Process Control and Grading in Primary Wood Processing

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Abstract

Round timber and wood products are measured, sorted, and graded at different stages in the wood-value chain starting already at the stem level in the forest. This chapter gives an overview of grading methodologies and techniques for the measurement and grading of round timber, sawn timber, veneer, and wood-panel products. The section concerning round timber focuses on the grading and sorting of logs for sawmill and veneer production. For sawn timber, visual and strength grading are discussed,

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for both the European and the North American markets. Techniques for measurement and process control in the wood-panel industry are finally discussed, where the different industrial methods used today are in focus rather than the specific grading rules used in the industry. The technologies presented have a broader application outside the field of the wood-panel industry, and can be of interest for the measurement of wood composites in general.

Keywords

Grading methodologies · Grading techniques · Log scaling · Log measurement · Round timber grading · Measurement of round timber · Veneer grading · Quality control · Wood-based panels

20.1 Forest Assortments

The raw material available and the needs of the market are the determining factors in the choice of processing system for the refining of trees to forest products, when the concept of "raw material" includes a number of factors such as tree species or species mix, and the range of dimensions of the round timber (sometimes also called roundwood) from the forest. The maximum and minimum diameters and the dimensional distribution are necessary statistical information together with details of available quantities. It is also important to know whether the supply can be maintained evenly throughout the year or only at certain periods because of, e.g., climatic hindrances such as snow or rain. The means of transport may affect the supply at different times of the year and also the condition of the round timber; grit and stones, for example, may cause considerable trouble during processing. The workability of the round timber is important and aspects to be considered include, for example, the rate of wear on tools, the tendency to split, and the presence of internal stresses, which are released when the timber is sawn and which deform the sawn timber. The quality of the round timber must, of course, also be known to make it possible to assess for what it can best be used.

Within the framework of the raw material situation, the types of product that can be manufactured from the available forest raw material are very diverse, but the forest materials for industrial use can be divided into six main groups: round timber for industrial products, for sawing, veneer production, wood-composite production, paper-pulp production, and energy conversion, resulting in different intermediate products for further processing to a variety of end products (Fig. 20.1).

Round timber may vary considerably in appearance and shape. Some common features can however be discerned, such as the fact that the cross-section reveals circles or ellipses related to the natural growth of the tree and its expanding diameter. In addition to species-specific variations in cross-section and features such as knots, injuries and buttresses can create irregularities that cause the shape to become more or less irregular and to deviate considerably from a circular shape. The longitudinal shape of the tree also varies considerably. Long-, spiral-, and butt-crooks are examples of this. Another factor related to the natural growth of a tree is that the diameter of the cross-section decreases with height, i.e., trees taper from the root toward the top.

Logging embraces all the work associated with felling. In some cases, this includes debarking in the forest, adjusting the trees to suit specific purposes, and all the means necessary for hauling and transport. When trees are cut into length of about 2–3 or more, the sections are generally referred to as logs. By contrast, shorter pieces are called pit props, bolts or sticks. The process of measuring volumes of individual logs is termed scaling. An important part of logging is grading, i.e., the cross-cutting of the tree to different assortments (grades), which may be done in the forest, at the mill, or in a combination of both. The purpose of the cross-cutting is to gain as high a value as possible from the tree. The butt-log of a tree ripe for felling (matured tree), i.e., the log from the stem's root end commonly used as a sawlog, usually accounts for more than half the value of the tree, and it has historically been the part of the tree that is financially the most important for the forest owner. The adjusting of trees into sawlog lengths is thus a very important matter, since not only can a large amount of wood be lost by injudicious adjustment, but a further loss can occur if the more valuable dimensions are not taken into consideration. Modified tree length logs, i.e., those with the maximum butt diameter, minimum top diameter, and minimum length specifications, are commonly scanned and cut to shorter lengths at a mill in order to maximize the yield.

The price of a batch of round timber is based on an impartial, uniform, and correct manner of measuring (scaling) the species, the amount (volume or weight) of wood and the nature of the round timber. Scaling of timber should be carried out by trained and certified timber-scaling personnel, in some cases supervised by a professional forester who is also trained and certified in timber measurement. In some countries, e.g., Sweden, the scaling is performed by a representative of *The Measurement Society*, which is an impartial organization owned by sellers and buyers of round timber for sawing, pulpwood, and by-products from the industry. The scaling rules are decided by the timber-scaling committee, which has members from different stakeholders in the raw-material market.

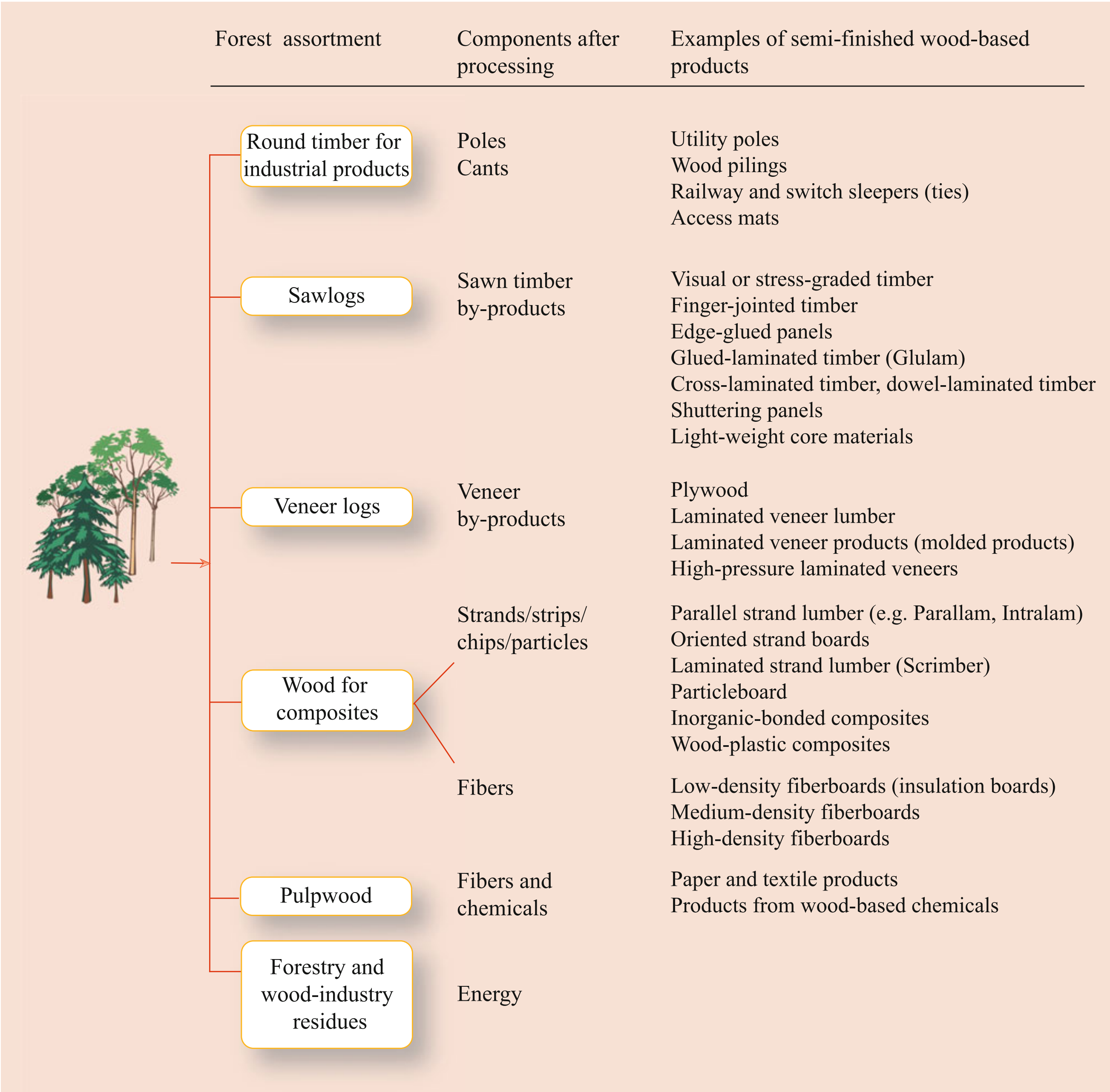

Fig. 20.1 The industrial use of the forest resource. Depending on species, dimensions, and categories in the use after refinement, the forest raw materials after harvesting are sorted into different classes according to their industrial use, i.e. tound timber for industrial products sawlogs, veneer logs, wood for composites, pulpwood, and residues for energy conversion, modified after [1]. Useful acronyms for EGP – edge-glued panels, GLT – glued-laminated timber, CLT – cross-laminated timber, DLT - dowel-laminated timber, SP – shuttering panels, LVL – laminated veneer lumber, LVP – laminated veneer products, HPLV – high-pressure laminated veneers, PSL – parallel strand lumber, OSB – oriented strand boards, LSL – laminated strand lumber, WPC – wood-plastic composites, and LDF/MDF/HDF – low-, medium-, and high-density fiberboards

The scaling of saw logs is performed as the first step in the sawmill process. Log diameter and length are automatically measured by optical scanners or by X-ray equipment. The scaler employed by the Measurement Society then judges the species, quality, and, if necessary, the type of bark and the amount of missing bark. The scaler can also be responsible for delivering all measurement data to a central authority that calculates volume, value, and some statistical information for each consignment. In principle, each single log shall be scaled, but for larger consignments, it is possible to assess the volume of a truck load from the scaling of a sample of logs from a small fraction of the consignment, or just a measure for the whole truck load. This speeds up the scaling process. Higher production facilities purchase logs based on solely minimum specifications and weight, as there is not time to scale every log as it enters the log yard.

A detailed description of the requirements set on the different forest assortments is beyond the scope of this chapter, and here, as a background to the different grading technologies presented, some general and frequently used characteristics of the main forest assortments will be described. For a deeper understanding of the forest's various assortments, reference is made to national regulations and to definitions given in, e.g., the European standard EN 844 [2].

20.1.1 Round Timber for Industrial Products

Round timber for industrial products such as poles, railway sleepers, and wood pilings for piers, wharves, and other waterfront structures, for bridges, or for construction foundations is about the single highest value product from the forest, and millions of cubic meters of mature and high grade trees are used in the global production of such products each year. Common products are utility poles for the transfer of electrical power or communications signals, and railways sleepers.

A railway sleeper is a rectangular support for the rails in railroad tracks, generally laid perpendicular to the rails for the transfer of load to the track ballast and subgrade. It holds the rails upright and keeps them spaced to the correct gauge. Historically, wooden sleepers were used, but today they are also made of concrete, steel, and recycled plastic. A variety of softwood and hardwoods timbers is used. European beech, jarrah, karr-i, oak are commonly used hardwoods, and Douglas fir and Scots pine are commonly used softwoods. Softwood is creosote treated, which is the most common preservative for railway sleepers but nontoxic preservatives are now being used, such as copper azole or micronized copper. A boron-based wood preservation technology is now being used by major US railroads in a dual treatment process in order to extend the life of wood ties in wet areas.

Another commercially available laminated industrial wood product is construction mats from low-value sweetgum and other hardwood species [3]. Historically, construction, crane, and dragline mats were manufactured from solid oak timber, even if end-of-life wooden railways sleepers are also commonly being used.

20.1.2 Sawlogs

Sawlogs are round timber used for the manufacture of sawn timber, i.e., in general a sawn piece of wood with a right-angled parallelepiped shape, which may subsequently be dried and graded for a specific use. Within the framework of the raw-material situation, sawmill location, ownership, etc., of the sawmills, and particularly the large softwood exporting mills, the aim is to gain the highest possible volume yield of best-quality sawn timber; High-quality timber is that which has good market demand and a high price, and by-products such as bark, chips, and sawdust having a much lower price than the sawn timber in general. The aim is thus to maximize the value of the sawmill's total production. The segregation of individual pieces of sawn timber, i.e., grading, for a customer gives the final assessment of how well the selection of sawlogs corresponds to the sawmill's strategy to achieve the highest possible value yield.

The principles for commercial grading differ between softwood and hardwood, and between regions. Softwood, whether from Russia, the Baltic countries, Central Europe, Asia, South or North America, is normally used for construction purposes, whereas hardwoods are used for their aesthetic properties. The value of the log can thus differ considerably depending on the final use of the wood.

The value of a log depends on, e.g., its geometric properties. A large-diameter sawlog, for example, typically yields more sawn timber as a proportion of the log volume than a smaller sawlog, and a straight log more than a crooked one. A good description of its geometric properties is essential in order to optimally evaluate and saw the log. The biological quality is also of great significance.

20.1.3 Veneer Logs

Veneer logs are round timber used for the manufacture of veneer, i.e., a thin layer of wood cut to a particular thickness of normally a few millimeters, that is used in two major ways: firstly, for engineered wood products such as plywood or laminates and secondly for decorative surface veneers, the latter often having a high value and a prominent or unusual appearance. This means that veneers can be divided into two categories: decorative and structural veneers [4]. The use of veneers has a long history and for thousands of years veneers were prepared by hand. Since the early nineteenth century, veneers have generally been produced industrially by three methods: sawing, slicing, or rotary cutting. The way in which the log is used in veneer production is, of course, much more important for decorative than for structural veneers. Some of the general quality requirements for decorative veneers are: butt logs (typically but not always), freshly cut, a round and straight log shape, straight-grained if not typically curly grain is looked for, free of knots, bark distortions, decay, seams, worm, holes, and bird peck; centered heartwood, with a uniform color, uniformly spaced growth rings, and free of metal contamination. The quality requirements for structural veneer logs are not as strict.

Veneer logs are in general the finest and rarest in the forest and a large fraction of a quality stand's round timber value is derived from this small fraction of trees. A high quality timber stand has perhaps 20% of red oak and 10% of white oak trees of potential veneer quality. A red oak veneer log may be worth three times as much as a sawlog of the same species, and a white oak veneer log can be five times as valuable and a cherry veneer log can be worth eight times as much as a sawlog.

20.1.4 Wood for Composites

Trees or parts of trees that are not suitable for use in the sawmill, in veneer processing or as pulpwood, have, if used for industrial purposes, two main uses: the manufacture of wood-based composites and energy conversion. These processes also use the by-products from the sawmill and veneer processes or residues from other wood-working industries, and in some cases also agricultural waste. The quality requirements for these materials are in general similar and very low.

The board industry produces a variety of wood-based panel products (oriented strand boards, flake boards, particleboards, hardboards, insulation boards, low-, medium-, and high-density fiberboards, cement-bonded boards, etc.) based on comminuted wood in different sizes from long and thin flakes (veneer flakes) to fiber bundles that are commonly bonded together by an adhesive or by an integral interfelting of fibers and in some cases by a ligneous bond. Other materials may be added to improve certain board properties. Wood plastic composites (WPCs) are a rather new building material on the market, based on a thermoplastic matrix and a wood component. The matrix is usually recycled polyethylene or polypropylene, and the wood is sawdust or shavings from the wood industry [5].

20.1.5 Pulpwood

Pulpwood is round timber used for the manufacture of paperpulp, i.e., a pulp for use in paper and boxboard production, and also for other products such as textiles.

The forest raw materials for use in the paper-pulp process, for the production of wood composites, or for energy conversion have similar characteristics and the competition for the raw material between these industries is very noticeable [6]. The solvency of the industries, i.e., the paper-pulp and wood composite market prices, and the energy price largely control the currents of this raw material.

A distinct difference in quality for pulpwood, composites, and energy conversion is that the raw material for paper-pulp production should in general be in the green state, i.e., never dried below fiber saturation, which means that chips from the sawmill's primary breakdown stage are used for paper-pulp production.

20.1.6 Forestry and Wood-industry Residues for Energy Conversion

Forestry and wood-industry residues for energy conversion are a broad range of materials for use in electricity production, for heating industrial facilities, or production processes, e.g., for heating kilns for sawn-timber drying, or for nonindustrial use. The quality requirements on the round timber or other grades for energy conversion are in general very low, and the energy content is the main quality target besides the requirement that the material should not be too contaminated with gravel, sand, or toxic compounds (see also ▶ Chap. 32).

20.2 Log Scaling and Grading Technologies

The first timber business was probably based on a simple agreement regarding the number of trees or logs, but this soon developed into a more accurate determination of the volume of the round timber by measuring each log's diameter and length. From the 1850s to the 1950s, this was largely a manual and labor-intensive process that began with harvesting in the winter, scaling and marking, floating transport on rivers or otherwise to the industry in the spring, and, in the case of floating transport, separating the round timber between buyers before water storage, sorting according to species and dimension and further processing. The sale type, i.e., as standing forest (Standing), as round timber beside a road in the forest (Roadside) or as round timber delivered to the industry (Delivered), also influenced the method of measurement, particularly when roadside or delivered material was sold as a product from more than one stand rather than as round timber from a single stand. After the 1950s, the scaling stage was increasingly moved to the industry and became mechanized, and this opened the way for an automatized scaling and sorting process. From the 1960s to the end of the 1980s, sawmills started to apply automated log sorting, rotary ring-barkers, chipper canters, automated edgers, and sorting equipment. Later, they focused on the improvement and sophistication of existing systems, and at least partly on the development of computer technology. Few real innovations were introduced into the industry before the X-ray LogScanner for the detection of internal log features was introduced in the mid-1990s, and in 2011 the first industrial high-speed computed tomography (CT Log) equipment was presented by the company Microtec. A CT Log was introduced as an industrial operation already in 2012 at the Arauco company to optimize the sorting between sawmill and plywood mill.

It is important to distinguish between the scaling of round timber for price setting ("remuneration measurement"), where the primary task is to calculate the correct value of a delivery, and scaling for sorting and production control. At small sawmills, the timber dimensions are in some cases measured manually with a calliper and measuring ribs, but at larger sawmills, log measurement is carried out in automatic scaling equipment, which registers the diameter and length of the log.

Based on the demands of different users, the round timber is divided into different assortments, each having specific requirements regarding dimensions, wood properties, permissible errors, damage, etc. Traditionally, round timber is divided into two main groups, sawlogs and pulpwood, but in recent years forest fuel has been added as a third group. Within the main group of sawlogs, a large number of special assortments exist, as shown in Fig. 20.1. Today, round timber is often sorted directly at the harvesting site into sawlogs, veneer logs, pulpwood, for wood composites or for energy conversion. Sawlogs and veneer logs are transported to a processing facility for further scaling and grading, while the other grades are scaled in a more simplified procedure in the forest or at the mill.

The main methods for measuring logs to determine their geometry include:

- Visual assessment, with an emphasis on the estimation of log dimensions and the presence of defects
- Manual measurement, using a tape or scale stick, and handheld callipers
- Mechanical callipers
- Weight scaling
- Optical scanning methods:
  - Parabolic light or laser scanners
  - Image displacement scanners
  - Photoelectric beam-breaking device
  - Camera-based technologies

In addition, methods for detecting and measuring internal characteristics of a log include:

- Acoustics-based (ultrasound, stress wave) technologies
- Radiography
- X-ray-based technologies

When scaling pulpwood, and round timber for wood composites or for energy conversion, the amount is assessed either as cubic meters under bark (m^3Sub) or by weight. The volume is estimated by "batch measurement" with perimeter weight assessment or log measurement by top-butt end measurement. Middle-length measurement is also allowed for standard lengths. An important feature of round timber measurement, particularly for pulpwood, was the development of sampling methods in parallel with the introduction of industrial measurement. For the volume determination by sampling, a representative sample of logs was taken from the pile for top-butt end measurement. For pulpwood, freshness and the permitted proportion of rotten damage wood are the main quality criteria applied.

For round timber other than pulpwood, the measurement methods have developed from a procedure where the logs were rolled to a single layer and measured manually to automated measurement stations with chain conveyers and advanced measurement equipment with a capacity of approximately 1000 logs per hour. In northern Europe, nearly all round timber is now scaled at a processing facility. When the logs are unloaded, they are either scaled directly or stored in trawls that are linked to the supplier in anticipation of scaling. The timber can also be delivered as whole stems to the scaling station and then optimized and cut with regard to the needs and prices of different dimensions and lengths. The most common methods and technologies for the scaling and grading of sawlogs and veneer logs are described in the following sections.

20.2.1 Log Grading and Sorting for Sawmilling and Veneer Production

Quality is a complex and multifaceted concept. Interpretations and definitions of the quality concept are many and have changed with time, but a frequently used definition of quality can now be found in ISO 9000 standards: "The quality of an organisation's products and services is determined by the ability to satisfy customers and the intended and unintended impacts on relevant interested parties. The quality of products and services includes not only their intended function and performance, but also their perceived value and benefit to the customer" [7].

In the forest products industry, the word "quality" is often used synonymously with "property, feature or grade."

Log Quality

Quality is not an exact feature of the tree itself, but has a meaning only in relation to the intended use of the tree. A tree may have a high quality for chemical or mechanical pulp production, but a low quality for sawn timber. This concept of quality has the same spirit as Joseph M. Juran's definition of "fitness of use," and is thus defined here as "degree of fitness for a particular usage or production." The quality concept is therefore used mainly to describe the biological properties of round timber, and the "grading rules" are tools to assess "quality" as the mutual understanding of the seller (forestry) and of the buyer (industry) in the sense of fitness for proper use.

There are many parameters that reduce the quality of a log, such as: knots, rot, compression wood, scar, spiral grain, crook, top breakage, etc. Of all these features, the knots are by far the most important.

The value of a log depends on the quality of the log. Therefore, logs are classified into different grades, either manually for value-assessment purposes or automatically for process-control purposes.

Timber measurement, whether it is carried out while the round timber is standing in the forest, at the forest roadside or at the processing facility, generally involves the quantification of large amounts of round timber, a bulky and irregular commodity. It can therefore be both difficult and impractical without the use of some form of sampling and a procedure for estimating the total quantity. Estimates may be computed in a number of ways and their accuracy depends on the choice of an appropriate stratification and sampling intensity. The precision of such estimates is greatly influenced by the combination of conventions and procedures used in the measurement of the samples.

A harvested and merchantable tree is bucked into shorter segments according to their log dimensions and quality features, and this leads to targeted wood process chains. These specifications may be large, medium, or small diameter logs for sawmilling (sawlogs), logs for veneer production, pulpwood for pulping processes and wood-based panel industries, and chip wood for fuel. The techniques used for measuring and grading high-value round timber for sawmilling and veneer production are described here (see also ▶ Chaps. 29 and ▶ 31 for round timber for pulping and energy conversion). When the measurement techniques for logs for sawn timber and logs for veneer are similar, only the term *log* is used.

