	38.05
0.30-0.35	535	10.55	50.69	0.325	0.0342	8.27	32.90
0.25-0.30	1193	23.52	40.14	0.275	0.0646	15.62	24.63
0.20-0.25	843	16.62	16.62	0.225	0.0373	9.01	9.01
0.15-0.20	0	0	0	0.175	0	0	0
Totals	5073	100.00	— —		0.414	100.00	— —
	Median specific gravity = 0.347				Mean specific gravity = 0.414		

which shows typical integrator count data for a single increment core, equalized to 12% moisture content and obtained using the X-ray densitometry technique of Echols (1973). The counts represent the volume distribution of material in the core by 0.05 specific gravity classes (12% moisture content weight and volume basis). It is assumed that the material (counts) in any given increment class are normally distributed. By dividing the counts in each class by the total counts, the volume percentage by class was obtained. The cumulative percent counts for each class were determined and the resulting volume distribution is shown in Fig. 1. The median specific gravity, 0.347, was determined as being that specific gravity value at which 50% of the counts (volume) lie above and 50% lie below.

The mass distribution, on the other hand, indicates the amount or percentage of the total mass found in each specific gravity class. With such integrator output data, a weighted-class count technique must be employed to determine the mean specific gravity. An assumption of this method is that there is a normal distribution of counts in each class, i.e., an equal number of counts lie above and below the midpoint value of each specific gravity class. Specific gravity increments for each class can be calculated by multiplying the midpoint value by the percentage of total counts found in the class. These increments are then summed to give the total mass, or mean specific gravity. The percentage of total mass together with the cumulative percent mass in each class are also determined. The mass distribution for the data in Table 1 is shown in Fig. 1.

It is obvious from Fig. 1 that the volume and mass distributions are significantly different. For example, approximately 51%

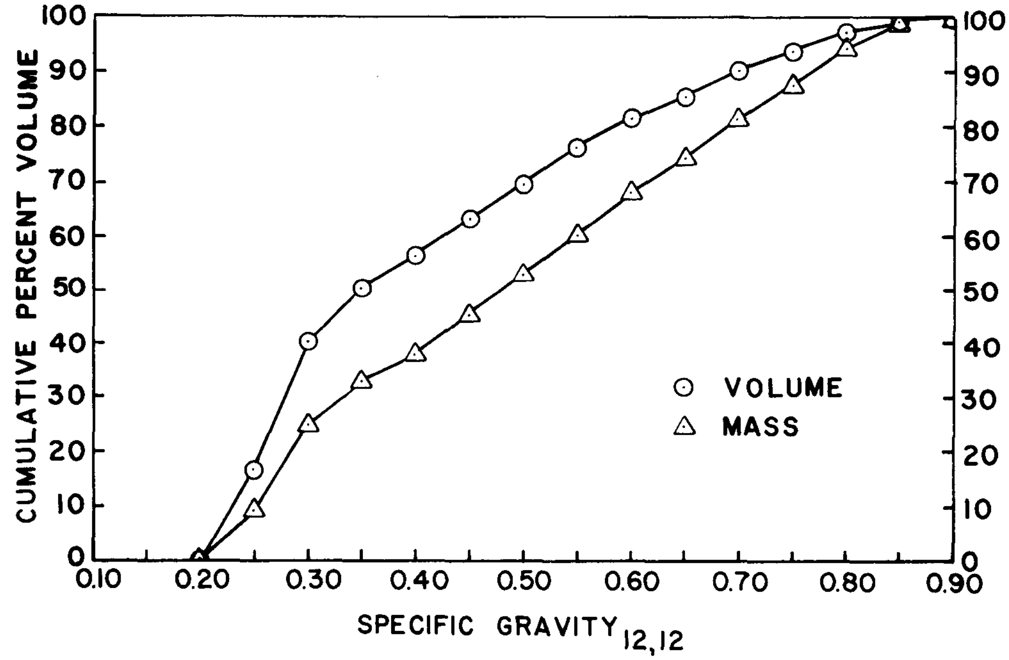

FIG. 1. A comparison of cumulative volume and mass specific gravity distributions within a single increment core (weight and volume on a 12 percent moisture content basis).