The grading of logs is an attempt to predict the output of the breakdown operation, i.e., the quality of the center yield for sawlogs and the quality of the veneer for veneer logs. Properties in the stem, at the log surface, or in the cross-section surfaces of the log (i.e., log features) that affect the properties of the products can be used as indirect measures of product quality. Knowing the number, appearance, size, and position of these features, they can be introduced into a rule-based system to indicate the quality of the log.

Logs are assessed according to diameter and length, log shape, and specific features such as knottiness, etc. To assess the quality of logs and their value, different grading rules are applied in different countries and regions. Many different round timber measurements and volume calculations are in use in the world, and even in Europe. The log measurement principles are here exemplified following the European standards developed and published by CEN – European Committee for Standardization, such as:

EN 844:2019	Round and sawn timber – Terminology, is defining the terminology used in EU for round timber and sawn timber [2]
EN 1309-2:2006	Round and sawn timber – Method of measurement of dimensions. Part B: Round timber – Requirements for measurement and volume calculation rules [8]
EN 1310:1997	Round and sawn timber – Method of measurement of features [9]
EN 1311:1997	Round and sawn timber – Method of measurement of biological degradation [10]
EN 1315:2010	Dimensional classification of round timber [11]
EN 1927-1:2008	Qualitative classification of softwood round timber – Part A: Spruce and firs [12]
EN 1927-2:2008	Qualitative classification of softwood round timber – Part B: Pines [13]
EN 1927-3:2008	Qualitative classification of softwood round timber – Part C: Larches and Douglas firs [14]

Despite the existence of CEN standards, most round timber is still traded according to country-specific rules, because current timber trading rules are parts of the legal frameworks of specific countries, whereas a CEN standard is a voluntary technical specification, which has to be added to a sales contract.

The ability to measure a log has always been a central task in sawmilling and veneer production. The control and adjustment of the production process is today totally computerized and the measurement technology is essential for the ability to steer the processes. The tree or part of it may be measured, sorted, and graded several time at different places between the forest and the sawmill. Current harvesting technology provides rather accurate individual log data and the operator can add other information such as the general quality of the stand, soil, and other factors. The information acquired increases rapidly throughout the harvesting proceedings, and is used mostly for statistics and is in general not transferred and used in the subsequent measuring stage where other levels of accuracy and different types of information are needed. Individual log marking (e.g., by fingerprint technology based on individual log features, sensors, bar codes) at the harvesting site can be used in the further processing of the logs.

The tree or log is normally measured on three different occasions, with different purposes:

1. When the tree is bucked, to maximize the tree value and to be able to deliver requested dimensions and qualities
2. At the pre-sorting station at the sawmill or at the veneer production unit, to assess a value based on quality and volume, and to sort the logs into different classes/grades for production planning
3. Adjacent to the sawing or veneer production, to describe the log as accurately as possible, so that the value and volume yields of sawn timber or veneer leaving the production machines are maximized

The tree felling and bucking process, i.e., cutting a stem into logs, may take place manually, but it is more often done by a harvester, which is remotely connected to the log purchasing organization from which the operator receives information about the desired log grades and sizes, and where to send the bucking data related to the actual logs. The processor of a harvester includes equipment such as feeder rolls (tires), holding arms, limbing knifes, and a chain saw with conduits for color code paint spraying. The feeder roles include a rotary encoder for length measurement. Most systems for diameter measurement on harvesters are based on contact measurement where the diameter is estimated by measuring the position of the limbing knifes.

A value assessment normally involves estimating the total value of a large quantity of logs. To describe the logs, it is usually sufficient to measure the value-determining factors such as diameter and length (and quality/features), which determine the value of the logs. This is usually done at the pre-sorting station at the mill. It is important that the assessment is made uniformly and objectively, and this is the task of the scaling organization. Detailed information about individual logs is less important, but it is important that the combined measurements correctly describe the volume and value of the consignment. Certain requirements regarding accuracy and precision are therefore specified. There are also limits regarding log straightness and rules pertaining to limbing accuracy and preparation.

In production planning, the situation is different since the task here can, for instance, be how best to utilize the existing or prospective raw material. There may be several sawing-pattern alternatives to choose from for a given type of log (with given diameter intervals). And the planning should provide guidelines and limits for optimal production. The log description should correspond to the level of accuracy desired in the plan, and this varies depending on the finished product dimensions on which the sawmill focuses, and on what alternatives may be offered by the sawing line. It is also of interest to know the distributions of length, ovalness, crook, and quality of the logs, but the production planning still requires a certain "bulk handling" of the log data. An excessively detailed description of the raw material thus hardly provides better information than a more sweeping but correct description of the most essential log variables. Sometimes, it is also necessary to use as a starting-point the expected properties of the logs, which during the planning stage, may be stored in the forest or still be a standing crop.

A log that has been bucked in the forest often ends up in a different diameter class at the sawmill, and sometimes only 50% of the logs fall in the specified 10 mm diameter class at a sawmill. Thus, the logs delivered to the sawmill often fail to meet the desired specifications, perhaps because the measurement techniques used by the harvesters differ from those used by the mills, or because intermittent measuring errors can occur in the forest, e.g.:

- Harvester operators fail to ensure that the stem maintains contact with the limbing knifes during diameter measurement
- The limbing knifes cut into the bark
- Variations in bark thickness result in an incorrect bark allowance

From a technical point of view, the main problem with harvester measurement is the difficult environmental conditions where the machines operate. Besides feeder-roll slip and problems caused by stem swellings (bumps) and branches, errors may also due to accumulated snow and ice, and to the advancing and reversing of the stem, which may deform the whole stem. Mechanical and electrical protection of the components is also of vital importance.

Measurements are made at the actual time of sawing to describe the log as accurately as possible and to maximize the value and volume yield of sawn timber. The relevant dimension alternatives for each log are established by pre-sorting or by making a sawing-pattern estimate. It is assumed that certain predictions about log appearance and sawing will be accurate. Thus, sawing-pattern alternatives need to be corrected for deviations from the expected log shape, in order for the positioning to be done efficiently.

Automatic Log Grading
The variables used in classification have been developed for visual inspection and the capacity of the human brain, which means that only these features of the log such as knots and bumpiness have been taken into consideration.

The main task for the grader is to set a correct price for a supply of logs, which means that other aspects such as process control and production planning have a much lower priority in the grading operation. The increasing automation of the production, the need for better prediction of the output from a log, new measurement techniques, increasing computer capacity, etc., have opened up new possibilities for how to measure the characteristics of a log and how to perform the grading. Table 20.1 shows how some common log features are characterized by traditional visual inspection, and the corresponding wood metric features, which can be used in an automatized grading system.

The modulus of elasticity (MOE) of trees, stems and logs can be determined by nondestructive acoustic methods to improve sorting and matching with desired levels of sawn timber or veneer [16]. The tome-of-flight (TOF) of a sound wave or the resonance frequency of a stress wave through a standing tree or a log has been shown to be very effective in predicting the MOE and the amount of, e.g., machine-stress-graded sawn timber that can be sawn from it [17–20]. Hand-held acoustic assessment tools for measuring wood stiffness in sawlogs and standing trees have been developed using these technologies [21, 22]. To take advantage of the ability of the acoustic technology to test every tree or log, the acoustic unit can also be attached to the computer-controlled mechanized harvester heads [23]. Tools based on resonance frequency are better suited for measuring logs and sawn timber, as they rely on the reflection of sound waves from the cut end. TOF tools can be used for logs and sawn timber, but they are more commonly used on standing trees to measure the TOF between two transducers embedded a known distance apart in the stem [23].

True log quality depends not only on size and geometry but also on internal characteristics, which can only be assessed when a three-dimensional internal image of the log is available. Even this does not give the full picture of all the factors involved in the grading of logs, and especially not in automatic log-grade classification. Jäppinen [24] classified factors influencing automatic log grading into five groups (measuring technique, log features for the prediction of grade (variables), classification models, availability of logs, and final product quality requirements, as shown in Fig. 20.2.

20.2.2 External Log Geometry Measurements

The perfect unit of measurement would be one that is absolute, unambiguous, accurate, simple, and inexpensive. There are different methods for measuring and calculating the volume of a log [25]. In Sweden as an example, two methods are use parallel, i.e., the volume of round timber is specified as the *top-cylinder volume* ($m^3$to) or the *solid-wood volume* (m^3s), always with the bark excluded. In Finland, the log volume includes bark. In Central and Eastern Europe, the log volume is always based on mid-diameter measure (HUBER formula). The length and diameter of the log at the top end are used for the volume calculation when top-cylinder volume is considered. When the volume is expressed in m^3s, this is an estimate of the true log volume taking into account the taper of the log. The log volume is then calculated from the log diameter at half the log length (center measurement) or by measuring the diameter at the butt and top ends of the log. In practical scaling and in order to agree on a "reasonable" trade measure, many estimates have to be made and difficult measurements and marginal deviations must be ignored.

The use of weight as a measure for purchasing wood has been adopted since at least 1950s in the pulp and paper industry in lieu of linear measurement of stacked pulpwood, and also occur in the sawmill industry. The chief difference from pulpwood is that price adjustments must be made in weight scaling sawlogs to take care of the variations in log quality and size. Without such adjustments, crocked or defective logs, i.e., logs yielding less sawn timber per ton logs, could bring as much as larger logs. The true log volume can also be estimated by xylometer measurement where the Archimedes principle is applied. Xylometer measurement is mainly used for pulpwood (Fig. 20.3).

Length of a Log
The length of a log (log length) is the length in full units of an applied measurement rule. EN 1309-2 [8] requires to define the rules how the length should be measured. In case when no national, regional, or provincial rules exist, the length shall, according to EN1309-2, be expressed in meters rounded down to one decimal place, and if a nominal length is required the length shall be rounded down to the nearest nominal length. For a straight log or a log with a simple sweep, the shortest length shall be measured as the distance between two parallel planes, one at each end of the log, where the full cross-section is enclosed and perpendicular to the longitudinal axis of the log. Logs with a compound sweep shall be divided at theoretical crosscut points into straight portions or portions with a single sweep, and the lengths of the different portions shall be individually measured and then totaled. If an undercut or a butt trimming exists at the log end, the measure shall be from the middle of the undercut or from the butt trimming surface.

Table 20.1 Common log properties used in traditional visual grading (human perceived features), metrics for measurement by a technical system (wood metric features), and examples of measurement systems, based on [15]. CT - computed tomography, NMR - nuclear magnetic resonance

Property occurring in traditional log grading rules	Visually perceived features	Wood metric features	Measurement system
Log type			
At harvesting	Position in the tree	Length from the stump	Mechanical measurement Laser scanning – Handheld Laser scanning – Drown
	Bark type	Spatial variation, color, bark thickness	
	Shape	Taper	
	Branchiness Stiffness	Branch strength Longitudinal time-of-flight (TOF) of a sound wave	Acoustic measuring system
At the sawmill	Bark type	Spatial variation, color, bark thickness	Gray-scale or color scanning, radar
	Shape Stiffness	Density variations, taper, heartwood ratio, ovality, bow, crook, bumpiness Acoustic wave velocity (longitudinal wave signals)	Internal scanning, e.g., X-ray scanning, X-ray CT, NMR External scanning, e.g., 2D-3D profile scanners, true outer shape scanners Acoustic measuring system
Knot type			
Sound or dry knots	Shape and color of visible knots	Bumpiness, density variation, diameter of knot	Internal scanning: Log-scanner, X-ray CT scanner
Bark-ringed, rotten, or spike knots	Bark, color, shape, position	Density variation, grayscale and color variation	
Growth-ring width	Early/latewood pattern	Density, grayscale and color variation	Internal scanning, matrix- or line-scanning cameras
Decay	Color	Color Optical variations	Surface scanning Light absorption/reflectance, internal scanning (X-ray CT) Tracheid effect
	Position Acoustic effects	Density variation Density, stiffness	NIR Acoustic measuring system
Compression wood	Ovality of log cross-section, bow	Ovality, bow	Internal or external scanning
	Latewood ratio in growth rings	Density variation	Internal scanning: Log-scanner X-ray CT scanner
	Pattern in cross-section, color Optical effects	Color scanning Tracheid effect	Matrix- or line-scanning cameras Laser scanner
Shape	Crook, ovality	3D shape	Internal scanning, 2D-profile scanners, true outer-shape scanners
Color stain	Color	Color	Surface scanning
Cracks	Splitting the wood, shadows	Density variation, grayscale contrast	Internal scanning
Scar	Bark, shape	Shape, density	Internal scanning, true outer-shape scanners
Pitch wood **Pitch pockets**	Extractive content, color Pitch and pockets on sawn surfaces	Density, color or optical variations Shape and density variation	Internal or surface scanning Internal scanning, X-ray CT to some extent
Spiral and curly grain	Grain angle	Bumpiness, surface unevenness, density variation. Directional streaks in virtual radial surfaces	External or internal scanning, log-scanner X-ray CT scanner

Diameter of a Log

The EN1309-2 standard [8] recommends that the diameter be measured at the mid length of the log and used for the determination of the log volume, but other diameter measures are common. The only measurement method specified in the standard is the calliper measurement, and when using callipers the following procedure should be adopted:

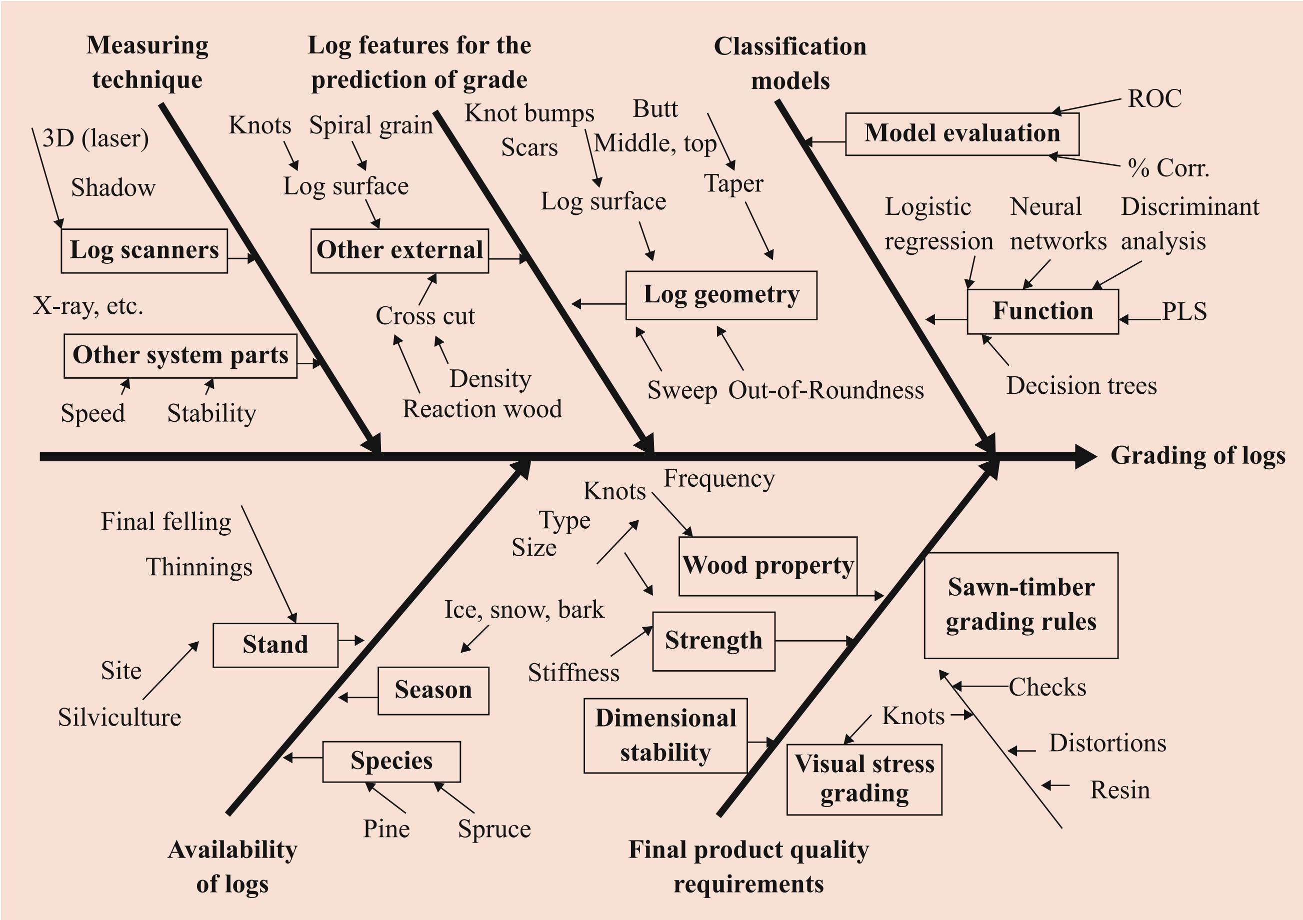

Fig. 20.2 The main factors involved in automatic log-grade classification illustrated as an Ishikawa graph, after [24]

Fig. 20.3 Xylometer measurement of pulpwood in Finland by weighing in the grip above and under the water

(a) For a log of diameter estimated as not exceeding 19 cm, measure once by positioning the callipers so that the diameter measured is the mean diameter, but if the round timber is considered to be oval, two diameter measurements perpendicular to each other should be taken

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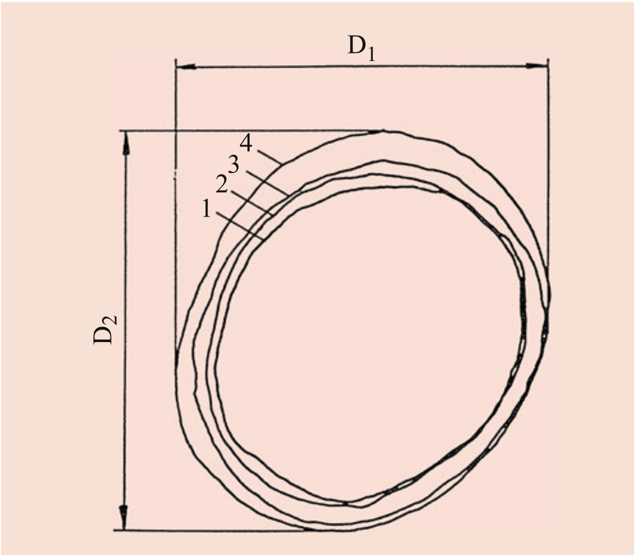

Fig. 20.4 Depending on the diameter of the log, the diameter of a log cross-section should be measured as one diameter or as a mean value of two mutually perpendicular measurements (D1 and D2). Example of how the outer shape of a log may vary along its length: 1 and 4 at the top- and butt-end of the log, 2 and 3 at 1500 mm and 3000 mm, respectively, from the top

(b) For a log of diameter estimated to be 20 cm or more, measure two diameters perpendicular to each other

Figure 20.4 shows how the shape and diameter can vary both in the cross-section and in the longitudinal direction of the log.

A correct diameter measurement is important for value assessment, planning, and control of the production. The diameter measure is in general more important in sawmill production than in veneer production, and the diameter is the most important parameter determining how each log should be sawn. Because of the irregular shape of a log, the presence of bark, etc., it is difficult to obtain sufficiently correct diameter measurements for use in the planning and optimization of the volume yield in the sawmill production. Several factors affect the result of a diameter measurement, such as:

- Measurement principle
- How the bark is measured (bark function and classification, missing bark on the log surface)
- Equipment errors
- The longitudinal position of the log at which the diameter is determined

The method adopted for measuring the diameter of a log has a great influence on the result. As shown in Fig. 20.4, an irregular stem cross-section may lead to several different diameters, and the result then depends on the number of measurement directions and on the measurement principle used. The principles for automated measurement of logs are:

- One random direction
- Average diameter
- Smallest average diameter (three or more directions)
- Smallest diameter

The principle that gives the most relevant measurement depends on the intended use of the diameter information. Since a measurement by, e.g., a calliper or a light-curtain scanner is often disturbed by bumps that increase the log cross-section at the actual measurement location, there is always a tendency to overestimate the diameter. This means that the "smallest average diameter" or "smallest diameter" is often the most relevant measurement. It is particularly difficult to obtain a relevant measure of the diameter when the smallest sub-bark diameter of a log with bark is estimated. In general, the more directions measured, the smaller is the diameter measurement.

When making a value assessment, it is important to eliminate systematic errors. If all the errors are random, they tend to neutralize each other and do not adversely affect a reasonably correct assessment for any large consignment, but when measurements are made for the individual sawing of the logs, it is not sufficient to exclude only systematic errors. Random errors must also be minimized, and the common ways to eliminate random errors are:

- To measure debarked logs
- To use several measurement directions
- To measure diameters at several longitudinal positions and select the smallest
- To maintain and calibrate the equipment regularly

The diameter measurement depends on whether the measurement is made including or excluding the bark, and on errors related to the measuring equipment and the conveyor. It is the sub-bark measurement that is required for a decision about sawing. If the measurement is made after debarking, as some sawmills are doing, this problem is eliminated. If measurements include bark, a deduction must be made. In the case of automatic measurement, this deduction is normally based on statistically derived functions providing a bark deduction depending on geographical zone, measured diameter, species and, in the case of e.g. pine, bark type.

The EN1309-2 standard [8] recommends the following methods to convert an over bark measure to a diameter under bark:

1. Reduce the measurement by twice the estimated thickness of the bark at the point of measurement. Where there are doubts about the thickness, determine this at the position at which the diameter is measured
2. Use a bark allowance stated in writing and agreed between buyer and seller
3. If agreement cannot be reached, use an appropriate bark allowance given in bark thickness tables or grading rules published in the supplying country

It is of course possible to measure over bark, if it is agreed between seller and buyer.

Accurate and local statistical data about bark thickness is important for deciding on a deduction for the bark thickness, but the variation in thickness is in general large and on-bark measurement of the diameter will always give a less accurate value than a sub-bark measurement. Standard deviations for different bark functions for Scots pine and Norway spruce are shown in Table 20.2, together with the range of variation.

The average standard deviation for bark thickness of Scots pine and Norway spruce is about 2.5 mm. Assuming that the bark thickness is normally distributed, 35% of logs thus have a diameter error greater than 2.5 mm because of the natural variation in bark thickness. The presence of abrasions, snow, and ice contributes to greater errors in individual logs. Since bark functions are estimated for specific geographical areas, there is also a risk of a systematic error when logs are taken from outside the region normally providing material for the sawmill.

Measurement equipment usually has an accuracy of ±1–2 mm, and this is the maximum divergence between the true and the measured diameter, assuming that the equipment is correctly calibrated and maintained. In automatic measuring, it is also important that the entire space where the log is placed is covered by the measuring device, if not, there is a risk that parts of the log will fall below the measurement area and thus give a diameter, which is too low. Uneven progress and vibrations in the equipment disturb the diameter measurement.