of the total volume of material in this particular sample had a specific gravity less than 0.35, while only 33% of the total mass came from material with a specific gravity in this same range. Either distribution can be used in calculating uniformity of specific gravity. Since at the present time the majority of wood involved in processing is bought and sold on a volume basis, the volume distribution is probably more appropriate for the calculation of uniformity of specific gravity. That is, the volume of wood above and below some desired level, e.g., the median specific gravity, is more meaningful than the weight or mass of cell-wall substance above and below some base level, e.g., the mean specific gravity. If a volume distribution is used, it is necessary then to use a median specific gravity value as the reference point.

A new measure of uniformity of specific gravity, which has been termed the *uniformity factor,* is proposed. It is a measure of the *volume variation* of specific gravity within an increment of wood or, in other words, the deviation with regard to wood volume from a reference *median* specific gravity. The reference point can, and perhaps should, be changed depending upon the nature of the comparisons to be made. For example, if one is analyzing within-tree variations, a breast height median specific gravity value may be appropriate. On the other hand, in comparing different trees of the same species, either the species median specific gravity or a median value representative of what one hopes the forest will have in the future may be suitable.

One should note that the suggested use of a volume distribution does not mean that the mass distribution of the more readily available mean specific gravity cannot be utilized. There are undoubtedly certain applications where this calculational procedure may be more appropriate than the volume basis. All of the following calculations of the uniformity factor could be made using the mass distribution with the mean specific gravity as the reference base if desired.

TABLE 2. *Example data illustrating the calculation of uniformity factor using twenty 0.05 specific gravity classes for a specimen with a median specific gravity of 0.347*

Increment (i)	Cumulative % Volume	Specific Gravity at upper Limit of Volume Class (S_i)	Uniformity Increment $[S_i - S_{median}]^2$
1	5	0.215	0.0174
2	10	0.230	0.0137
3	15	0.245	0.0104
4	20	0.257	0.0081
5	25	0.268	0.0063
6	30	0.278	0.0047
7	35	0.289	0.0034
8	40	0.300	0.0022
9	45	0.323	0.0006
10	50	0.347	0
11	55	0.388	0.0017
12	60	0.425	0.0062
13	65	0.462	0.0132
14	70	0.502	0.0239
15	75	0.541	0.0377
16	80	0.585	0.0568
17	85	0.642	0.0867
18	90	0.697	0.1226
19	95	0.768	0.1772
20	100	0.900	0.3058

Total Uniformity Increment = 0.899

A PROPOSED UNIFORMITY CALCULATION—THE UNIFORMITY FACTOR

The uniformity factor is thus calculated using the volume distribution. Example data to illustrate the uniformity factor calculational procedures are given in Table 2 for a specimen with a reference median specific gravity value of 0.347. The procedure begins with an examination of the cumulative percent volume versus specific gravity curve (Fig. 1). Here one determines the specific gravity values that correspond to the upper limit of each successive five percent cumulative volume class, or 20 values in total. One then calculates the uniformity increment for each of the 20 classes. The uniformity increment is the square of the difference between the specific gravity value at each upper volume class limit (S_i) and the reference specific gravity value, or for example, using the median value (S_{median}):

$$\text{Uniformity increment} = (S_i - S_{\text{median}})^2. \quad (1)$$

Squaring the difference, $S_i - S_{\text{median}}$, eliminates negative values.

The uniformity increments are summed to obtain the total uniformity increment:

$$\text{Total uniformity increment} = \sum_{i=1}^{20} (S_i - S_{\text{median}})^2. \quad (2)$$

The total uniformity increment is structurally similar to one statistical measure of dispersion, the variance. However, each uniformity increment is based upon a selected reference value.