The dimension estimate for a given log is usually based on its smallest diameter and an average projection of its taper. If the diameter measurement is made at a fixed point in the length direction of the log, there is a risk of measuring over a knot, for instance. The smallest diameter is then not actually gauged, and the log is sorted into a too large a log class. When a manual assessment is being made, a common procedure is for the diameter to be measured 10 cm from the log end. If this spot falls on a knot, the diameters on each side of the knot are measured and the average is then considered to be the valid diameter of the log. When measuring for sawing, the best method is to measure the smallest diameter of the log and determine the taper. This is possible with, e.g., optic-electronic measuring frames. When value assessments are being made automatically, the smallest log diameter is recorded.

Ovalness of a Log (Out-of-Roundness)

The meaning of the term “ovalness” is less than clear in the measurement of logs. As a concept, ovalness can be interpreted rather freely, e.g., as an unevenly rounded, egg-shaped, elongated, round, or elliptical cross-sectional area of the log, as shown in Fig. 20.5. Of these different shapes, only *elliptical* is precisely defined.

In order to use these very noncircular shapes in estimations of the log volume, several circumferential measurement points are required if the estimate is to be used to regulate the sawing or veneer-cutting process. Judging from variations in log-positioning and quality projects in Sweden for Scots pine and Norway spruce, it is in most cases sufficient to measure peripherally of 3 cm. With this resolution, a relatively good description of irregularities such as buttresses and felling damage is obtained. Measuring at 3 cm intervals means

Table 20.2 Standard deviations (STD) for double-bark thickness for Scots pine and Norway spruce from Sweden

Specie	Type of bark	Range of double bark thickness (mm)	STD (mm)
Scots pine	Rough bark	12–20	3.3–5.5
	Transition bark	8–13	2.2–3.9
	Smooth bark	6–9	1.3–2.2
Norway spruce	All types of bark	12–16	2.2–3.2

Fig. 20.5 Example of different cross-sectional shapes of a log

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about 20 measurement points per cross-section on a log with a diameter of about 20 cm.

The description of a cross-section as an ellipse is a compromise between a sweeping description of a circular cross-section and a detailed description with one point for every 3 cm. For an elliptical description, it is sufficient to give the long and short axes and their rotational positions in relation to a fixed point, but it is not known whether or to what extent an elliptical description increases the possibility of optimizing the sawing, compared to describing the cross-section as round. Nowadays, it is possible to use data from real X-ray CT-scanned logs and these provide unique possibility to describe the log geometry, and the factor limiting the yield optimization of the sawing is the machine-equipment precision for the positioning of the log rather than the geometrical description of the log itself.

Taper of a Log

Log taper is defined as the gradual decrease in stem diameter toward the top, i.e., the taper indicates the height position in the stem and stem form. Most wood properties vary with height in a tree and can thus be estimated indirectly using taper or taper functions. In round timber for sawing, taper is usually measured in mm/m or cm/m, i.e., the diameter decrease per log length, and it is usually based on the relationship between the mid-point diameter and the top diameter. Taper values can be used to estimate the actual volume of the log, starting with the top-measured volume, and to simulate the appearance of the log for the sawing process.

There is no unified definition of taper. If a taper measurement is made to estimate the debarked log shape, sub-bark diameter measurements are used in order to avoid the influence of the varying bark thickness along the tree height. Otherwise there is a risk that the measurements will refer to different bark types. A Scots pine butt log, for example, may have transitional bark at the top and rough bark in the mid-section. In this case, measurements including the bark lead to an overestimation of the taper. In most models of the sawing process, logs have a projected taper, which is constant along their full length. They appear as truncated cones, and this is a simplification of reality. According to EN 1310:1997 [9] the taper is the difference between two diameters measured at each end (at least 5 cm from the ends, in the case of butt logs 1 meter from the butt end). In Germany, taper is calculated on diameter measurements every 50 cm from small-end to large-end, excluding 50 cm from both log ends, and 100 cm from butt end for butt logs to avoid measuring the butt flare (root-end swelling). In Austria, taper is calculated as the regression line of all diameters from mid-point diameter and small-end diameter.

The stem of a tree can roughly be divided into three parts: butt, middle, and top, as indicated in Fig. 20.6. Closest to the root, stems normally bulge or swell, which means that butt ends have a significant taper (poor stem shape) and sometimes also butt flare that must be removed before further processing. The size of the butt flare and the stem shape vary among species and among individual trees within a species. The mid-section of the stem normally displays only a slight taper and the top part of a tree stem normally tapers significantly.

More accurate taper models than the truncated cone model are based on three-splined logarithmic functions [26]. The first function describes the stem form and taper in the living crown from the top down to 60% of the tree height from ground, the second describes the form from 60% to the start of the butt flare, and the third describes the butt flare. The start of the butt flare and thus the higher taper is calculated to be at about 15% of the tree height for a mature tree with a form factor of 0.65–0.70.

The root-end swelling on butt logs (up to 10–15% of the original height of a tree) of especially pine species is one of the reasons why taper is normally measured in relation not to the butt diameter but to the mid-section diameter. Another factor to consider when describing taper is that "the diameter alters in leaps at the branch whorls, especially at living limbs." This is sometimes referred to as diameter "branch theft." It is difficult to describe in a model describing the sawing process but it should be considered when marking for cross-cutting.

Sweep – Crook of a Log

The ordinary terms for crookedness of logs for sawing are bow height or sweep, defined as the maximum perpendicular distance between a straight line through the end centers of a log, and the log mid-line, as shown in Fig. 20.7.

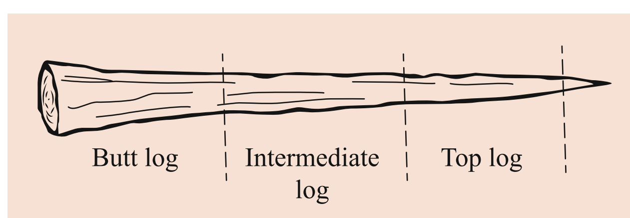

Fig. 20.6 General sketch of a stem showing butt, middle or intermediate, and top logs, and examples of estimated form functions

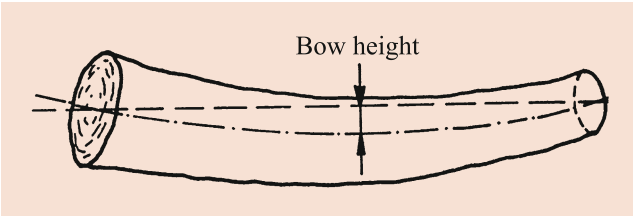

Fig. 20.7 Definition of bow height

EN 1310:1997 [9] defines only sweep, and in practice sweep is measured manually on the surface and not in the center-line as shown in EN 1310. Sweep is typically expressed as ratio between bow height and measurement length in mm/m as ratio between bow height and mid-diameter in percentage.

Different forms of sweep may indicate uneven crown development, the presence of double leaders, spike knots, or compression wood. Logs with sweep often contain compression wood [27]. The influence of sweep on distortion of the sawn timber is reduced by curve sawing, even though distortion problems due to compression wood remain.

Other definitions of crook are:

- Long crook, i.e., crook which is at least 1 meter long. An even crook encompassing a whole log is called an even long crook
- Spiral crook, i.e., crook on more than one plane
- Butt crook, i.e., crook appearing within 1/4 of the butt end of the log

The "bow height" is only a distance measurement and does not specify where the bow height is positioned. By measuring the bow height at one or more fixed points along the log, for example, at 0.5 × L, 0.25 × L, and 0.75 × L (where L is the log length), it is possible to construct a geometric image of the log, but the description is still limited to an even sweep. In order to measure variations in bow height, there must be some prediction as to how the log appears between the measurement points.

The term "bow radius" has the advantage of denoting shape independently of length, whereas bow height varies with log length even for the same log crook, as shown in Fig. 20.8. A disadvantage of using the term "bow radius" is that it can apply only to an even long crook.

When measurements are made automatically in several directions, it is possible to fix the mid-point for each cross-section and thereby obtain articulated crook shapes. Extreme mid-point measurements should be excluded since the log surface is more or less uneven and extreme results may arise from unilateral log unevenness. Another problem is fixing a

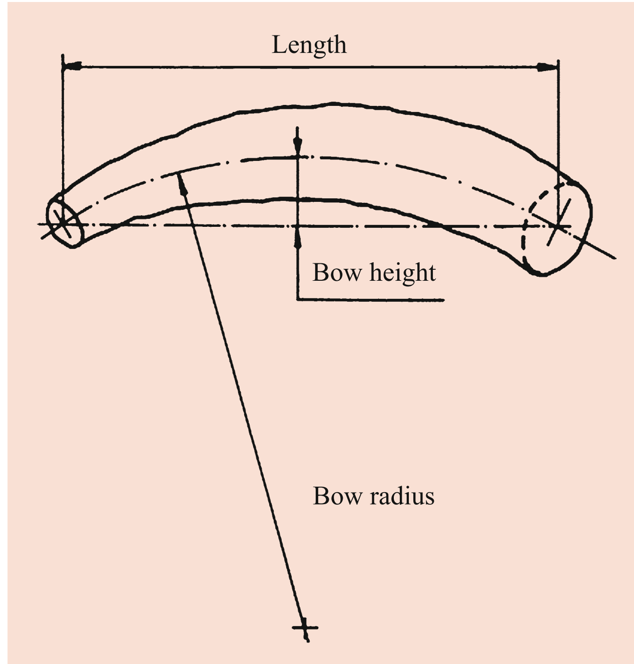

Fig. 20.8 Illustration of bow radius. Example: A log with a length of 4 m and a bow height of 2 cm has a bow radius of ca. 100 m

mid-point on a log butt end with a large root swell. Some equipment measures bow height only on half the log, toward the top end. In practical terms, only one bow height measurement is used, giving only a single-plane image of the crook.

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20.2.3 Internal Log Features

By tradition, irregularities that decrease the value of round timber or sawn timber are classed as defects. The identification of defects is important in the quality assessment and grading of logs, and it is generally done by measuring visible external indicators such as sweep and ovalness of the log, injuries from biological attack, and branch scars. Other defects such as red heartwood formation in beech can be more difficult to detect via external indicators [28].

Knots

One of the major defects in log grading is knots, divided into sound knots and dead knots, where a sound knot, in contrast to a dead knot, is intergrown with the surrounding wood. There is a correlation between knot size and type at the log surface and knot size and type in the sawn timber [26, 29, 30], and all direct measurements of knot size and type are of value in log grading or sorting [31, 32]. Other aspects of knots, as predicting or response variables in grading rules, include the size, frequency, relative positions, and type, such as sound, loose or rotted. When a branch loosens from the trunk, either as a natural effect or by pruning, further growth layers cover and occlude the remaining part of the branch, and in time the branch stub becomes less visible on the surface of the trunk. Subsequently, in the outer parts of the trunk, there is a zone of clear (knot-free) stem wood, although the stem wood is knotty closer to the pith. For log-grading purposes, it is important to be able to estimate the proportions of these different zones in the wood. The overgrown branch stubs are associated with changes in the bark texture called branch scar, and the scarred bark layers persist for many years of growth as a reminder of the buried defect.

Spiral Grain

Fiber orientation (grain angle) on the surface of logs indicate the fiber orientation in the sawn timber and this is in turn related to the twist and strength of the sawn timber [33].

Bark

Bark, bark type, and bark pattern reflect, among other things, tree age [15]. The local patterns in the bark can indicate enclosed knots or grain distortion around knots [34].

Density

Density is a measure of the amount of cell-wall material in the wood and is therefore dependent on the ratio of earlywood to latewood, and on the cell wall thickness and cell diameter [35]. For species for which it is possible to find a relation between growth-ring width or earlywood/latewood ratio and density, the growth-ring width at the log end (cross-section) can be used as a rough estimate of density and thus of the stiffness and strength.

Other Internal Features

A number of other log features are generally considered to be defects and undesirable; compression wood, rot, sap stain, resin pockets, etc. The occurrence of these properties in log ends may be used to predict the total amount in the log as, e.g. [36] has shown for resin pockets.

20.2.4 Equipment for Automatic Log Measurement

Various types of measurement equipment for round timber are now available at all large-scale sawmills and new technical procedures are constantly evolving. There is also a rapid development of the more or less automatic measurement of those wood properties that are important for pricing, production management, and refinement. The systems are developing at a rapid pace toward the complete digitalization of the wood processing chain. Prior to optical log scanning, log breakdown relied on "estimation made by the equipment operator." The operators were incredibly skilled, but the system performance nevertheless varied from operator to operator, and from day to day.

The first log-diameter scanners were front scanners with front-lit cameras or shadow scanners using incandescent lighting and spinning mirrors, both of which required considerable maintenance, especially the camera systems. A breakthrough in log scanning came with the "shadow-style scanning" making use of solid-state components (Opcon 200 from Dynamic control system) in 1974.

For many tree species, it has also been found possible to judge the inner structure through relations from the outer shape of the log. Examples of this are taper measurements for different parts of the log; crook measurements describing deviation from a perfect cone, deviations from a perfect circular cross-section, and outer-surface unevenness often expressed as bumpiness. These measurements are related to the position in the tree from which the log is taken, which is related to the internal structure. Other geometric measurements are associated with knot structure, reaction wood, injuries, and defects of various kinds.

The introduction of gamma-ray and X-ray technologies for round timber scaling has increased the ability to measure internal features and to base the scaling, sorting, and production control on these data.

The development of computer capacity, and of optical and X-ray systems has accelerated the evolution of wood measurement methodology. Digital image methods reduce the subjectivity in the assessment of surface and internal wood features and employ computer software for the analysis of digital images to obtain information about properties such as the number and width of the growth rings.

Nowadays, automatic log grading is usually performed by either optical or X-ray log scanners. The optical scanners measure outer shape parameters such as:

- Diameter on bark (if the log is not already barked)
- Taper
- Bumpiness

While X-ray scanners measure both external shape parameters and internal features such as:

- Diameter under bark
- Knot structure and knot whorl parameters
- Amount of heartwood/sapwood
- Average growth-ring width
- Density

Table 20.3 Sorting accuracy of different scanning techniques and bark variations

Technique	Number of measurement directions	Standard deviation (mm)	Correctly sorted logs when 10 mm class interval (%)
X-ray on bark	2-directions	3.9	69
Optical without bark	2-directions	3.6	71
	3-directions	2.8	78
	3D	0.8	93
Optical with errors due to variation in bark thickness	2-directions	4.7	63
	3-directions	4.2	67
	3D	3.2	74
Optical with errors due to variation in bark thickness + 10% missing bark	2-directions	4.9	62
	3-directions	4.5	65
	3D	3.6	71
Optical with errors due to variation in bark thickness + 10% missing bark	2–directions	5.1	60
	3–directions	4.7	63
	3D	4.0	68

The measured parameters derived by image processing techniques are merged together to sorting algorithms with the aid of advanced statistical methods. Other techniques for log grading such as acoustic-based technologies are also briefly described here:

Choice of Equipment for Automatic Log Scaling

The choice of automatic scaling equipment for round timber depends on factors such as the trade strategy for round timber, the capacity of the mill, the accuracy required in scaling for price setting and process control, and the information needed for digitalization of the production chain, not only within the mill, but also outside the business controlled by the mill, etc. In general, the accuracy required in measurement is greater for production control than for cost assessment.

Table 20.3 lists the sorting accuracy associated with different scanning techniques and bark variations, and shows how this can influence the choice of equipment. The table shows that bark variations and missing bark greatly affect the sorting accuracy. Even with a 3D-scanner, as much as 30% of the logs will be sorted into the wrong bin if the diameter is measured before debarking. The 2-directional X-ray log scanner is not affected by the bark, but it has only two measurement directions and performs at the same level as the 3D-scanner on bark. To obtain the best possible sorting diameter, the logs shall be measured after debarking with a 3D-scanner or under bark with an X-ray CT-scanner for logs.

Automatic log grading is installed in almost all large sawmills, and its use is increasing. The logs are normally graded into two classes and sorted into two different bins. The driving force for increasing the use of automatic log grading is the increase in market demands for special dimensions of specified grades.

The quality grading of logs is a difficult task, whether manual or automatic. The grading accuracy is not 100%. When logs are graded into three classes with an X-ray log scanner (2-direction measurements), the accuracy is typically about 85%, which is better than that achieved with optical scanners and much better than that achieved by manual-visual judgment.

Optical Scanning Technologies

The quality sorting of logs prior to sawing or veneer production requires that the product quality (sawn timber or veneer) is predicted from log measurements. Nowadays, most sawmills are using automatic scanning devices to measure the length and diameter of each log. Most common are optical devices making measurements in one, two, or three directions, but in recent decades optical 3D-scanners have been successfully introduced. The 3D-scanners measure the true shape of a cross-section every centimeter along the log, and also provide information about taper, bumpiness, and other variables that may affect the log quality, see e.g. [37–39]. Such predictions, based on partial least squares (PLS) modeling of 3D data in the quality software, have proven successful and have become widespread in, e.g., Sweden.

Automated optical log scanning involves creating a "shadow profile" in a number of directions of the log. In these systems, logs are passed through a scanning zone consisting of one or more emitter/receiver pairs, one pair per axis. The scanner makes diameter and offset measurements at each scan location along the length and, for optimization purposes, a geometric model is used to represent each cross-section. A circle is used in a uniaxial system, and an oval in a biaxial system. The more advanced devices, such as 3D-scanners, depict the log based on a large number of measurement points along the log surface generated by laser triangulation using laser light and different types of cameras.

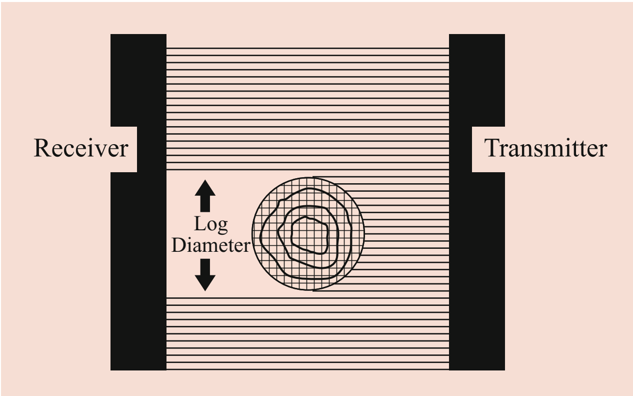

Fig. 20.9 Principle for shadow profile scanning of a log to determine its diameter

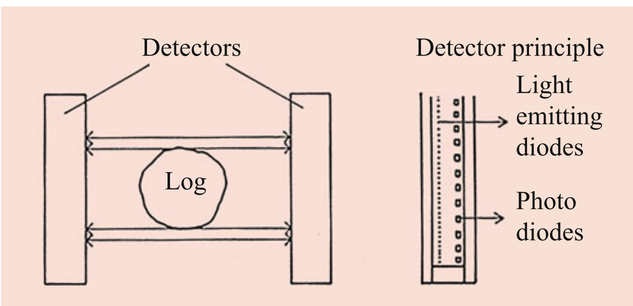

Fig. 20.10 An optical diode-based log scanner in one direction

Shadow profile scanning uses a row of photo-transmitters in line, typically at 2.5 mm intervals, on one side of the log with a corresponding row of photo-receivers on the opposite side of the log. Each transmitter is turned on and off (one at a time in rapid succession) while the opposite receiver is set to detect light. The numbers that do not detect light (shadowed) determine the diameter of the log, as shown in Fig. 20.9. Using solid state components, this scanning method proved to be rugged and reliable, easy to install, align and maintain, and easy to operate at a low cost for the performance.

Several types of equipment are available for the automatic measurement of the diameter of logs using different principles for the measurement:

Diode-based systems consist of two units (often called bars) between which the log passes as shown in Fig. 20.10. Each unit has a series of light emitting diodes (LEDs) and a series of photodiodes. Each LED emits, e.g., six infrared rays so that IR-rays go in both directions between the bars, crossing each other so that a raster of rays is formed in the measurement region.

The log diameter is calculated from the rays that the log obscures. Measurements are made 100 times/s, which means that, at a feed rate of 60 meters per minute, a measure of the diameter is obtained every 10 mm along the log length. Infrared radiation is used to make the system less sensitive to, e.g., reflection from the log surface, which is a problem when visible light is used. The system can have 1, 2, or 3 measurement directions.

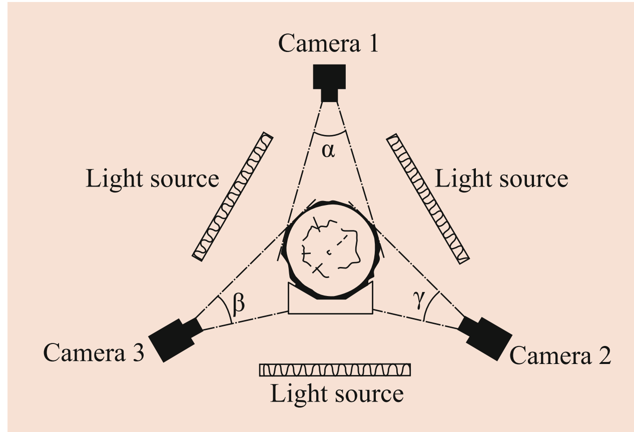

Fig. 20.11 The principle for log measurement in a line-scan camera systems

Line-scan camera technology consists of three line cameras mounted symmetrically at angles of 120° around the conveyor path (Fig. 20.11). Opposite each camera there is a light source, which gives a clear contour of the logs that pass in front of the camera. Each camera detects the angle (α, β, and γ) of the shadow projected by the log. From these angles and the distances between the cameras, the diameter and ovality of the log can be calculated.

A 1D measurement system is applicable for log rotation control and other targets where the 2D or 3D features are not required.

The 2D measurement system normally has a measurement frequency of 500–1000 measurements per second with an accuracy of 0.1 mm. The measurement range is typically 650 mm. A 2D system uses the measurement data to calculate the log volume, diameter, length, sweep, taper, and ovality, and is used in installations where 3D features are not necessarily required.

The new-generation 3D measurement system identifies the actual log form and, if accompanied by suitable software, enables the sorting to be based on the saw pattern instead of top diameter. Provided that the saw pattern can be controlled in real time, these systems can optimize the saw pattern for each individual log based on the log shape, volume, diameter, length, sweep, taper, and ovality. The software uses these data to compute the most profitable saw pattern for each log and controls the log sorting accordingly. In saw-pattern-based sorting, the system matches the log profile to the categories stored in the pattern library and directs the log into the selected slot.

A laser-based system consists of a laser, the beam from which meets a rotating three-sided prism. After reflection in the prism and in a parabolic mirror, the beam hits a receiver consisting of a fiber-optic grid as shown in Fig. 20.12. When the prism rotates, the beam sweeps over the parabolic mirror and is reflected as a parallel beam, which sweeps across the log in the measuring range, and the distances x, y, and z are recorded. At a feeding speed of 60 m/min for the log, the system measures the diameter approximately every 30 mm along the log. The principle can be used for multiple directions.

X-Ray Technologies

The goal of a sawmill or veneer producer is to produce as much valuable sawn timber and veneer as possible from a given amount of round timber. Although most distinguishing characteristics are visible only after sawing, each log is different. As a result, the decision as to how best to saw the log is driven mainly by the log's external appearance, and this significantly reduces the ability to exploit the round timber's true value. To know the real internal characteristics of a log before deciding how to saw it has remained but a dream for the sawmills. The economy of the sawing or veneer peeling process would be greatly improved if the internal properties of logs were known beforehand, since the output quality would be more predictable, resulting in a higher value yield and better utilization of the round timber.

Several techniques are available for the nondestructive investigation of wood, e.g., gamma radiation, X-rays, microwaves, ultrasound, nuclear magnetic resonance (NMR), vibrations, and stress waves. It has however been found that the best technologies for the nondestructive detection of internal log features are gamma rays and X-rays combined with semiconductor detectors, which are fast enough to image logs at the speed used in industrial production. Both these radiation types consist of high-energy photons able to penetrate a log and give an image of its interior. Gamma rays are continuously emitted by radioactive isotopes, whereas X-rays are derived from an electronic source that can be switched on and off on demand.

An early example of a gamma-ray system was the TINA scanner that was installed in a Swedish sawmill (the Färila sawmill) in 1978. This scanner uses two sources of gamma radiation, as shown in Fig. 20.13. The absorption of gamma radiation by the wood material is a measure of the density of the material. Because stem wood, branch wood, and bark have different green densities, it is possible from the absorption of the gamma rays to gain an idea of the geometric distribution of knots and branch whorls along the length of the log and also to obtain a measure of the diameter of the log under bark. TINA measures two intensity profiles every 2 cm along the length of the log. It provides a better assessment of the log diameter under bark than the optical measurement methods, because TINA is independent of bark type assessment, bark function insecurity, and bark aversion, snow, ice, etc.

Since the intensity of the radiation declines with time, frequent calibration of the equipment is necessary and the isotopes must be regularly replaced. It has thus been concluded that for both practical and safety reasons scanning by an electronic X-ray source is preferable. Today, several types of equipment based on X-ray technology are commercially available.

An X-ray scanner is a radiographic imaging system where a beam of high-energy photons is generated by an X-ray tube and sent through the object to be imaged. The radiation transmitted through the object is collected by a detector to give an image or radiograph showing a projection of the object. Detectors can be of different kinds, such as

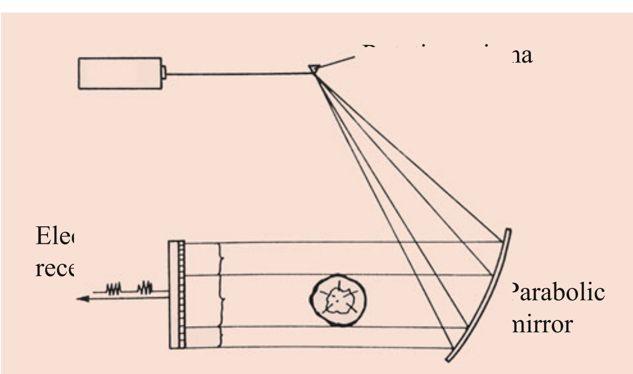

Fig. 20.12 The principle for log measurement in a laser-based system

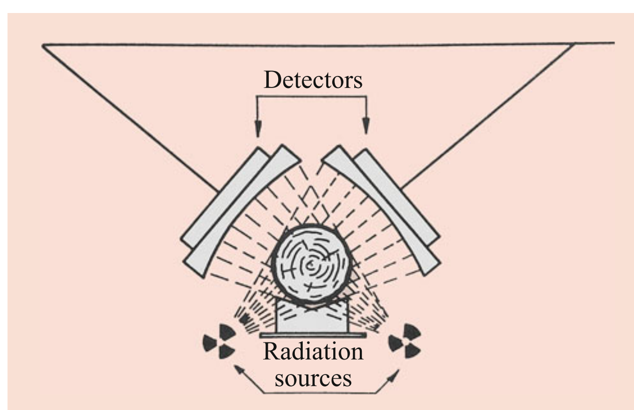

Fig. 20.13 Detection of internal log properties with gamma radiation according to the Swedish TINA system

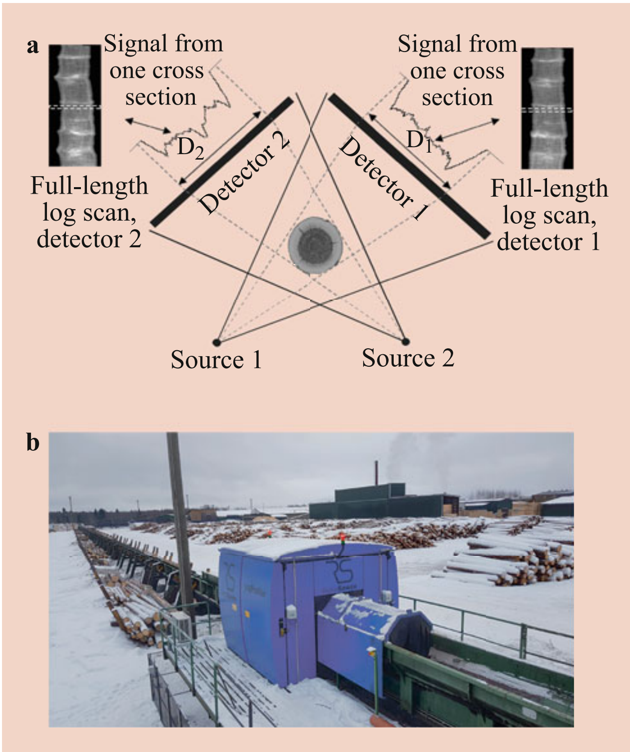

Fig. 20.14 The measurement principle for an X-ray log scanner with two measurement directions (**a**) and an industrial X-ray log scanner from RemaSawco AB company, Sweden (**b**)

photographic plates and X-ray photographic film, but they are nowadays mostly replaced by various digitizing devices like image plates or flat panel detectors.

Industrial X-ray scanners are typically based on discrete X-ray scanning in 1–4 directions while the log is being fed through the scanner. The most common device on the market is a two-directional X-ray scanner producing two mutually perpendicular radiographs while the log is being fed through the scanner, as shown in Fig. 20.14. These X-ray projections are collected one cross-section at a time using a detector array that measures the intensity of the X-ray radiation arriving at each detector (pixel). The industrial use for discrete X-ray scanning is mainly log sorting in sawmills; Fig. 20.14 shows a commercial system from RemaSawco AB company, Sweden.

The X-ray projection shows the internal attenuation distribution within the log and it is possible to distinguish internal features, such as heartwood border, knots, and other geometric features. With the help of discrete X-ray scanning in an industrial environment, it is possible to measure properties such as: diameter under bark, amounts of heartwood and sapwood, density, knot whorl parameters (volume and distance), average growth-ring width, log type (butt, middle, top), species (e.g., spruce, pine), spiral grain, and growth-ring width. Measuring the size and position of individual knots requires at least six directions [40, 41], but simulations have shown that the number of high quality boards can be increased even if information about knot-whorl asymmetries obtained by only a two-directional X-ray log scanner is used to find the best sawing position [42]. Detected log features can be used to predict strength and stiffness.

Industrial X-ray computed tomography (CT) log scanners are one of the major technological breakthroughs in recent years in the sawmill industry, and medical CT scanning has been the base for this development since the beginning of the 1990s. Industrial CT scanning of logs provides a much more detailed insight into each individual log than 3D outer shape log scanning and discrete X-ray scanning. The detailed knowledge of the interior of a log before it is sawn is used to optimize the value of the output from the sawing process, but the information can also be used to improve the digitalization of the wood value chain. Many studies have demonstrated that scanning to obtain the internal characteristics of each log before breakdown in order to optimize the process results in a significant increase in the value yield of the sawmill and veneer mill. It is, for example, possible to increase the value of sawn timber from Norway spruce logs by 5–20% when using log positioning optimization based on CT scanning [43, 44] rather than on a visual assessment. Similar improvements can be expected if rotation optimization is used to maximize timber strength, particularly in combination with log pre-grading.

X-ray CT was introduced in the medical field in the early 1970s to obtain a density profile through a body following the same principle as in other radiographic technologies. Benson-Cooper and co-workers, and Funt and Bryant (1987) [45, 46] were among the first to try medical CT imaging for the detection of internal log defects. They developed an automatic method for interpreting CT images to identify knots, rot, and cracks in a log, but they also met the same problem as others at that time – the scanning time was about 3 min for a single cross-section volume of the log, i.e., a ca. 1 cm long slice of the log (a disc). The technology was far from realistic for industrial conditions. Since the early 1990s, medical CT has been used in wood research at Luleå University of Technology (LTU) for wood material studies and for the development of discrete X-ray scanning and X-ray CT scanning for integrated use in the sawmill processes. In wood science, CT is used mostly for steady-state studies of internal anatomical features of the wood material, but at LTU it is also possible to study processes such as drying, thermal modification, water absorption, internal and external cracking, and material deformation in a temperature- and humidity-controlled environment.

In 2008, Microtec company developed the first prototype of a CT-scanner for log imaging, using a 180 kV, 10 mA X-ray source, rotating at 2.8 rev/s, and implementing spiral tomography with a small cone angle of 0.5 degrees. The FDK algorithm developed by Feldkamp, Davies, and Kress in the 1980s [47] was implemented for the tomographic inversion, but the maximum scanning speed was only 5 m/min, much less than desired.

In most modern industrial and medical CT scanners, the X-ray is emitted from the source in a cone-beam geometry, as opposed to the fan-beam geometry that was initially used. The challenge is the reconstruction of three-dimensional images from this cone-beam geometry, because the object is moving through the beam, and either the object or the combination of detector and X-ray tube is turning (spiral CT). Several solutions have been proposed for the reconstruction of cone-beam geometries [47–49], some of which are implemented in commercial medical spiral CT scanners. However, all reconstruction algorithms are approximate in their nature [50]. They are reliable for small cone angles, but wider cone angles result in cone beam artifacts, blurring the image [51]. Iterative algorithms can give high quality reconstructions also with wider angles but they are computationally too expensive for in-line industrial applications [52].

The breakthrough by Professor Katsevich [53, 54] was to find and implement an exact analytical reconstruction algorithm, widely known today as the Katsevich algorithm. The algorithm was subsequently further refined (2004) and solved not only the cone-beam artifact problem, but was also clearly better suited for use in situations where a fast movement or a high pitch in spiral CT scanners is necessary [51], an important prerequisite for a high-speed CT log scanner. Professor Katsevich therefore laid the theoretical foundation for a fast industrial spiral CT scanning method and paved the way for the application of CT scanners operating at full speed in sawmills. This was realized in 2012 when the first functional industrial CT log scanner was developed by Microtec with the contribution of researchers at LTU, at the Forest Research Institute in Baden-Württemberg and SP Technical Research Institute in Sweden. The CT log scanner from Microtec provides continuous, qualitative, and full 3D log reconstruction. The CT data is used to control and optimize the sawn timber output by sawing the logs in a way that increases the value (by approximately 10% in practice) of the sawn products. Under ideal conditions, a theoretical increase in value of more than 20% is possible [43, 44].

In industrial CT-scanning technology, a number of challenges regarding mechanical constraints, data transfer, safety regulations, image processing, and optimization algorithms have been addressed. The CT Log is easy to install in any sawmill, and it helps loggers to get the most out of each sawn tree. Currently, (autumn 2022) 15 sawmills or veneer plants in Europe and the Americas have a CT Log equipment from Microtec able to scan and optimize the processing of the logs (Fig. 20.15).

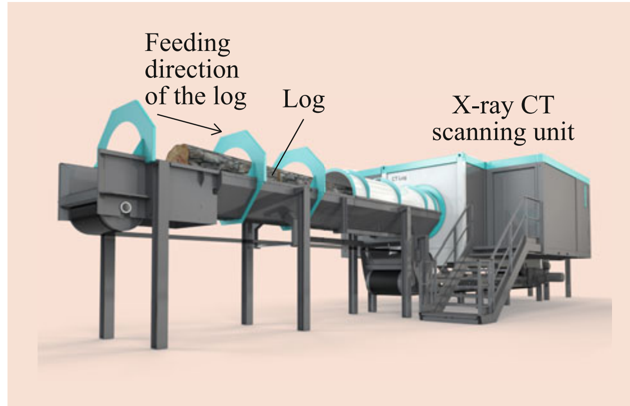

Fig. 20.15 Microtec CT Log scanner

The advances in X-ray source technologies and the exact cone-beam algorithm developed in recent years have led to an industrial CT scanner for the analysis of each log in a modern sawmill. This new technology and its successful implementation mark the start of a new era in nondestructive round-timber scanning. The pioneering research and its innovative implementation have opened new horizons, facilitating the further optimization of the sawing process for the timber industry. Compared to the product value derived from existing technologies in modern European sawmills, where 3D scanning of the shape of the log is still being used, an approximate increase of 10–15% in the value of the output can be expected. If all the advantages of having access to the internal features of the logs are realized, a value increase of the order of 20–25% is theoretically possible. For an average-sized sawmill, an investment in this kind of equipment should have a payback time of not much more than a year. There has until now (2022) been no success in real-time determination of wood moisture-content using X-ray computed tomography scanning with the so-called dual-energy CT [55]. On a laboratory-scale it is possible to measure the moisture content with the help of CT, but the estimation of the pixel-wise distribution of the moisture content in wood using X-ray computed tomography requires two scans of the same wood specimen at different moisture contents, one of which is known. Image-processing algorithms are also needed to compensate for the anisotropic distortion that wood undergoes as it dries.

20

High-speed scanners will also be pivotal in further integrating related scientific research into the sawing optimization process and will most certainly stimulate further research in the wood processing field.

Other Technologies
There are several techniques to detect or measure specific features of logs or sawn timber such the fiber orientation and knots, or for the traceability of trees or wood products. Some examples of such techniques are mentioned here.

The tracheid effect: The tracheid effect is the phenomenon that wood fibers scatter light in the fiber direction to a greater extent than across the fibers. This effect is mainly used in the scanning of boards, not so common for detection of features on logs where it is mainly used to detect the presence of bark.

Normal wood scatters light well in the longitudinal direction of the wood, but not in knots and other parts with deviating fiber orientation. This can be used to detect features such as knots and fiber deviation in the wood surface, and bark [56]. Compression wood with a steeper microfibril angle and helical cavities in the lumen also tends to scatter light less than normal wood, and this can be used to detect compression wood regions. Two different types of laser are used: a laser dot or an array of dots, and a line laser.

Figure 20.16 shows the principle of a set-up for measurement with a line laser. The wood specimen is scanned with a GPC-camera based on the MAPP2200 smart image sensor, while a 635 nm, 3 mW laser diode with line optics (manufactured by Lasiris Inc.) illuminates a thin line on the wood surface. The laser is aligned with the sensor so that the plane of light coincides with the camera's optical plane, and this means that regardless of the thickness of the wood (a log or sawn timber) the laser is always detected at the same position on the sensor array. The light scattered on both sides of the line is summed to decrease the integration time needed and to compensate for small misalignments of the laser line in relation to the sensor. Six lines on each side of the laser line are summed while four lines in the center are ignored because they are hit directly by the laser light.

This method produces an image where normal wood with straight fibers is displayed as light, since much light is scattered in the longitudinal direction. Wood with a deviant fiber orientation, knots, or wood with poor fiber properties such as compression wood scatters light badly in the length direction of the sawn timber and gives a darker image.

Log end-surface detection methods: Techniques and methods are under development for the measurement of annular ring patterns, felling splits, reaction wood, heartwood content, compression wood, wood degradation, pith position, etc., in the end surfaces of logs. Several methods are based on photography with subsequent image processing, NIR, IR, ultrasound, and other techniques being tested. Imaging end faces at sawmills is made difficult because it is not usually possible to treat the end faces in any way before acquisition [57]. The untreated end faces require methods for analysis that are robust to the rough surface that is the result of harvesting, storage, and transport of the logs from the forest to the sawmill. End faces are sometimes also partly covered with dirt or snow.

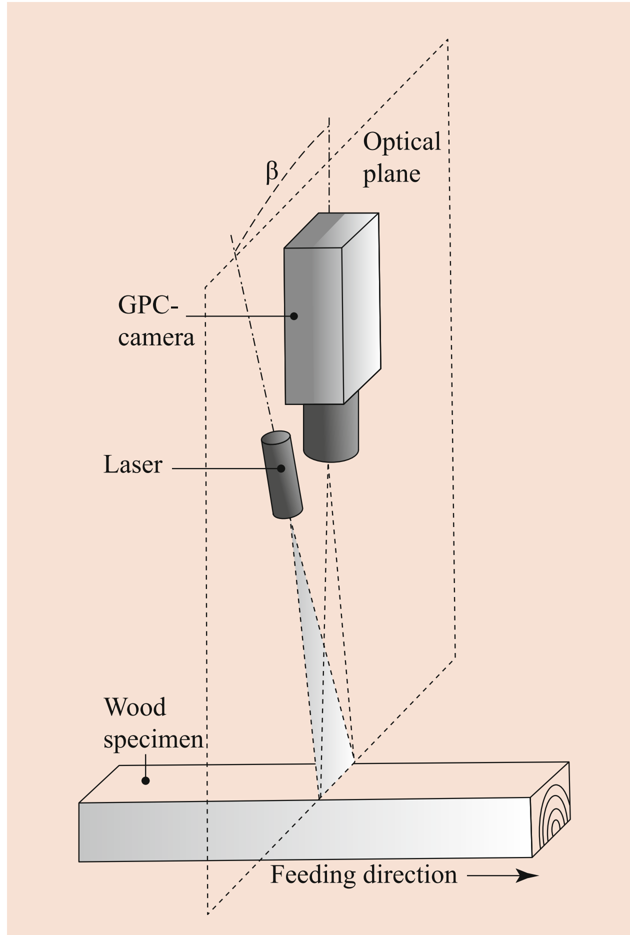

Fig. 20.16 Set-up of the tracheid scanning system. The laser is aligned with the camera in the same optical plane, but at an angle $\beta = 8°$ from the camera's optical axis

Wood fingerprint recognition: A "wood fingerprint" is a feature that can be used to keep track of an individual log or wood product through a production chain. Using high-resolution sensors, it is possible to map features of the wood material and to use this information to identify a specific log or a piece of sawn timber. One major advantage of traceability of wood products is the possibility for an immediate feedback in the event of an error, making it easier to localize the origin of the problem. Another requirement is to be able to connect information through the whole value chain and to adjust processing parameters to meet customer demands and optimize for value.

Human fingerprint systems rely on extracting certain details to identify individuals. Ridge endings, ridge bifurcations, and singular points are usual descriptors together with the coordinates and orientation of these descriptors. A similar technique can be applied to identify wood boards, where, for example, knots and the annual-ring pattern describe an individual board in the same way as the ridges on a finger. Fingerprint identification systems, whether for humans or for wood, usually need to address the following design steps [58]:

1. Image acquisition
2. Fingerprint representation
3. Feature extraction
4. Matching

To be able quickly to match against very large databases, great care must be taken when choosing representation. Identification must often be made in haste because of production speed. The "search space" for the identification of an individual log or wood product consists of all the scanned logs or wood products that are in the production chain and that are on their way to be recognized. This is therefore a so-called "closed-set" identification task, where the sought individual is known to be in the database.

A great advantage has emerged due to the possibility looking into the interior of a log with high resolution at a production speed of sawmills, i.e., computed tomography (CT) scanning. The sawing process can be done virtually and a fingerprint extracted for later recognition by a surface scanner. Chiorescu and Grönlund [59] tested a method to identify debarked logs between the log sorting station and the saw intake using a pair of identical 3D log scanners. Variables such as volume, length, taper, and bumpiness were used. Almost 90% of the logs could be recognized. Flodin and co-worker [60] investigated the possibility of tracing a log by comparing surface scanned images of sawn timber (the center yield) with the X-ray images of logs. The fingerprint was first extracted at the log sorting station using a unidimensional X-ray log scanner and later using a cross-fed surface scanning system for the sawn timber at the green grading station. More than 95% of the sawn timber could be matched to the log from which they had been sawn. Today image sensors are available in the sawmill process chain for sorting logs by quality, e.g., 3D shape, discrete X-ray, and X-ray CT scanners. Surface scanners are present within the green and dry sorting stations for sawn timber and a number of process feedback sensors can be utilized to track and control each individual piece of sawn timber in the process. The sensors have different outputs and show different properties depending on the sensor type. The problem that remains to be solved is to find appropriate fingerprint parameters and matching algorithms so that the wood products can be recognized at every point in the process.

20.3 Veneer-Grading Technologies

20.3.1 Veneer and Its Use

A veneer is a relatively thin sheet of wood used as a surface covering on core stock or other material, for decorative purposes or for building up laminates for strength. This means that veneers can be divided into two categories: decorative veneers and structural veneers. In laminated wood bending, for example, both these categories are used in the same construction; a veneer for strength purposes in the core (internal or core veneer), and a decorative veneer on the surface (face veneer).

Veneers are the most economical high-quality, genuine wood-facing materials. Modern production technology makes the exploitation of wood to veneers possible in many ways. Between 800 and 1000 m^2 of veneer can be obtained from a single cubic meter of wood. No other kind of wood processing gives such an yield. A veneer can be rotary cut, sliced, or sawn from a log. Of the total volume of veneer production, approximately 95% is rotary cut, 3–4% is sliced, and the rest, approximately 1%, is sawn. The first step in veneer production is to decide how to use the log. This is much more important in decorative veneer production than in structural veneer production. The properties of the log that are important are: straightness, heart and tension cracking, visible defects such as knots, pin-knots, decay, etc., dimensions, color, texture, and shape. The procedure for scaling and grading veneer logs has already been described in the previous chapter. To meet present day quality standards for decorative veneers, a veneer surface must as far as possible be free from defects, uniformly colored and evenly textured. This section describes the equipment used for veneer grading in the production of plywood and laminated veneer lumber (LVL). For the further description of veneer production, ▶ Chap. 26 is recommended.

Grading of Veneer for Plywood and Laminated Veneer Lumber

The launching of laminated veneer lumber (LVL) onto the market at the end of the 1970s has brought remarkable technological improvements in grading and stacking compared to the plywood industry. These improvements have made possible a decisive upgrading of the technical properties of LVL products. With accurate veneer grading, it is possible to attain a higher strength level than was previously possible from the same raw material.