The uniformity factor is then calculated as follows:

$$\text{Uniformity factor} = \frac{1}{\text{Total uniformity increment}} \times 200. \quad (3)$$

Taking the inverse of the total uniformity increment and using a multiplier factor of 200 are not necessary but were simply incorporated to make the uniformity factor values more practical to use and compare. For the increment core data of Table 2, a uniformity factor value of 222.5 is obtained using this procedure.

A variety of other reference base median specific gravity values could be used. Meyer (personal communication 1977) has suggested, for example, that the uniformity factor always be calculated using 0.5 as the reference value and 0.05 specific gravity units as a class interval, or represented symbolically as $U_{0.5/0.05}$. He has further suggested using this reference system with the following nomenclature $U^{ew/lw}_{0.5/0.05}$, $U^{vert}_{0.5/0.05}$, and $U^{bh/rad}_{0.5/0.05}$ for uniformity of early-latewood, vertical variation, and radial variation at breast height, respectively. This would standardize the calculation and permit direct comparison of all uniformity data obtained by different researchers. This approach, however, may not always give a satisfactory uniformity factor value, since only a single standard reference point is used without regard to the wood species, position in tree, etc.

EVALUATION OF THE UNIFORMITY FACTOR

The uniformity factor appears to satisfy the five requirements of a suitable specific gravity uniformity indicator. Since its calculation is based upon the count (volume) distribution by 0.05 specific gravity classes, it is possible to calculate the uniformity factor from the numerical densitometric output of any type of X-ray unit. The requirement of a base or reference point is met by the utilization of a selected median specific gravity and thus, comparisons between samples can be made. A higher uniformity factor value does, in fact, denote higher uniformity, or less variation in specific gravity. Finally, as will be shown shortly, this indicator can be used to express specific gravity variation whether it be within an annual ring or tree or between different trees. The latter statement is based upon a limited sample of two species known to differ in specific gravity uniformity.

To test the usefulness of the uniformity factor, 18 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and 30 white fir (*Abies concolor* Gord. and Glend.) trees were randomly selected on different sites at the University of California's Blodgett Forest Research Station in El Dorado County, California, located in the Central Sierra-Nevada Mountains. A single 12-mm increment core was extracted at breast height from each tree. The cores were equalized to 12% moisture content, X-rayed, and analyzed using the procedures of Echols (1973) and individual uniformity factors calculated. From these sample trees, breast height median specific gravity values (12% moisture content weight and volume basis) of 0.322 and 0.431 were determined for white fir and Douglas-fir, respectively.

Frequency distributions of the determined uniformity factors for the two species are given in Fig. 2. The average and standard deviations of the uniformity factor for white fir were 305.7 and 70.2, respectively. With the less uniform Douglas-fir, the uniformity factor shifted toward the lower uniformity end with an average and standard deviation of 227.4 and 71.6, respectively. These results show that considerable variation in breast height uniformity factor was obtainable for each of these species. It should, however, be pointed out that the uniformity factor might be unsuitable when considering variability within an extremely nonuniform species. Further refinement of the calculational procedure might be necessary because of skewing and tightening of the frequency distributions at the lower end of the range. Testing must be made on very nonuniform species to determine if this is indeed the case.

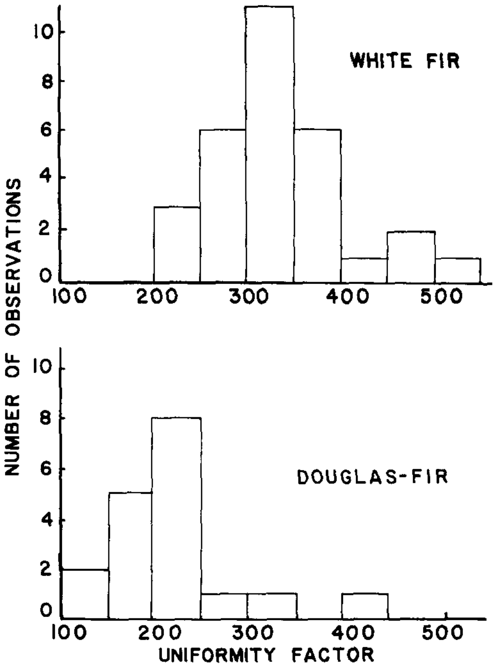

FIG. 2. Uniformity factor frequency distribution for two species of different uniformities.