Ultrasonic veneer grading was first adopted in the USA. The concept of determining wave propagation time, stress-wave velocity, and modulus of elasticity (MOE) for veneer was based on studies on sawn timber [61, 62], which were applied to veneer by Roy Pellerin of Washington State University and Peter Koch of the United States Department of Agriculture, Forest Service, Southern Forest Experiment Station in New Orleans, Louisiana.

The Metriguard company in the USA was the manufacturer of ultrasound-based veneer-grading equipment (Fig. 20.17). Their first commercial system was installed in 1977 at the LVL plant of Trus Joist Corporation in Eugene, Oregon [63]. Today Metriguard is a part of the Finish Raute company.

In Finland, the Vitka veneer density grading system led to an essential improvement in the characteristic properties of the product, when an online surface density and moisture measuring device was developed in cooperation with the Radio Laboratory of Helsinki University of Technology (now Aalto University), with a pilot unit in 1991 and a production prototype in 1992. The operating principle of the device is based on technology developed by [64]. The Vitka system measures the moisture content, temperature, and density of dried veneer sheets as they pass through the system on a conveyor line. Within the machine frame, an upper row of 4–6 sensors sends a series of radio frequencies through the veneer (50–60 per veneer sheet) and the signals are received by a lower row of sensors. The changes in signal speed and intensity are determined and used to establish the grade of the veneer.

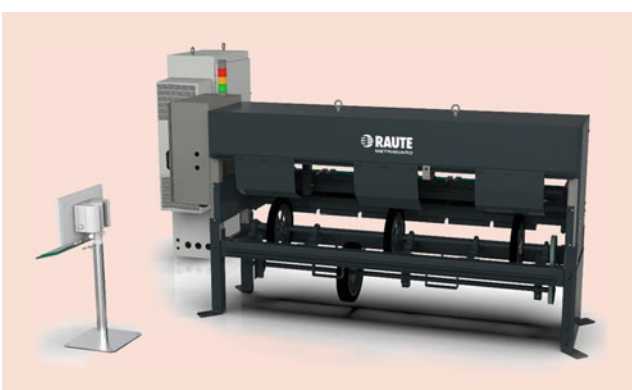

Fig. 20.17 Ultrasonic veneer grader (Veneer Strength Analyzer) using a radio-frequency probe to determine the density and moisture content of each veneer sheet. The ultrasound probe moves between the rollers positioned at the ends while the veneer runs between them in a cross-grain direction. The pairs of 4–6 sensors in the middle measure the changes in the speed and intensity of the radio wave passing through the veneer

A license for the patented Vitka, owned by Finnforest Oyj, was sold in 1998 to Metriguard Inc., which launched a commercial version of the device. Technical advances have combined the velocity of the wave (MOE) with the use of a radio frequency probe to determine the density and moisture content of each veneer [65]. This *DME Veneer Tester* provides information about the density, moisture content, and modulus of elasticity (i.e., DME) of the peeled veneer. It is possible to define the aggregate number of knots and density in an individual veneer at a number of points to give an average density value, which represents a sufficiently reliable density value for the entire sheet. It is also possible to determine the modulus of elasticity of each individual sheet. A combination of these two properties correlates well with the strength of the single veneer. When veneers are used for the manufacture of plywood or LVL, it is possible to achieve a Coefficient of Variation (COV) or relative distribution of tensile strength values of less than 10% by grading the veneers in advance.

Machine Vision for Veneer Industry

In the early 1990s, Markku Korhonen and his company Mecano Group Oy in Kajaani, Finland, developed the first vision system specially tailored for the veneer-based industry. The system was built around two separate analogue interface gray-level cameras and separate rack unit without any particular user interface. The only feedback to the operator of the machine was the row of light-emitting diodes (LEDs) blinking with a number describing the grade of the veneer sheet. This machine platform was called *G1* (First generation). The veneers were illuminated with high-frequency fluorescent light, with the draw back that this has a short lifetime and is a potential fire hazard.

The development was fairly challenging with such a platform, but a few years later the first PC-based (WinNT) analyzer was introduced with digital line-scan cameras. This *G2* system from the late 1990s and early 2000s was based on two computers, one for the grade analysis and the camera interface, and the other for the Windows-based user interface. The resolution was double that of the G1 system, and an almost noise-free gray-level image provided a more detailed analysis. The main differences between the systems were cameras with improved resolution, a defect-classifying algorithm that was adjustable by the operator, and an LED-based illumination that significantly improved the noise-to-signal ratio.

The development of a third-generation system started around 2004 (Windows XP) with three major goals:

– It has to run on a single computer
– It has to support color analysis
– It has to be a platform for many different applications (clipping, patching, grading, composing, panel repairing, etc.)

Those goals were all reached and the third-generation *G3* was a successful platform for over a decade with more than ten major production releases, a very long run for the world's first color analysis. This system also had a new type of LED illumination, which maintained a foundation for different imaging methods, especially in the color domain.

Limitations of Windows XP as well as end-of-life of the technology in the G3 system, increased the demand for the development of a new grading system, but the market for analyzers grew at such a pace that the G4 system never left the test laboratory before the *G5* generation was introduced in late 2015.

The G5 system embodied multiple analyzers acting as one and opened a world of digital services providing a path way toward full process control and optimization, with a "one machine, one operator" concept that was missing compared to other process-oriented industries, like the mining and metal refining industries.

The G5 system introduced multiple camera interfaces, simultaneous F- and S-imaging, higher resolution and better color dynamics providing more detailed information about wood features, and calculation-oriented analyzers, but the system recovered some of the advantages of earlier generations, such as a distributed user interface in a stand-alone PC and dedicated calculation in another single computer.

Future systems will be built on this platform. Machine learning, being able to optimize previous and next process stages by communicating with each other will be standard. X-ray technology will be introduced to detect the interior of logs, and microwave and sound velocity analysis will also become more common. The 5G analyzer already combines five to ten different imaging domains simultaneously and additional dimensions will probably be required in the future.

20.3.2 Grading of Veneers

Automatic veneer grading has been available since the 1990s in the plywood and LVL industries. These early visual, moisture, and strength analyzers graded the veneer based on individual measurements and without communication between analyzers or between production lines. In modern grading machines the different grading functions are combined in a single machine.

The grading and stacking line is programmed to grade the veneers automatically according to their visual quality using first a Veneer Moisture Analyzer followed by a Veneer Strength Analyzer and finally a Veneer Visual Analyzer unit to analyze and grade the green veneers (Fig. 20.18). A sufficient number of bins are provided for stacking the different grades. For plywood, several bins are needed for different face qualities, for veneers for the core and for veneers to be repaired.

A Veneer Visual Analyzer R7 with a color-camera is a standard equipment for the most demanding applications to ensure excellent pitch recognition and wane separation. It identifies defects such as blue stain, rot, heartwood, and watermarks (Figs. 20.19, 20.20, and 20.21). A Veneer Visual Analyzer R5 with a gray-scale camera is used for standard grading

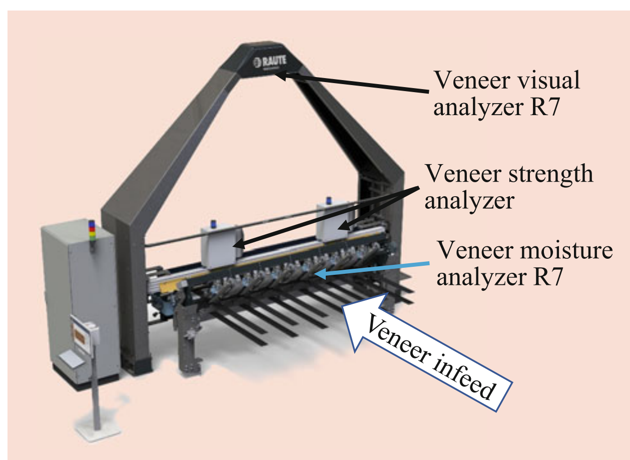

Fig. 20.18 After rotary peeling and before the clipper first Veneer Moisture Analyzer, then Veneer Strength Analyzer and last Veneer Visual Analyzer unit is analyzing and grading of green veneer ribbon (Raute Mecano products)

applications and includes the recognition of open defects. Both systems are available for two-sided analysis (face and back).

Standard plywood is classified according to the grade of its face veneer according to the EN 635 standard, the grade categories being based on the recommendations of the International Standardization Organization [66].

The automatic moisture analyzer combined with optical grading enables the removal of over-wet veneers into their own bin (Fig. 20.22).

Sensor fusion between a Veneer Visual Analyzer and a Veneer Strength Analyzer, (or any analyzer providing strength-related information) provides precise estimate of the real strength properties of the raw material (Fig. 20.23). The system can give an intelligent output by utilizing all the interacting information. A cross-grain area or dense knot row

Fig. 20.19 Veneer Visual Analyzer is showing cross grain area or dense knot row for Veneer Strength Analyzer (see chapter veneer grading after drying)

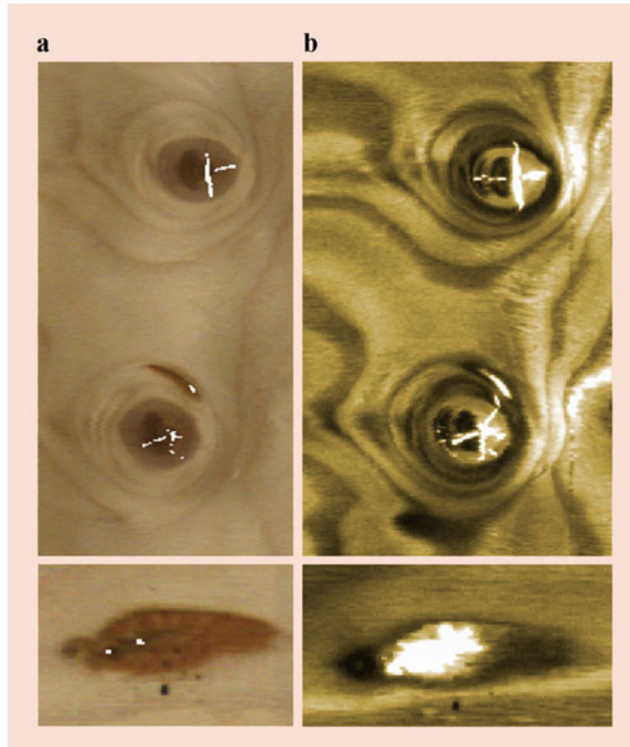

Fig. 20.21 Thin areas of a veneer that are invisible to a conventional camera (**a**), can be found using F-imaging (**b**) and information on strength calculation

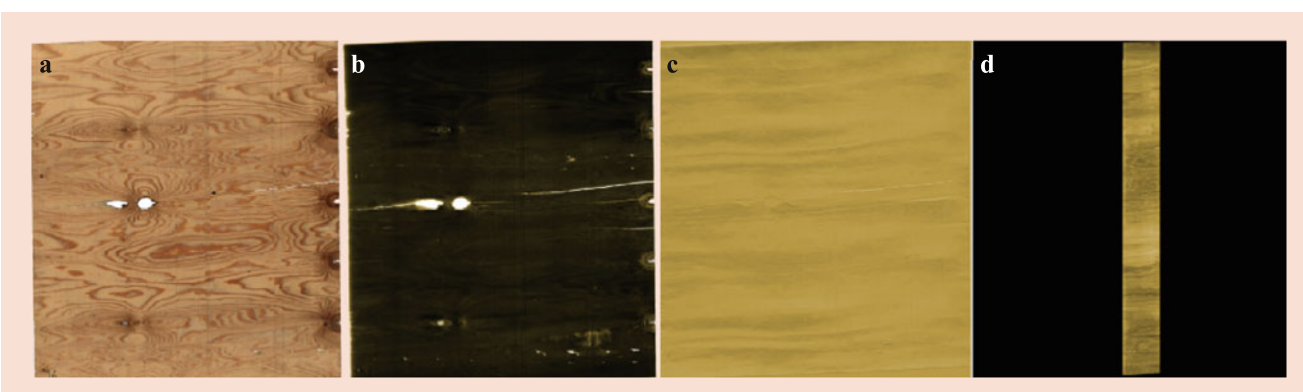

Fig. 20.20 Example of output from Veneer Visual Analyzer: a) high-resolution color image with added dynamics, b) result of f-imaging showing, e.g., thin spot and slope of grain, c) result of s-imaging showing, e.g., overlaps, coarseness, trash on surface, shelling, and inner defects (decay streaks), and d) result of X-ray imaging (the colored section) used for density measurement

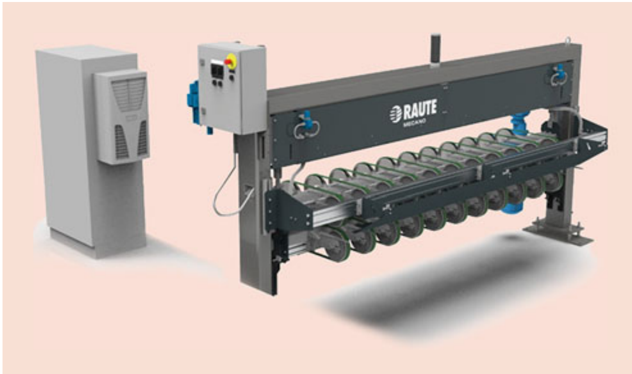

Fig. 20.22 Veneer Moisture Analyzer. Veneers pass through the analyzer one by one, making it possible to use advanced moisture maps, moisture trending, and moisture areas. The features include sophisticated moisture limit settings, moisture pocket detection, and moisture history recording (Raute Mecano products)

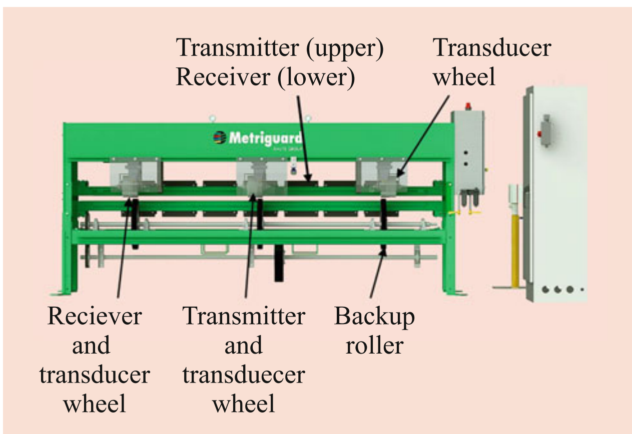

Fig. 20.23 Veneer Strength Analyzer with density and sound velocity measuring (Raute Metriguard products)

within good density and good sound velocity can, for example, compensate strength measurement in the right direction. A very low or missing sound velocity on an area where small cross grain or a thin region is detected does not necessarily downgrade the whole veneer sheet if the strength can be calculated properly.

With modern techniques, it is possible to define the aggregate number of knots and density in an individual veneer sheet as a map (map grading) to enable an average density value to be calculated, representing sufficiently reliably the density of the entire sheet. It is also possible to define the modulus of elasticity of each individual sheet, and the combination of these two properties correlates extremely well with the strength of a single veneer (Figs. 20.24 and 20.25).

When dimensions for timber structural elements are calculated, a "characteristic strength" is given to represent the strength properties of the products. The characteristic strength is the limit strength value obtained in statistical testing, which the tear strength of the product continuously exceeds with a probability of 95%. The strength properties of the tested veneer are distributed normally (Fig. 20.26), and the tear strength can be described with a function such as Coefficient of Variation (COV), as pointed out in the EN 14279 and EN 14358 standards [67, 68]. The possibility of attaining higher characteristic strength values from the same veneers for LVL as presented in Fig. 20.26 is based on the mean value principle, in contrast to the weakest link principle used for sawn timber.

For plywood, the G5 grading opens new opportunities to develop superior added value products like LNG-plywood (plywood for liquefied natural gas carriers), components for the carrier vehicle industry, or high visual furniture.

Grading Technology for Plywood and LVL Production
Automatic veneer grading systems have developed from being moisture and strength analyzers based on individual measurements and without communication between analyzers or between production lines to being fully integrated production systems. Nowadays, the most sophisticated grading systems can combine all measurements in a single multilayer data map, which enables a more accurate grading. All new analyzers are connected to the Internet-of-Things (IoT), and all data from the mill are used for optimization of the production and are also saved for further analysis (Figs. 20.27 and 20.28).

In addition to measuring the diameter and shape of the incoming logs, it is also possible to grade the logs based on X-ray scanners. In plywood production, it is possible to sort the logs according to the yield of the face veneer to optimize the raw material cost. In the production of LVL, the logs can be graded into density classes before the veneer flow of the production to a specific product is homogenized.

Modern optimization can calculate the true recovery already in the veneer peeling stage and send unusable material directly to waste (green chips). In a modern plywood factory, the online data can be collected and used to optimize the total raw material yield in different stages of the production, both before and after the drying of the veneer (Table 20.4).

20.4 Sawn Timber Grading Technologies: United States Systems

Stress grades were developed for structural sawn timber in the United States because designers wanted an economical means of obtaining reliable working stress values for sawn

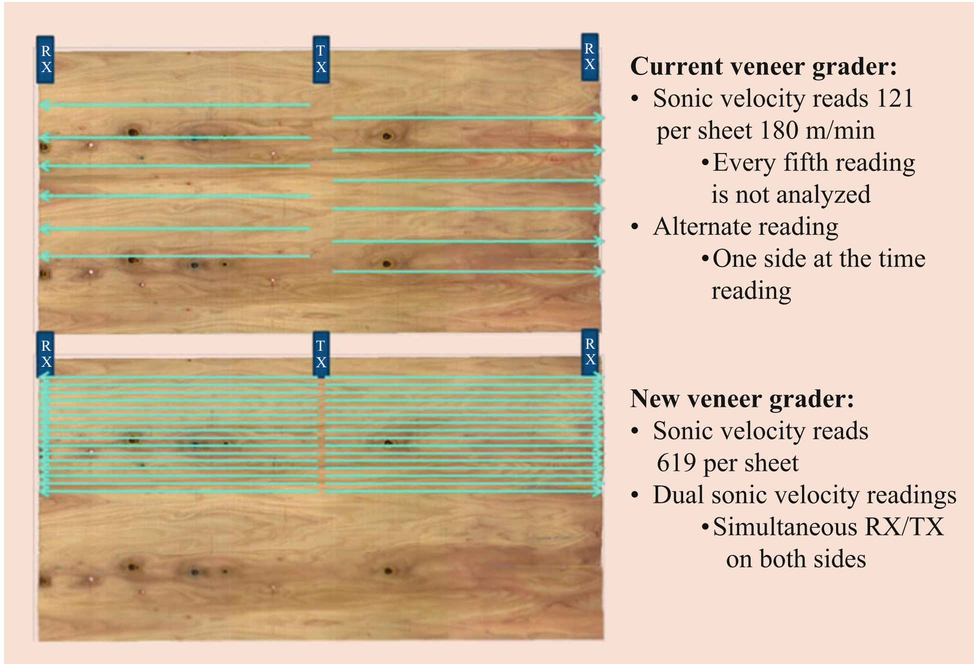

Fig. 20.24 Sonic velocity measurement with Veneer Strength Analyzer for MOE. The veneer runs in cross-grain direction (Raute Metriguard products)

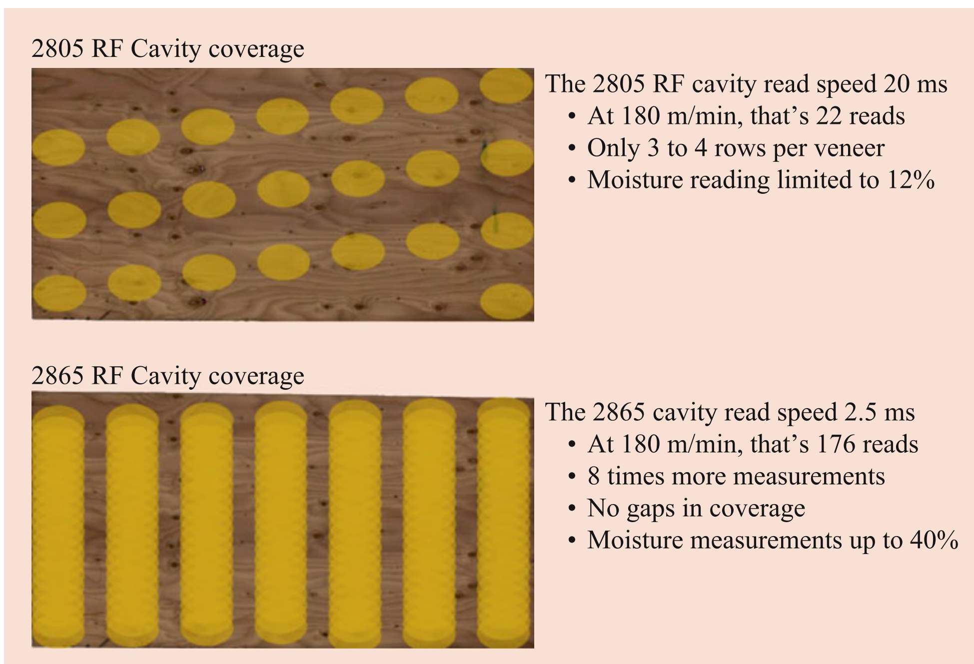

Fig. 20.25 Moisture and density resolution comparison with Veneer Strength Analyzer. The veneer runs in cross-grain direction (Raute Metriguard products)

timber. In 1923, the US Department of Agriculture (USDA), Forest Service, Forest Products Laboratory (FPL), published a set of basic grading rules that relied upon visual characteristics of sawn timber and other timber products, with corresponding assigned stress values. These stress grades, designed for only the better sawn timber cut from a tree, were used by designers in the United States for more than 20 years.

World War II brought dramatic changes in the grading system for structural sawn timber, the initial influence being a temporary increase in acceptable design stress values. For example, the US Army employed an 85% increase in design stresses. After the war, some of the temporary increases were made permanent. At the same time, the growing need for timber due to the increasing US housing demand put pressure on the grading system. Research organizations and grading agencies responded by investigating the properties of structural materials and making appropriate adjustments to the acceptable design stress values.

A significant body of technical knowledge on the properties, performance characteristics, and grading of structural sawn timber and other wood products has been developed by university, industry, and government research scientists and engineers. Much of this knowledge has been summarized in scientific and technical publications, and ultimately translated into practice through industrial trade associations and grading agencies in North America. To list all the published technical information related to the development of grading criteria for structural wood products is beyond the scope of this presentation. Excellent summaries can be found in Galligan et al., Galligan and McDonald, Kretschmann, Ross, and Ross and Wang [16, 69–73]. These documents provide the foundation for this section. In addition, this section summarizes research conducted on the fundamental nondestructive evaluation concepts now used in the grading of sawn timber in the United States.

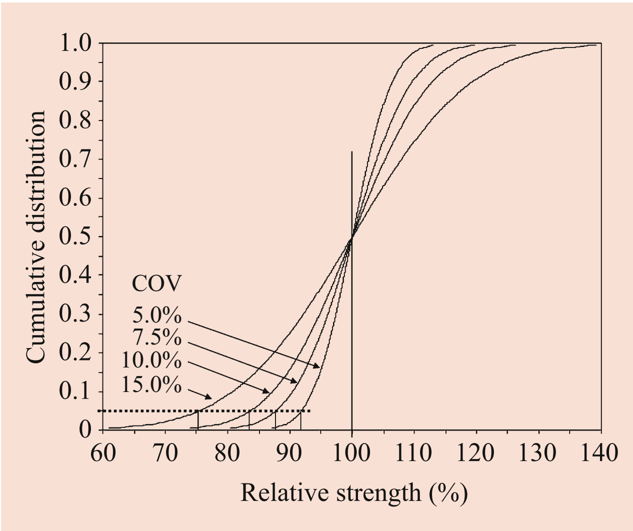

Fig. 20.26 It is possible to reduce the relative distribution of the strength (COV) of veneer-based products by grading so that the COV is reduced from 15% to 7.5%, and the characteristic strength rises from 75.5 to 87.5. This means that the characteristic strength is increased by 15% even when the same raw material is used

20

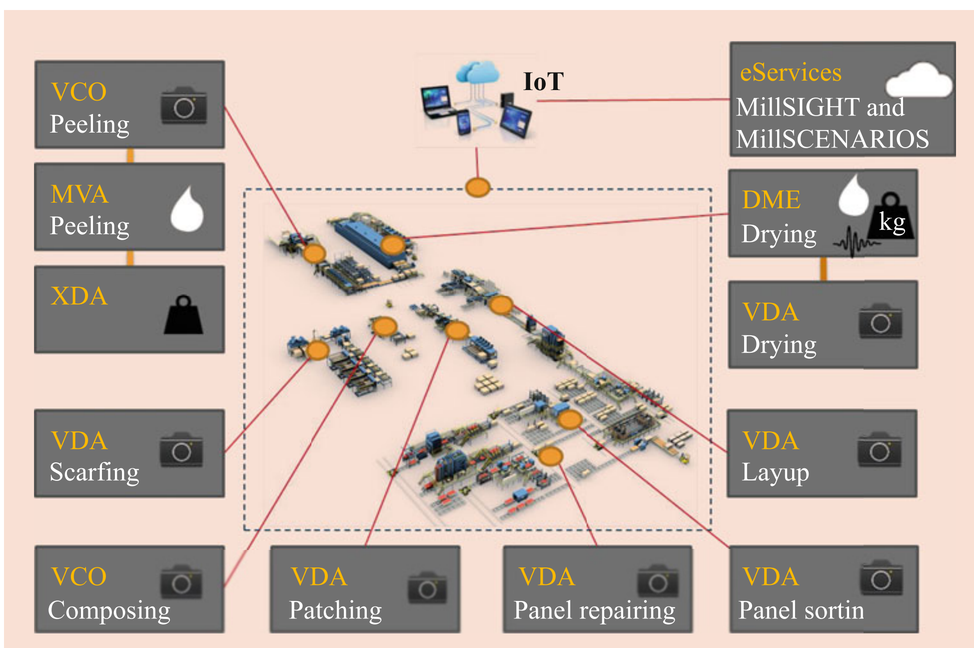

Fig. 20.27 Fifth generation (G5) analyzers in a plywood-production line (Raute). The Internet-of-things (IoT) is the extension of Internet connectivity into physical devices and everyday objects

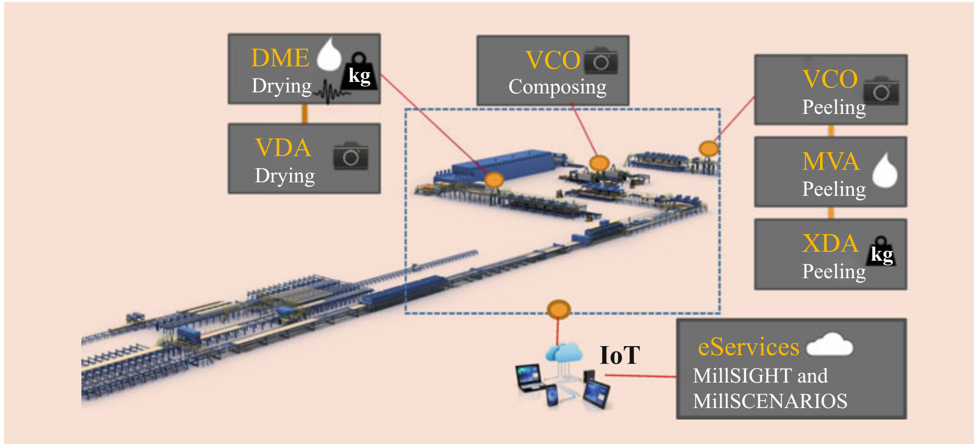

Fig. 20.28 Fifth generation (G5) analyzers on a LVL-production line (Raute)

Table 20.4 Green and dry clipping is controlled by automatic veneer analyzers

Control of green veneer:		
Visual clipping optimizer (VCO)	**Moisture volume analyzer (MVA)**	**X-ray density analyzer (XDA)**
Visual grading	Moisture	Density
Knots, resin, and wane	Temperature	Exact clipping size based on shrinkage
Micro-cracks	Sap/zebra/ heart wood separation	
Overlaps		
Undersized (thin) veneer		
Roughness		
Harvester marks		
Control of dried veneer:		
Map-grading	**Visual defect analyzer (VDA)**	**DME Veneer Tester (Model 2865)**
Map-grading integrates visual, moisture, and strength information and enables more accurate strength grading for LVL production	Visual grading	Moisture
	Knot row analysis	Density
	Knots, resin, and wane	Sonic velocity
	Micro-cracks	
	Overlaps	
	Undersized (thin) veneer	
	Roughness	
	Harvester marks	

20.4.1 Visual and Optical Grading Systems

Evaluation of visual characteristics of a piece of sawn timber is one of the most widely used nondestructive techniques in the forest products industry. Characteristics such as size, number, and location of knots are common visual characteristics considered when grading both structural and non-structural sawn timber.

The visual grading system has served the US sawn timber manufacturing industry well for many years. It has provided basic technical information to the design community and reliable structural products to the construction industry, and this has contributed to the widespread use of wood in a variety of structural applications.

The visual grading process is founded on the use of fundamental mechanical property information for clear, defect-free wood from a particular species or group of species that have similar clear wood properties. It assumes that structural sawn timber products have mechanical properties different from those of clear wood due to the presence of growth and manufacturing defects and that these defects can be detected visually. Knots, annual growth ring count, and the presence of decay are characteristics related to tree growth that are commonly looked for in the grading of sawn timber. Defects such as slope-of-grain, splits, checks, and wane are common defects related, at least in part, to the sawn timber manufacturing process. In practice, an individual with specialized training examines each piece of sawn timber produced and assigns a grade based on observed defects and criteria established for specific grades.

The strong feature of this system is that it permits the production of vast quantities of structural materials that are compatible with a major construction need in the United States, i.e., light-frame housing. Several points of concern with the visual grading system include (1) human performance issues, such as fatigue, in a high-production industrial environment, and (2) the wide variety of sawn timber grade-species combinations that have evolved and are in use.

Machines that can visually grade sawn timber and replace human sawn timber graders have been in development for more than a decade. Early machines had difficulty in detecting several types of defects that could be detected by a human, such as hairline cracks, knots of a color similar to the surrounding wood, and worm holes [15]. Machines are now available that can determine visual grades with precision. These machines can identify defects in individual pieces of sawn timber and process this information to provide trimming options for crosscut saws, resulting in the highest value timber mix based on market conditions. In addition, they can interface directly with mechanical grading equipment.

20.4.2 Mechanical Grading Systems

A Brief History and Scientific Foundation

In the 1950s, technological and economic pressures introduced a second sawn timber grading system somewhat competing with the visual grading system, i.e., mechanical grading. Initially referred to as Machine-Stress-Rating because of the fundamental principles employed at the time, mechanical grading of structural sawn timber has been implemented in commercial operations in North America since 1963.

The foundations for the mechanical grading of sawn timber are experimentally derived relationships between nondestructively measured parameters, such as density and modulus of elasticity, and the stiffness and strength properties of sawn timber. In a production environment, a nondestructive test is performed on individual pieces of sawn timber. The information obtained, coupled with a visual assessment, is then used to assign a grade to each individual piece of sawn timber. The visual assessment focuses primarily on the presence of knots on the edges and ends of individual boards. An additional requirement for the mechanical grading of sawn timber is the subsequent testing of a sample of sawn timber specimens removed from the graded timber.

Measuring the modulus of elasticity (MOE) of sawn timber using bending, transverse vibration, or longitudinal stress wave (acoustic) test is a nondestructive technique employed in sawn timber production operations worldwide. Considerable laboratory research conducted in the early 1960s examined the use of these test methods to estimate the stiffness and strength of softwood sawn timber. Useful correlative relationships were discovered and used as the technical basis for establishing design values. Sawn timber that has been evaluated on the basis of a measurement of the MOE of the timber is referred to as Machine-Stress-Rated (MSR) sawn timber.

A commercial density-based grading system was developed in the mid- to late 1980s. Initial work focused on the use of gamma ray absorption to measure density and generate density profiles of individual pieces of sawn timber. As development progressed, the use of a radiation source was discontinued in favor of using X-rays, which were found to be more suitable for commercial installations, and the first commercial X-ray sawn timber grading equipment was built and installed in 1993 [74]. One advantage of this concept was the capability to scan the entire piece of sawn timber from end to end. This capability eliminated the need to apply additional visual restrictions to the ends of the pieces as is common with stiffness-based machines. Machine Evaluated Lumber (MEL) refers to sawn timber that has been evaluated by equipment that measures the density of individual pieces.

Production Statistics for North America

By 1996, mechanical grading systems had achieved a commercially important level of usage in North America. Approximately 2.35 million m^3 of mechanically graded sawn timber was produced in 1996, the majority being sawn timber produced for use in metal plate trusses. MSR sawn timber production peaked during strong construction markets in 2004–2006, with a significant decline of over 50% during the recession of 2007–2012. Recently, production has recovered. Table 20.5 shows the total MSR sawn timber production volume by species in North America from1995 to 2016 [75].

Table 20.6 shows the numbers of sawmills that use visual grading and machine grading. There was a slight reduction to no growth in mechanical grading machines from 2004 to 2015 in the West Coast, Inland West, and Central/East regions, but in the South, the use of this technology roughly tripled. The expansion of machine grading technology in the South began when the allowable bending strength for Southern pine sawn timber that was visually graded was lowered. The number of total mills decreased in all regions from 2004

Table 20.5 Machine-graded sawn timber production for 1995–2016 in North America (1000 × m^3)

Species [a]	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
DFL	290	315	317	417	375	347	346	349	384	410	379	315	182	211	153	241	228	283	383	353	439	514
HF	82	104	143	157	158	135	151	148	133	143	135	140	82	84	34	32	45	29	29	28	28	34
SPF	1540	1687	1789	2099	2253	3031	2902	3522	3535	3928	4273	4061	2493	2319	2000	1968	1844	1858	2234	1947	1950	1157
SYP	264	274	328	364	475	438	535	640	686	653	819	660	470	427	291	316	353	580	556	862	797	1970
Total	2176	2381	2576	3037	3261	3951	3933	4658	4738	5135	5607	5175	3227	3041	2478	2556	2470	2751	3201	3189	3213	3676

[a] *DFL* Douglas fir–larch, *HF* hemlock–Fir, *SPF* spruce–pine–fir, *SYP* southern yellow pine

Table 20.6 Mills using visual and MSR sawn timber grading technologies by region and year

	West Coast			Inland West			South			Central/East			
	Visual	MSR	Total Mills	Visual	MSR	Total Mills	Visual	MSR	Total Mills	Visual	MSR	Total Mills	Total Sawmills
2004	87	6	93	104	5	109	262	15	277	82	2	84	563
2005	94	4	98	98	4	102	256	16	272	83	1	84	556
2007	89	5	94	92	4	96	232	16	248	74	1	75	513
2008	87	4	91	93	4	97	198	17	215	73	1	74	477
2009	81	4	85	89	4	93	181	18	199	68	1	69	446
2010	78	5	83	74	9	83	162	16	178	63	1	64	408
2012	69	5	74	70	5	75	137	32	169	51	0	51	369
2013	67	3	70	70	5	75	127	38	165	49	0	49	359
2014	66	3	69	66	8	74	118	43	161	49	0	49	353
2015	61	3	64	66	5	71	113	44	157	49	0	49	341

to 2015, amounting a 39.4% decrease in the total number of mills.

American Lumber Standard Committee

Voluntary product standards have been developed under procedures published by the US Department of Commerce. The Department of Commerce National Institute of Standards and Technology (NIST), working with rules-writing agencies, sawn timber inspection agencies, sawn timber producers, distributors, and wholesalers, retailers, end users, members of Federal agencies, and others, operates through the American Lumber Standard Committee (ALSC) to maintain a voluntary consensus softwood standard, the American Softwood Lumber Standard (PS 20) [76]. This standard prescribes the ways in which stress-grading principles can be used to formulate grading rules designated as conforming to the American Lumber Standard. Under the auspices of the ALSC, the National Grading Rule specifies grading characteristics for different grade specifications. These methods for developing design values for sawn timber rely on the use of several ASTM standards related to the testing of clear wood and sawn timber, and those used to establish appropriate design values [77].

Organizations that write and publish grading rule books containing stress-grade descriptions are called rules-writing agencies. Grading rules that specify American Softwood Lumber Standard (ASLS) PS 20 must be certified by the ALSC Board of Review for conformance with this standard. Organizations that write grading rules, as well as independent agencies, can be accredited by the ALSC Board of Review to provide grading and grade-marking supervision and re-inspection services to individual sawn timber manufacturers. Accredited rules-writing and independent agencies are listed in Table 20.7. The continued accreditation of these organizations is under the scrutiny of the ALSC Board of Review [71].

Most commercial softwood sawn timber manufactured in the United States is stress graded under American Lumber Standard practice and is called American Lumber Standard (ALS) program lumber. Distinctive grade marks for each species or species grouping are provided by accredited agencies. The principles of stress grading are also applied to several hardwood species under provisions of the American Softwood Lumber Standard. Sawn timber found in the marketplace may be stress graded under grading rules developed in accordance with methods approved by the ALSC or by some other stress-grading rule, or it may not be stress graded.

Table 20.8 lists the manufacturers of sawn timber grading equipment approved by the ALSC and currently in production and the underlying nondestructive test method used. For additional details on approved equipment, consult the ALSC website (www.alsc.org).

Table 20.7 Sawn timber grading agencies [a]

Rules-writing agencies
Northeastern Lumber Manufacturers Association (NeLMA)
Northern Softwood Lumber Bureau (NSLB)
Redwood Inspection Service (RIS)
Southern Pine Inspection Bureau (SPIB)
West Coast Lumber Inspection Bureau (WCLIB)
Western Wood Products Association (WWPA)
National Lumber Grades Authority (NLGA)
Independent agencies
American Institute of Timber Construction
Continental Inspection Agency, LLC
Pacific Lumber Inspection Bureau, Inc.
Renewable Resource Associates, Inc.
Stafford Inspection and Consulting, LLC
Renewable Resource Associates, Inc.
Timber Products Inspection
Alberta Forest Products Association
Canadian Lumbermen's Association
Canadian Mill Services Association
Canadian Softwood Inspection Agency, Inc.
Central Forest Products Association
Council of Forest Industries
MacDonald Inspection
Maritime Lumber Bureau
Newfoundland and Labrador Lumber Producers Association
Quebec Forest Industry Council

[a]For updated information, contact American Lumber Standard Committee, www.alsc.org

20.5 Sawn Timber Grading Technologies: European Systems

In order to guarantee the structural safety of buildings and infrastructures, materials and structural elements are required to have reliable and predictable properties. Compared to other building materials, sawn timber as a naturally grown material exhibits large variations in physical and mechanical properties, not only between different species and different growth regions but also between individual pieces of sawn timber. Large variations can indeed be observed even within each individual timber member, due to knots and other growth irregularities [78, 79]. Besides the further processing of the raw material to engineered wood products with desired and controlled properties, strength grading of sawn timber is one of the possible ways to obtain reliable building products, which allow the designer to use wood in structural design.

Strength grading is straightforward: Sawn timber with usually a rectangular cross-section is classified into different groups based on nondestructively measurable indicators.

Table 20.8 Commercial sawn timber grading machines known to be in production

Equipment manufacturer	Nondestructive test method
Brookhuis Micro Electronics Institutenweg 15 7521 PH Enschede Enschede, Netherlands www.brookhuis.com	Stress wave/acoustic
Calibre Equipment Limited PO Box 2783 Wellington, New Zealand www.calibre-equipment.com	Stress wave/acoustic
Conception R.P., Inc. 405 Galilee Ave, Quebec, QC, Canada, G1P 4 M6 www.conceptionrp.com	Bending
CRiQ, Centre de recherche industrielle du Québec 333 rue Franquet QC, G1P4C7, Canada www.criq.qc.ca	Bending
Dimter GmbH Maschineenfabric Illertissen, Germany www.weinig.com	Density Stress wave/acoustic
Dynalyse AB Brodalsvägen 7, SE-43338 Partille, Sweden www.dynalyse.se	Stress wave/acoustic
Falcon Engineering US 4475 Mission Blvd #234 San Diego, CA 92109 www.falconengineeringusa.com	Stress wave/acoustic
Lucidyne Technologies, Inc. 155 SW Madison Ave. Corvallis, OR 97333 www.lucidyne.com	Density
Measuring and Process Control Ltd. Unit 2 Tabrums Industrial Estate, Tabrums Lane Battlesbridge, Essex, SS11 7QX UK www.mpcuk.co.uk	Bending
Metriguard, Inc. 2465 NE Hopkins Ct, PO Box 399 Pullman WA 99163 USA www.metriguard.com	Bending Transverse vibration Stress wave/acoustic
Microtec Via Julius-Durst Str. 98 39,042 Bressanone/Brixen (BZ), Italy www.microtec.eu/en	Stress wave/acoustic Density
USNR 1981 Schurman Way Woodland, WA USA 98674 (approved under Newnes Machine Ltd. Company) www.usnr.com	Density
Weyerhaeuser Company PO Box 9777 CH 2C27 Federal Way, WA 98063 http://www.weyerhaeuser.com/	Density

Indicators are measured and detected either visually or by means of machine-controlled systems. Two different types of grading method have been developed and successfully applied in practice: visual grading and machine grading.

Strength Grading in the Context of Structural Reliability
In modern design standards such as the Structural Eurocodes, verification of the serviceability, and safety of structures is based on the load and resistance design format according to EN 1990 [80]. For ultimate limit states, partial safety factors are applied to characteristic values of actions (loads) and resistances in order to achieve an acceptable level of safety, which can be expressed by a target reliability index β corresponding to a yearly failure probability P_f. The characteristic values of the ultimate resistances of the construction material are reduced by partial safety factors that are calibrated for each individual construction material. For more predictable material properties, a lower partial safety factor can be set. With regard to structural sawn timber, predictability and reduction of variation in properties can primarily be reached by strength grading.

History of Strength Grading and its Codification in Europe
In Europe, rules for the strength grading of timber have been developed since the 1930s [81]. These grading rules have typically been applied in limited regions, due to geographical differences, like wood species or timber quality, as well as the wish to keep strength grading and associated standards nationally independent. During the last decades in the framework of CEN standardization aiming to simplify cross-border trade within the European Union, lots of harmonized standards (including standards for strength grading of structural timber) have been developed at the European level. Nowadays, strength grading is performed in accordance with a series of harmonized standards EN 14081 and its subordinate regulations [83–85]. The framework of strength grading in Europe is illustrated in Fig. 20.29. Strength grading can be performed either visually or by means of machine-controlled systems; the principles for both are regulated in EN 14081-1 [82]. Visual grading rules for individual strength grades are usually defined in national standards. In EN 1912 [85], strength grades are assigned to strength classes and specifications indicate which set of grading rules is to be applied to grade which wood species from which regional source to

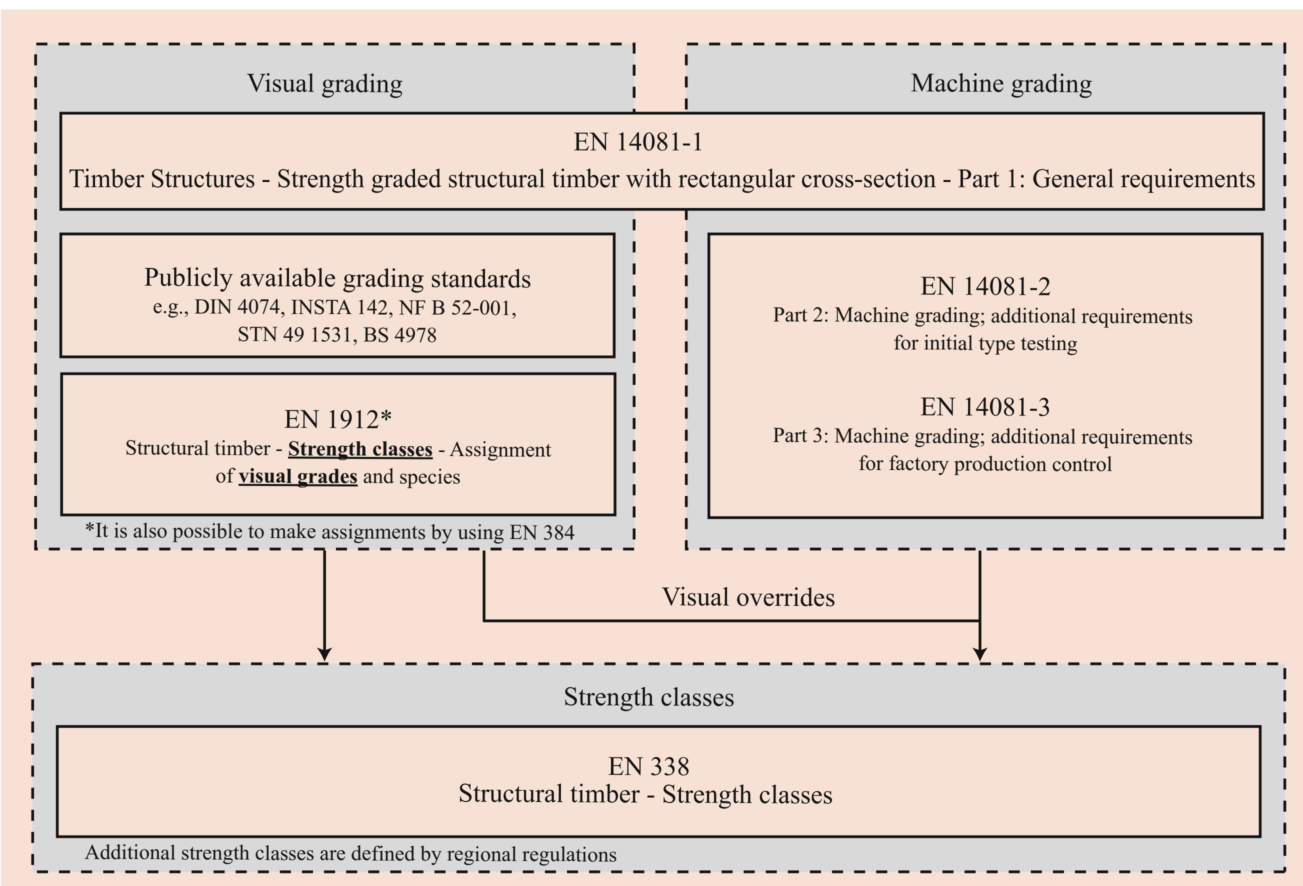

Fig. 20.29 Overview of the strength-grading system in Europe

what grades. The principles for machine grading are described in EN 14081: additional requirements for initial type testing [83], additional requirements for factory production control [84] and grading machine settings for machine-controlled systems. The assignments to strength classes are based on grading reports. When these grading reports are evaluated and approved by the European Committee for Standardization (CEN/TC124/WG2/TG1, they become Approved Grading Reports (AGR), which are required for assigning visual grades to EN 1912 and for machine control. In contrast to visual grading, the graded timber members can be directly categorized into strength classes. As some strength-reducing effects cannot automatically be detected by machine grading, additional visual overrides are required. The final outcome of both the visual and the machine strength grading processes are timber members that are allocated to specific strength classes.