Hypothetical data on within-tree variation have been developed to compare the uniformity factor and the previously used density distribution index. Densitometric data at four different heights in a tree are given in Table 3. In all cases the total volume of material lies within three specific gravity classes, or within 0.15 specific gravity units. In calculating the density distribution index (Echols 1972a, 1973), the same value, 100, is obtained at all heights. It is obvious, however, that the actual uniformity of specific gravity should vary between heights since there are large differences in specific gravity distributions

TABLE 3. *Comparison of uniformity factor and density distribution index using hypothetical data on within-tree variations (using a breast height median specific gravity value of 0.475 as the reference point for uniformity factor calculation)*

Specific Gravity Class	Percentage of Total Volume at a Tree Height of			
	48 ft	32 ft	16 ft	Breast Height
0.55-0.60	0	0	0	0
0.50-0.55	0	0	0	25
0.45-0.50	0	0	25	50
0.40-0.45	0	25	50	25
0.35-0.40	25	50	25	0
0.30-0.35	50	25	0	0
0.25-0.30	25	0	0	0
0.20-0.25	0	0	0	0
Median Specific Gravity	0.325	0.375	0.425	0.475
Density Distribution Index	100	100	100	100
Uniformity Factor	438	933	2783	6808

and that this variation cannot be expressed by the density distribution index. With this index the median specific gravity value at each height is used as the reference base. However, in using the uniformity factor only one reference value, the breast height median specific gravity (0.475), is selected, and all specific gravity variations within the tree can be compared to this base value. The resulting uniformity factors range from 438 to 6808 at heights of 48 ft to breast height, respectively. A total tree uniformity factor might then be obtained by weighting the individual values at each height by their corresponding volume in the tree.

The above results indicate that the uniformity factor can be used to examine both within- and between-tree variations in uniformity of specific gravity. In appraising its use, however, one should ask—what do differences in this value signify in a real world situation, or in other words, what is an acceptable or unacceptable uniformity factor value? This question it would appear can only be answered empirically through experimentation where variations in specific gravity uniformity are directly related to processing and/or end use performance.

One might also ask—what is the uniformity factor value for a perfectly uniform specimen? If all of the volume were within any single 0.05 specific gravity class and if the median specific gravity reference point was set as the midpoint specific gravity value of this class, the calculated uniformity factor value would be approximately 50,000 (47,790 to be exact). This then is the upper limit while the lower limit is zero.

One might additionally point out that the proposed approach cannot explain everything about the total nature of the measured variation when using only one reference point. For example, for a core taken at breast height, does lack of uniformity result from simple within annual ring variation or from between-ring variation occurring along the core? This can be resolved, however, by separately determining within-ring and between-ring uniformity values.

It seems difficult to imagine that a single uniformity expression can ever be found that will express all of the forms and types of variation that occur within a biological material such as wood. It would appear that the uniformity factor with appropriate selection of the reference base permits many desired comparisons to be made. It is hoped that its proposal will lead to other research and approaches so that some standardized expression for this important property of wood will be developed, accepted, and used by wood quality researchers throughout the world.

SUMMARY AND CONCLUSIONS

1. Existing indicators of specific gravity uniformity are shown to not completely satisfy all of the requirements believed necessary for a suitable uniformity indicator.
2. The wood substance within a given increment of wood can be analyzed in light of its mass or volume distributions.

3. Using the volume distribution of material, a new indicator of uniformity of specific gravity, designated the uniformity factor, has been proposed.
4. This indicator is defined as a measure of the volume distribution of specific gravity within an increment of wood, or the deviation of wood volume from a reference or base median specific gravity.
5. A comparison of uniformity factor data on Douglas-fir and white fir shows that the indicator expresses considerable variation in species of different uniformities.

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