Strength Grades and Strength Classes

In the current versions of the European regulations, the wording is not totally consistent, but in general a distinction is made between "strength grades" or "grades" and "strength classes." A strength grade is an entity describing the relative quality of timber members, whereas a strength class is an entity describing the physical and mechanical properties of timber members that can be used in structural design [86]. It is not possible to predict the mechanical properties of a single timber member. The physical and mechanical properties of a strength class relate to the basic population or to representative samples. Accordingly, instead of individual strength properties, characteristic values (mean values and 5-percentile values) of the physical and mechanical properties are specified in the respective European standards, e.g., EN 338 [87]. Classification according to strength grading in Europe is based on three material properties: strength, modulus of elasticity, and density, but the criteria are optimized for one selected material property only, and the other physical and mechanical properties are conservatively estimated. In the 2016 version of EN 338, strength classes based on edgewise bending tests and on tension tests (T-classes) are defined. The class labels consist of a preceding letter C (for coniferous timber) (C-classes can also be used for hardwoods with matching strength, stiffness, and density profiles, as, e.g., poplar or sweet-chestnut.) and D (for deciduous timber) and a two-digit number specifying the respective characteristic value of bending strength (C- and D-classes) or tensile strength (T-classes). The T-classes were introduced in 2013, mainly for a more reliable prediction of the mechanical properties of glued-laminated timber (GLT). [N.B. there was also an older (1951) Swedish strength-grading system for sawn timber classing into T-classes.] Besides the strength classes presented in EN 338, other strength classes are used in Europe for specific purposes, e.g., the strength class TR26 for trussed rafters in the UK.

Determination of Characteristic Values of Mechanical Properties and Classification

Structural design codes can only function effectively if standard methods exist for determining the mechanical and physical properties. In Europe, the classification of structural timber and assignment of characteristic values is carried out according to a set of three linked standards [88]:

- The physical and mechanical properties of sawn timber are derived applying the test standard EN 408 [89]. The delivered properties accordingly depend upon the test methods used and upon several parameters such as moisture content, duration of load, member size. Tests are to be carried out on timber members in structural dimensions, which are conditioned in the standard environment of 20 ± 2 °C and 65 ± 5% relative humidity until constant mass is reached, which for most softwoods results in a moisture content of approximately 12%
- Characteristic values of mechanical properties and density are derived from the test data according to EN 384 [90]. The standard permits the use of test data from various test campaigns. It provides rules for sampling, analyzing (e.g., calculating adjusted 5-percentile values weighted according to the number of specimens in each sample) and adjusting test values to geometrical or climatic conditions differing from the reference conditions specified in EN 408
- Timber members are finally classified according to EN 338, which defines 12 strength classes for softwoods based on edgewise bending tests (C14 – C50), 18 strength classes for softwoods based on tensile tests (T8 – T30), and 14 strength classes for hardwoods based on edgewise bending tests (D18 – D80). The numbers represent the characteristic value of bending strength $f_{m,k}$ for each strength class (Cxx, Dxx) or the characteristic value of tensile strength parallel to the grain $f_{t,0,k}$ for each strength class (Txx). C- and T-classes may also apply to certain deciduous species with strength and density properties similar to those of softwoods as, e.g., poplar or European chestnut. A specific population can be assigned to a certain strength class if the characteristic values (5-percentile values) of density ρ_k and bending or tensile strength ($f_{m,k}$ or $f_{t,0,k}$ respectively) as well as modulus of elasticity (mean value, derived from edgewise bending tests) match or exceed the values of the desired class. Additional mechanical properties needed for the design of timber structures are derived from these basic values by means of empirically determined relationships, specified in EN 384 [90]

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20.5.1 Visual Grading

Visual grading is based exclusively on indicators that can be detected visually:

- Growth characteristics: knots, slope of grain, rate of growth (increment in annual ring width), reaction wood, resin, and bark pockets
- Biotic damage: Discoloration, rot, damage caused by fungal or insect attack
- Mechanical damage and cracks: cracks, curvatures, compression failure due to heavy wind load
- Sawing and geometrical characteristics: pith, wane, distortion (bow, crook, twist)

Visual grading techniques and the corresponding visual grading rules have been developed regionally. Currently, in EN 1912 [85], 12 European countries (Austria, Czech Republic, France, Germany, Ireland, Italy, Netherlands, Portugal, Spain, Slovak Republic, Slovenia, UK) and the Nordic countries as a group are listed as countries having published strength grading rules. Some countries have similar grading rules, e.g., several countries are currently applying grading rules based on the German grading standard DIN 4074. Regional grading rules can only be used for strength-graded timber members originating from a specific growth region. A growth region can consist of a single country or a larger region such as, e.g., Central, Eastern, or Northern Europe.

Strength grades are allocated to specific strength classes according to EN 1912. Due to the large number of wood species, growth regions, individual grading standards incl. individual grading rules, different strength grades can result in the same strength class. In Table 20.9, the strength grade assignment into strength classes for Norway spruce (*Picea abies* L.) timber is presented for selected countries.

Table 20.9 Strength class assignments for selected strength grades of Norway spruce (*Picea abies* L.) according to EN 1912. The timber source corresponds to the specific country

Strength class	C30	C24	C18	C16	C14
Germany, Austria, Czech Republic	S13 [a],	S10 [a],	S7 [a],	–	–
Nordic countries [b], The Netherlands	T3 [a]	T2 [a]	T1 [a]	–	T0 [a]
Slovak Republic	S0	SI	–	SII	–
France	–	ST-II	ST-III	–	–
Italy	–	S2 and better	S3	–	–
Slovenia	–	S10	S7	–	–
UK	–	SS [a]	SS	GS [a]	GS
Ireland	–	–	SS	–	GS

[a]Timber source: Central, Northern, and Eastern Europe
[b]Denmark, Finland, and Sweden

Visual grading rules define upper or lower limits of certain visually detectable characteristics for each strength grade. The German grading standard DIN 4074 [91–95], for example, defines lower limits for single knots in sawn timber. For strength grade S7 the knot parameter for single knots has to be $\leq 1/2$, for strength grade S10 $\leq 1/3$, and for strength grade S13 $\leq 1/5$. Similar limits or rejection criteria exist for all visual grading parameters. Only if all the requirements are fulfilled, can a timber member be assigned to a certain strength grade.

Visual grading can be performed by humans or by machines. If visual grading is performed by humans, the process is time-consuming. Furthermore, high selectivity between strength grades cannot be achieved and reproducibility is limited. Nowadays, visual grading can also be performed by machines using optical methods. In order to fulfil the requirements of visual grading standards, all visually detectable indicators defined in the specific national regulations have to be measured. Accordingly, each piece of sawn timber has to be investigated from all sides. Modern devices are able to detect parameters such as dimensions, knots, wane, twist, decay, rot, slope of grain, and pith location and identify the associated grading requirements in near real time. Operational speeds up to 240 pieces/minute are possible, which is a high speed compared to most machine grading devices (Table 20.8). Visual grading by machines is a rather new approach and still not universally accepted by visual grading experts [86].

Efficient grading can significantly reduce the variation in properties of a specific strength grade, but the final degree may be different between individual batches, as a result of the specific characteristics of properties of the sawn timber from different sources. Currently it is possible to grade the same batch into different groups; e.g., two strength grades (S7, S10) or three strength grades (S7, S10, S13). If the sawn timber is graded in two strength grades (S7, S10) all timber members that could be categorized S13 are allocated to S10. Accordingly, the stiffness and strength properties of grade S10 are higher but the variation also increases.

Rule-based automatic grading of sawn timber is the total dominant type of sorting system used in sawmills which, due to the number of available variables and the difficulty in objectively describing a subjectively determined grade, is intricate to customize for a specific customer. Rule-based automatic grading is, however, objective by nature and has the strength of being able to strictly follow standards, which in detail specify the grade of sawn timber that the sawmill is selling – with of course some of margin error. Olofsson *and co-workers* [96, 97] have introduced a multivariate PLS-regression-based holistic subjective automatic grading (HSAG) method to predict the quality of sawn timber. In such a system, the sawn timber grade is determined by "machine learning" where the customer decides whether a specific piece of sawn timber is accepted or not for the intended use. Based on results from a preliminary "learning period" a PLS-regression model is created and used in the daily sawmill production.

20.5.2 Machine Grading

Machine grading is harmonized in Europe. All requirements are specified in the EN 14081 standard [82–85]. When performing machine grading, one or several material properties (strength, stiffness, and density) are estimated using single or multiple nondestructive indicators. The estimated material properties are usually referred to as indicative properties (IP). Currently it is not possible to predict the real properties of individual sawn timber members, even with high-quality grading devices assessing multiple nondestructive indicators. Accordingly, machine grading also works with rejection criteria of the IP values, like visual grading. The main difference is that different settings are taken into account, so that the rejection criteria of a specific strength class may differ if two or three strength classes are graded at the same time. High strength classes (e.g., C40, C45) can only be graded with grading machines and not visually.

The first grading devices used for machine grading of sawn timber were developed based on mechanical structural evaluation. Usually bending tests in the direction of the weaker axis were performed, where either (a) the deformation due to a given bending force or (b) the force for a given deformation was determined at discrete locations along the sawn timber. In recent years, alternative methods and nondestructive parameters have been identified as valuable IPs, e.g., the Eigenfrequency determined by means of longitudinal or transverse vibration, ultrasonic runtime, X-ray (to determine the density and thus knots) and laser scanning (tracheid effects). Through these methods, it is nowadays also possible to strength grade sawn timber with larger cross-sectional dimensions.

In the European EN 14081-1 Standard [82], two different approaches for machine grading are defined: "Output control" and "Machine control." Nowadays the second approach is most common. For both methods, visual requirements – the so-called "visual overrides" – have to be fulfilled, including limits for the fissure length, bow, spring, twist, cup, wane, soft rot, dote, and insect damage. If a given parameter is not measured by the grading device, additional visual inspections are required. For grading machines that do not grade the sawn timber to their full length, such as machines performing mechanical bending, additional "visual overrides" for the parts not graded are required: limits to knots and slope of grain apply in such cases.

Output Controlled Machine Grading
When output-controlled machine grading is performed, the quality of the output, in terms of material properties, is controlled by test batches selected at regular intervals. If the quality of the output does not reflect the targets specified, the settings of the grading machine are adjusted. Adjustments can become necessary for safety or economic reasons. The major advantage of output-controlled machine grading is that the machine settings can be optimized for specific sources. Currently, the system is applied by a very limited number of sawmills in Europe. Output-controlled machine grading is more efficient for large sawmills, producing structural sawn timber from a limited number of species and with a limited number of dimensions. In particular, for modern grading systems, output-controlled machine grading has some potential in the future as the timber quality of individual sources is recorded and, can thus be optimized [98].

Machine-Controlled Grading
In machine-controlled grading, each individual grading machine has to be calibrated in advance based on a large number of experimental investigations. According to EN 14081-2 [83], several hundreds of tests are required. The number of tests depends on the number of species and strength classes. Due to the large variation in sawn timber quality between the growth regions, the validity of the settings is limited to specific regions, usually for individual or a few nations.

During recent years, numerous grading devices have been developed, e.g., portable devices that can be operated by individual persons and stationary devices, usually for grading on an industrial scale (Table 20.8). Nowadays maximum grading speeds up to 450 m/min or 200 pieces/min are possible.

20.5.3 Appearance Grading

For certain applications, besides or instead of a classification of the timber material, according to mechanical criteria also visual criteria regarding appearance of the surfaces are required. In such cases, the timber is graded into appearance classes according to its optical appearance applying similar procedures and criteria as during visual strength grading (see Sect. 20.5.2). The grading limits, however, are different for visual strength grading and for appearance grading.

20.6 Process and Quality Control Technologies for Wood-Based Panels

The rapid development of the wood-based panel industry during the last couple of decades led to a greatly increased production capacity. The production speed of continuous press lines was increased to 130 m/min and this, combined with an increasing demand for quality and cost efficiency as well as the large variety of panel types, requires an advanced in-line control. The aim of this section is to provide an overview of the current state-of-the-art in-line-control technology in the wood-based panel industry, as well as a preview of future trends within this field.

The most important measuring parameters for the quality of wood-based panels are moisture content, weight per unit area, board density, crosswise and lengthwise density distribution, density profile, thickness, and the weight of the board. Other factors such as surface quality, particle geometry, internal defects (e.g., blisters and foreign bodies) as well as the trending and forecasting of the board's quality are well-established and they are taken into consideration by in-line measuring systems today. All these parameters strongly influence the final mechanical properties of the product, e.g., internal bond strength (IB) and modulus of rupture (MOR), modulus of elasticity (MOE), surface soundness (SS), and also physical characteristics such as thickness swelling (TS) after 24 h, free formaldehyde emission, surface color, coating capability, etc. [99, 100].

Standardized quality control in the wood-based panel industry is usually based upon results obtained from time-consuming destructive tests in the laboratory. For a comprehensive and continuous process and board quality inspection, in-line-techniques and process-control systems have been developed and utilized within the wood processing industry for over 40 years and wood-based panel producers have had to face some continuous changing aspects such as:

- Wider diversification of wood-based panel types, with properties which meet specific customer requirements
- Increased flexibility for producing dozens of different panel types per day with customer-tailored product quality
- High productivity, based on increasing automation, reducing incidental stops and rejects amounts, and on further reducing production safety limits
- Permanent changes in the raw-material supply – various types of processing residues and recycled wood and increasing raw material costs

The quick reaction of equipment based on in-line process control systems allows variations to be reduced and a high panel quality to be maintained [101].

20.6.1 Moisture Measurement

Moisture measurement is one of the most important factors related to energy consumption and product quality, and it has to be continuously efficient throughout the production process. This starts with the incoming raw material, during storage, before and after drying and blending of the particles, continuing with intermediate storage, after mat forming, and finally after hot pressing on the board. The most common and modern online moisture measurement methods for wood-based panels are based on microwaves and near-infrared radiation (NIR), which are indirect electrical and optical measurements [100]. Neither resistance nor dielectric moisture meters are common as in-line measuring methods in the wood-based panel industry, because both methods have disadvantages in the in-line application to wood particles and show a strong dependence on variations in the temperature, density, and ionic conductivity. In the solid wood industry, however, they are more widely used. According to [102], none of these moisture meters provide accurate readings above a moisture content (MC) of 25–30%. The operating range for resistance moisture meters is from 7% to 25% moisture content and the operating range for dielectric moisture meters is generally considered to be greater than that for resistance moisture meters, and is often stated to range from 4.5% to 25% MC [102].

Direct measurement methods are thermogravimetric and analytical methods like the Karl Fischer titration [103]. In the wood-based panel industry, the reference method to calibrate the indirect measuring systems should always be a direct measurement system like the dryer oven method according to the EN 322 Standard [104]. According to EN 322, oven-dry wood is defined as wood dried to a relatively constant weight in a ventilated oven at 103 ± 2 °C. Rapid thermogravimetric methods like the infrared drying method should not be used as a reference system unless the accuracy is shown to be within the tolerance of 0.5% to the dry oven method.

Near-Infrared Moisture Measurement

Near-infrared reflectance (NIR) moisture measurement is the technology most frequently used in the wood-based panel industry to measure moisture in-line. The method is an indirect optical measurement. Moisture determination by infrared radiation analyzes the moisture of the product surface. The infrared radiation is projected by the measurement device onto the product surface to be measured and a certain part is reflected back to a detector (Fig. 20.30). Specific wavelengths as 1.45 μm or 1.93 μm are absorbed by water and are associated with the excitation of molecular vibrations. If a halogen light is used as a source, the specific wavelengths are generated by a filter wheel, which only the desired wavelengths can pass. Nowadays, developments are using specific LEDs as a source of monochromatic light. The known water

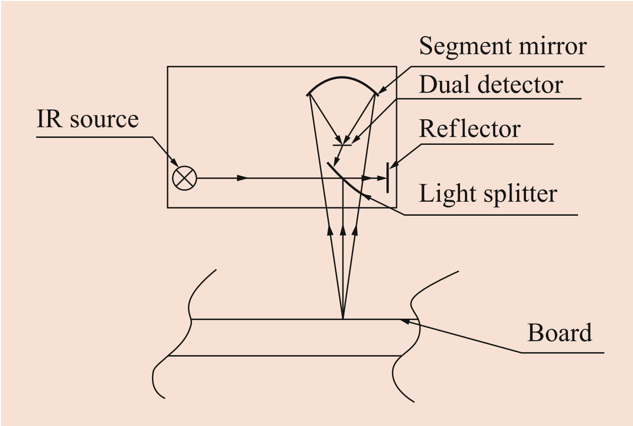

Fig. 20.30 Principle of near-infrared reflectance (NIR) moisture measurement

absorption wavelengths of the infrared radiation are constantly compared to reference wavelengths where no absorption of infrared radiation takes place. The ratio of these intensities are the concentration of moisture. Changes in the light sources and in the distance to the material can be almost eliminated by considering the ratio of the wavelengths.

Major advantages of the NIR method are that the moisture can be measured in a noncontact way during the whole production process. As the installation point of the equipment in the production process is known, a first calibration of the NIR-system is possible. The measurement accuracy depends on the surface color, external light sources, the distance between the material and the sensor, and dust development. Further aspects to keep in mind about the NIR-based moisture system are:

- Only the surface moisture of the mat is measured, i.e., only the face layer of the board
- Noncontact measurement can be made directly on the surface or through a glass window
- Color changes in the product require a change in device settings
- Ambient light can cause measurement errors
- Changes in distance large as 100 mm between sensor and material should be avoided, and
- Frozen material cannot be measured accurately

There is a need for a reliable moisture measuring system throughout the production line. Increasingly adjusted moisture content affects the whole production process and can lead, e.g., to excessive drying costs, to problems with the hot pressing or coating process, to incorrect thickness of the board with board defects such as blisters, internal bond strength loss, and additional costs because of the extension of the pressing time.

If the reference method can be made more accurate, the result is a more accurate online moisture measurement. Another major feature affecting the accuracy of the results is the position of the measurement head in the production line and the degree of automatic control of the process parameters. The later the information about the moisture of a particle becomes available, the longer is the time necessary for the adjustment of parameters (i.e., dryer temperature) and therefore product quality is impacted, and cost increase.

Microwave Moisture Measurement
Moisture measurement by microwaves, in contrast to NIR moisture measurement, determines the internal water content of a sample. Microwaves penetrate the material to be measured, causing no measurement errors due to surface effects. The ionic conductivity is not a major disturbance, due to the high frequencies [105]. There are no safety restrictions and the material to be measured is not heated by the microwaves, thanks to very low radiation power.

Various systems, consisting of measurement electronics and sensors (applicators) are available. Knöchel [106] points out that two basic designs have to be distinguished differing in the manner of interaction between the microwave energy and the material to be investigated: resonant sensors using stationary (standing wave) fields and aperiodic sensors applying traveling waves (Fig. 20.31). In the wood-based panel industry the resonance microwave sensor system is typically used, the resonators used as applicators being predominantly operated in the transmission mode, having an input and an output port, and showing a maximum energy transmission at resonance, which is evaluated.

Depending on the different requirements of the material to be measured, the resonant applicators are designed differently: they can be operated either single-sided as planar sensors with stray fields, where the material is placed in a half-space above the sensor, or as resonators with two opposite cavities and an intermediate gap, which can be filled by material plates, sometimes called fork or gap sensors. Planar sensors can be installed along a roller or belt conveyor or in a bunker sidewall to measure the moisture of bulk or solid materials in industrial processes. The product moves in direct contact or at a small distance across the sensor. The tubular resonator provides a cylinder in which rods or filaments of material are passed for measurement. Tubular sensors are used mainly for laboratory purposes in the wood-based industry. In gap or fork sensors, measurement fields fully penetrate sheets or plates of the product in a contactless transmission manner.

Aperiodic sensors are generally used as transmission paths with two antennae and the material under test in between. The antennae can even be on the same side of a layer of material if

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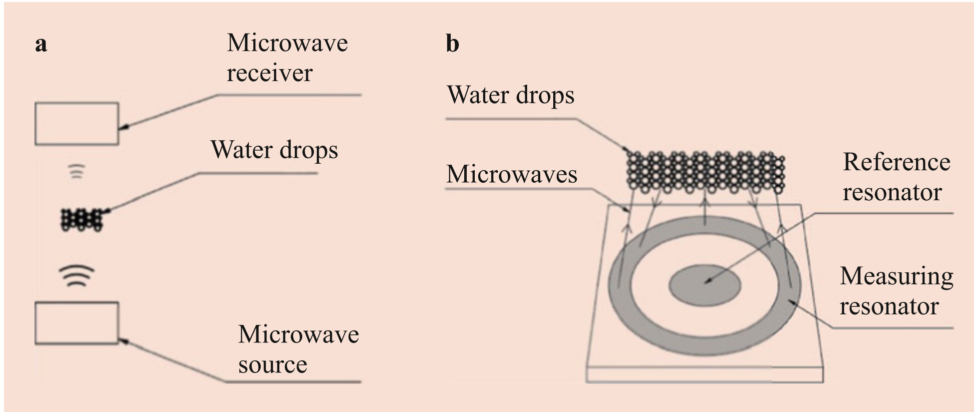

Fig. 20.31 Sensors with aperiodic signal transmission (**a**), and a planar resonator microwave system (**b**)

the transmitted microwave beam reflected or reradiated, at the opposite side.

According to Knöchel [106], the advantages of resonant sensors, i.e., their sensitivity and measurement accuracy, compact design, and need only for scalar measurements for multivariate results are accompanied by the disadvantage of being able to be loaded by only small amounts of pure water distributed in small masses of material or offering comparatively low penetration depths in the relevant portions of the fields. Sensors with aperiodic microwave transmission are complementary; they are less sensitive, but the propagation path can be longer and the amount of mass (including water) is limited only by the dynamic range of the measurement set-up. A larger mass of material can be penetrated by an aperiodic measurement to provide an average and a representative measurement of a large volume.

A microwave sensor using a narrow frequency band can measure two independent parameters: frequency shift (change in the propagation speed) and amplitude bandwidth (damping). Figure 20.32 shows different resonance curves. When the water content increases, the resonant frequency with respect to the unloaded resonator (right-hand curve in Fig. 20.32) decreases, while the bandwidth of the resonator increases, and is available with which two quantities can be determined: density and moisture. This makes a density-corrected moisture measurement possible. Systems that measure only one parameter (damping of the amplitude) cannot compensate the moisture signal for density variations, it can be used only for processes with a constant material density.

The advantages of microwave moisture measurement over NIR measurement are an accurate moisture measurement in a very short time, regardless of the density (only valid for two-parameter measurement), lighting sources, surface structure, color of the material and measurement inside the material. The advantage over the resistance- and capacitance measurement, aside from the fact that such systems are not suited for inherent density correction, is the very low influence of the ionic conductivity.

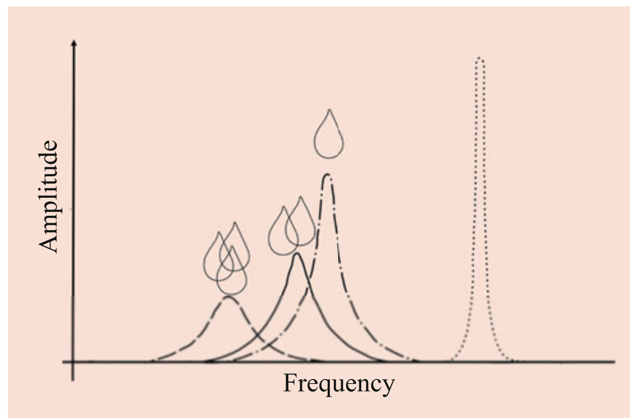

Fig. 20.32 Principal of microwave moisture measurement

In addition to the resonance frequency of the sensor, the relaxation frequency of the water and thus the permittivity of the moist material are also dependent on the temperature. For precise measurements, it is therefore essential to measure both the temperature of the material and that of the resonator, and to take these temperatures into account in the signal processing [105]. For processes with strongly fluctuating material temperatures, the calibration need increases, since the temperature effects must be calibrated in approx. 10 °C increments. Like at the NIR measurement, frozen material cannot be measured.

For wood-based panel industry applications, the maximum moisture that can be measured with a microwave resonance system is 18–20% on a dry base depending on the wood species and application.

20.6.2 Measurement of Mass per Unit Area

The mass of material per unit area should be controlled at different positions, viz.: before the resination (blender), in the forming heads, after the forming heads, after hot pressing, and either before or after trimming and sizing the hot-pressed boards. The results are used to adjust the content of resin and other ingredients, and to control the forming heads to keep the product density constant and the leveling scalper to secure an even distribution of the particles lengthwise as well as crosswise over the mat. The mass per unit area is measured online either with a belt scale or in a noncontact way by X-ray.

Belt Scale

The belt scale is based on the weight force measurements of the material. Depending on the point of installation of the belt scale, force sensors are placed under the belt (before the press) or the roller table (behind the press). The force is converted into an electronic signal, which indicates the weight force of a defined area. Since the length of the belt scale is known and the width of the produced plates is defined by the recipe settings, the area of the material can be determined. The mass per unit area (kg/m^2) can be calculated by dividing the weight by this area.

Using belt scales, mass flows of more than 1000 t/h can be monitored at speeds of up to 100 m/s. The accuracy is $\pm 1\%$ of the measurement value with optimal installation conditions. The great disadvantage of the belt scale is environmental influences. Deposits on the rollers lead to incorrect values, and movements of the material lead to deviations in the measured value, since the weight and acceleration forces are superposed during the material movement. In addition, the space required for the measurement system is quite large. The advantage is that the area around the belt scale does not need to be declared a safety zone.

X-Ray Source

The X-ray radiation is limited to a narrow area via a slit diaphragm and penetrates the mat or board. On the other side of the material, the radiation is received by a detector (Fig. 20.33).

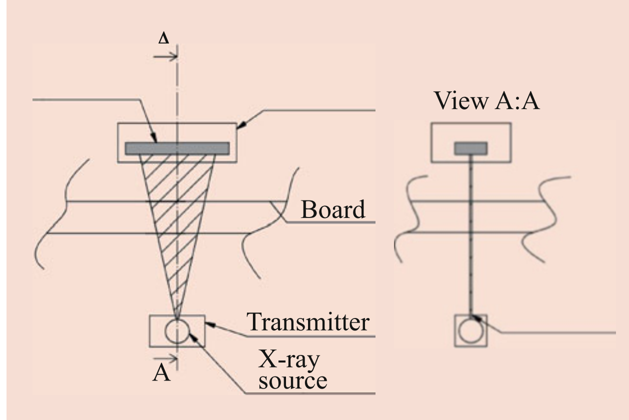

Fig. 20.33 Mass per unit area measurements with X-ray at one location

The radiant intensity measured by the sensor depends on the amount and specific weight of material and the mass per unit area (kg/m^2) can be calculated. Different measurement transducers are available, depending on material structure and place of installation.

Using the noncontact method, the most common procedure is to determine the mat weight area in a representative location or by traversing followed by calculation of an average over the whole mat width. There is however always the risk that variations in the weight in both mat directions (width and length) will not be detected. In addition, measurement of a part of the panel width is not representative of the whole mat. Problems can occur during the pressing process leading to density variations in the final product. A more representative value for the entire width of the mat can be obtained by using several systems. A possible arrangement would be to install one system for each forming head, but it will not be possible to obtain a value for the whole mat.

A complete inspection of the weight distribution crosswise and lengthwise of the mat/board is possible with a new in-line measurement system using an X-ray source with a larger opening angle and stronger power output. In addition, the distance between the source and the material is increased so that the radiation covers the entire mat, and a line detector consisting of an array distributed over the entire width of the mat is used (Fig. 20.34). The mass per unit area of continuous material in the production line is determined in high-resolution, area-wide and full width. With a precise control loop for the forming machine, it is possible to minimize crosswise and lengthwise density variations by using a continuous inspection of the whole product width. The system also has a supplementary safety feature to protect the steel belts of continuous presses through a full detection of hazardous particles.

Regardless of the configuration, X-ray-based systems have to be calibrated, and a common calibration method is based on samples of different known thicknesses and masses per unit area.

A disadvantage of determining the mass per unit area with X-rays is the radiation. The area around the system has to be well marked and secured. The general advantages of X-ray gauges compared to a belt scale is the smaller size of the system. The environmental influences are reduced and the measurement is more accurate, especially for low weights.

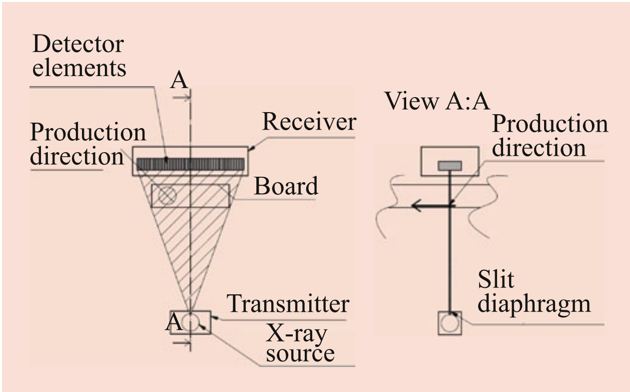

Fig. 20.34 Mass per unit area measurements with X-ray over the whole mat

20.6.3 Thickness Measurement

In almost all production lines in the wood material sector, the thickness of the measured product is an important characteristic, which is permanently determined and monitored. The tolerances are controlled by the thickness measurement, and the production process is safely controlled at the same time. The thickness of the wood materials is determined according to EN 324 [107] and EN 325 [108].

Several in-line methods for in-line methods exist. Critical selection criteria are the measurement range, ambient conditions, and surface properties. Methods employed include ultrasonic time of flight [109, 110], shading [111], and capacitive or inductive methods [112, 113]. In the wood-based industry, however, tactile measurements and noncontact measurements are mostly used.

For wood materials, there are two possible installation locations for an in-line thickness gauge, both located at the end of the production line, either after the hot press or in the grinding line. The spring-back and the thickness after cooling can be calculated if one thickness gauge is installed directly behind the hot press and the other behind the cooling.

Standard systems can measure the board thickness in three, five, or seven lines. Each line uses two sensors located on opposite sides of the board, from which a difference can be calculated. This ensures accurate measurements, even if panels bend or move vertically [109, 114].

The advantage is that a vertical board movement has no any influence on the measurement. The results can be presented as cross-section profiles, length profiles, or trend graphics. Direct feedback to the press or sander controls can be implemented so that the machines can be adjusted automatically [115].

Contact Measurement

Within the wood-based panel industry, the most common method is a contact measurement. The material moves between measuring rollers (Fig. 20.35), which are pressed against the material.

The measurement rollers are usually connected to a piston rod and the contact pressure is adjusted by springs or air pressure. The rollers contact the material and convert thickness variations into vertical motion. The thickness of the material is determined by an integrated electronic evaluation of this vertical motion (optical or inductive elements).

The challenge is to calibrate (Fig. 20.35a) the system during the production within approximately 1 second (usually the gap/time between two boards), but this is not possible when thin boards are manufactured at high speed. One possible solution is a moveable C-frame, which can be driven from the production line. Figure 20.36 shows the different frame variants. Figure 20.36a shows the C-frame, which makes it possible to calibrate outside the forming belt during production. The standard O-frame version is shown in Fig. 20.36b.

The roller gauge makes possible a thickness measurement resolution of 0.02 mm. The system is very robust and the accuracy is independent of the measurement range. Compared to the noncontact laser measurements, the contact roller is less sensitive to the dirty environment behind a hot press (no optics). A disadvantage of the method is the contact with the material, and the method is used only if contact with the material to be measured is possible and the pressure of the rollers does not significantly affect the measurement value.

Noncontact Measurement

For soft materials, or in cases where no contact measurement is possible, laser measurement systems are used. This is a purely geometrical method, where the thickness is determined by measuring the distance to the material. Laser triangulation sensors with measurement ranges from several millimeters to 100 meters are available. A light spot is generally produced on the material, from which the light is reflected according to the image geometry, and a receiving optical system projects this light onto a location-resolving detection plane, for example, a (Charge-Coupled-Device) CCD line or a Position Sensitive Detector (PSD) element (Fig. 20.37).

The focus of the light distribution on the sensor is determined. The location of the center of the brightness distribution is dependent on the distance of the sensor from the material and the distance can be calculated [109, 110, 116].

Integrated electronics compensate for the variation in the reflective properties of the measured objects and also suppress any disturbing signals from ambient lighting. Any

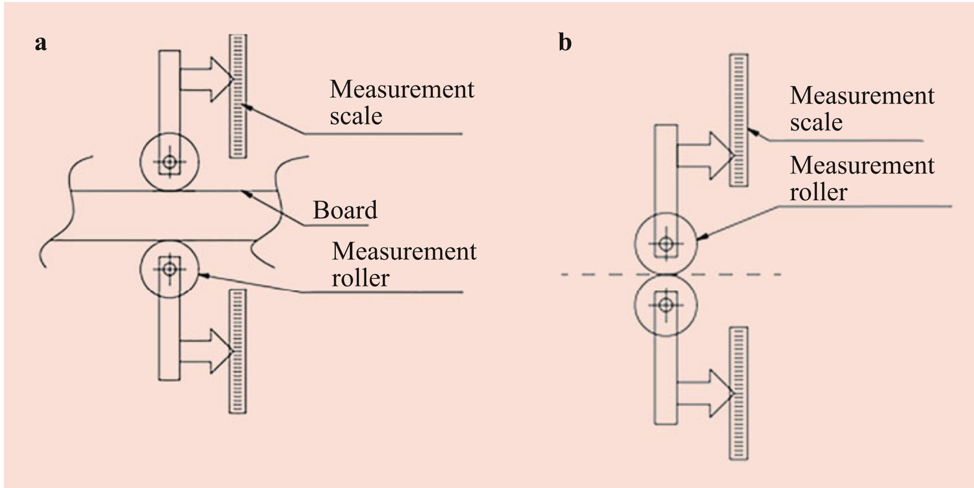

Fig. 20.35 Thickness measurement with rollers: (**a**) measurement position, and (**b**) calibration position

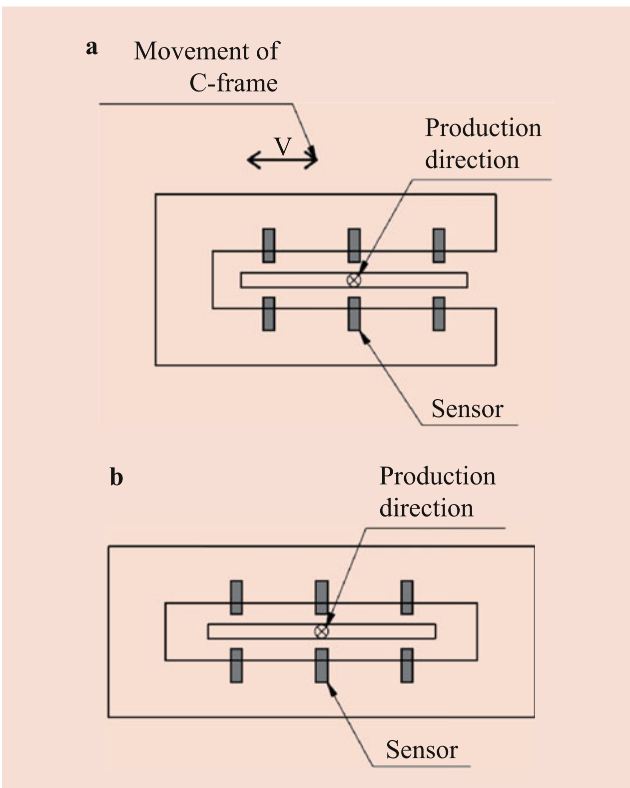

Fig. 20.36 Different frame designs for online thickness measurements systems: (**a**) C-frame, and (**b**) O-frame

material that gives diffuse reflection can be measured, such as wood, paper, plastics, metal, paper, concrete, etc., but reflecting surfaces and transparent materials are difficult to measure.

In order to determine the thickness of the material from the distance to the plate, the distance between the two sensors must be known. A calibration standard of known thickness is

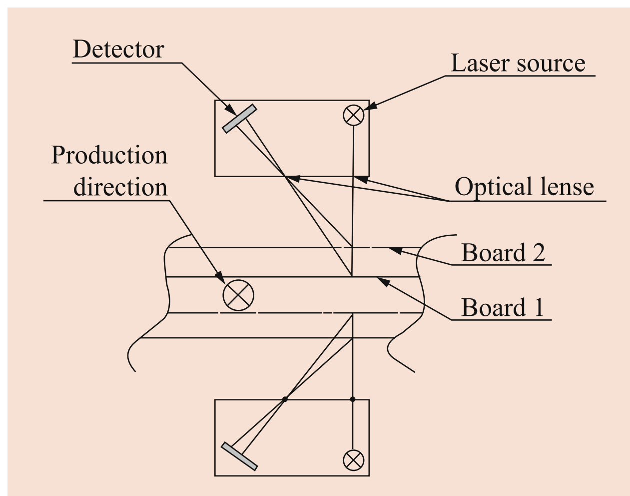

Fig. 20.37 Noncontact thickness measurement with laser

measured in the gaps between the plates. A permanent calibration process also compensates for deformations of the frame, which can result from temperature changes. If there is no gap for the calibration, a C-frame can be used by analogy with the contact measurement.

20.6.4 Blister Detection

Since wood composites consist of several structural elements that are glued with adhesives, there is a risk of blisters. These defects appear after hot pressing of boards due to the high moisture content of the mat, short pressing time, especially during the de-aeration phase and sometimes due to insufficient curing of the adhesive before the composite leave the hot press. Blisters reduce the load-carrying capacity and can

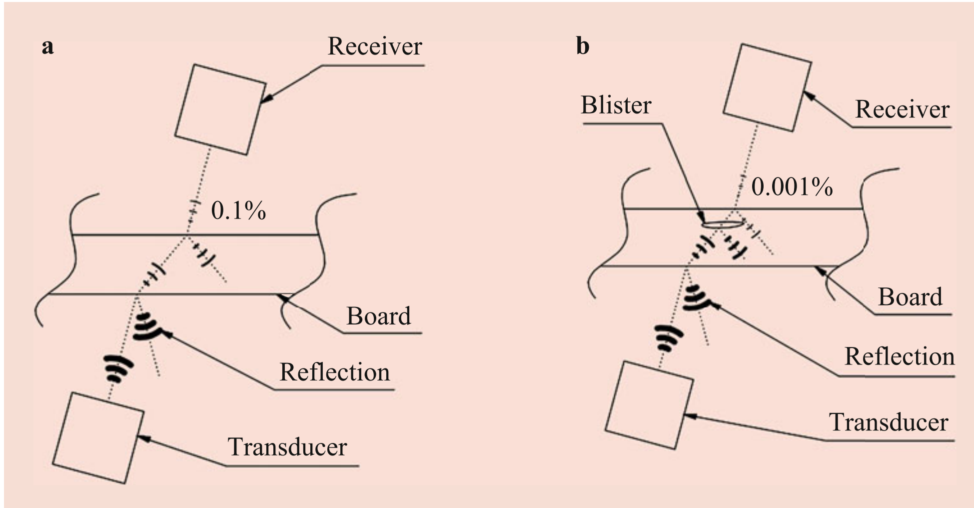

Fig. 20.38 Blister detection with air-coupled ultrasound: (**a**) transmission through a defect-free board, and (**b**) transmission through a board with a blister

lead to structural failure. Several methods can be used to detect blisters, e.g., microwave [117, 118], thermography [119], X-ray imaging [120, 121], acoustic/low frequency vibrations [118, 122], and ultrasound [123, 124]. The method that has proven its worth in industrial applications is blister detection with ultrasound. The air-coupled ultrasound (ACU) method is preferred since no coupling media, such as water or a gel, which lead to residues on the emitter/receiver plates, are needed.

The ACU measurement is usually carried out in a transmission setup. A transducer, beneath the board, emits an ultrasound impulse and the receiver, above the board, receives the ultrasound signal. Due to the great difference in acoustic impedance between the air and the panel material, strong reflections occur at the boundary between the two media [125]. Depending on various parameters, such as density and thickness of the plate, a defect-free plate already has an amplitude drop of 60 dB and thus only 0.1% of the sound energy is transmitted (Fig. 20.38a). In the case of a plate with a blister, the transmission signal is further reduced, depending on the size of the blister. In practice, the amplitude drop is ca. 40 dB, which means that only 0.001% of the output signal reached the receiver (Fig. 20.38b), and these plates are declared to be faulty.

In order to detect defects over the entire width of the board, several transmitter-receiver units (channels) can be used at the same time. In most cases, the detection is installed behind the diagonal saw as blisters can come directly after the hot press. Besides blister detection, the ultrasound amplitude can also be used to identify problems in the production process directly behind the hot press. Changes in moisture, temperature, press speed, and mass per unit area will be shown directly in the ultrasonic picture of the board. Due to a strong correlation between press factor and an ultrasonic signal, it is possible to reduce the pressing time to a time just above the point where blistering occur.

In addition to taking into account the amplitude, the time of flight (TOF) can be evaluated. The velocity of sound perpendicular to the panel surface is influenced mainly by the porous core layer, and it can therefore provide a satisfactory prediction of internal bond-strength (IB) [126]. Other mechanical characteristics such as the Young's or shear modulus strongly correlate with the sound velocity, and it has been found that the density profile of the board influences the ultrasonic transmission signal [128]. No satisfactory in-line determination of mechanical parameters has however yet been implemented in the wood-panel industry.

20.6.5 Density-profile Measurement

In addition to the mass per unit area distribution in the plane of the board, the density profile over the thickness is another important parameter. In 1970, the first investigations started to point out the correlation between the density profile and the mechanical properties of wood-based panels. Strong correlations between the density of the surface layer and the MOE and MOR have been shown for particleboard and MDF [129, 130], but several investigations found conflicting results regarding the correlation between the density of the core layer and the internal bond-strength (IB). It is assumed that some other important factors that influence the IB are not reflected in the density profile (e.g., resin content, resin curing, etc.). The density profile of panels strongly influences further processing such as edge milling and surface finishing, and it is therefore a valuable tool for panel quality control [101].

In an industrial environment, the in-line variation determines the density profile during production, but off-line measurements determine the profile in the laboratory.

In-Line Measurement
In 1995, Dueholm [131] presented an online technique, which uses the effects of damping and back-scattering (Compton effect of X-rays) to display the density profile in-line [132]. The density profile is in most cases determined directly after the hot press, and it is used to adjust the parameters regulating the pressing process, especially for MDF-production.

In the currently used techniques, the X-rays hit the board at an angle of approximately 45° after passing through a slit diaphragm. The receiver can either be positioned on the same side of the board as the transmitter or on the opposite side. The scattered radiation is received by a mobile detector, with the recipient direction of the detector perpendicular to the transmitter beam. The receiver moves parallel to the transmitter beam. In front of the receiver, there is a slit diaphragm to measure only the scatter from a thin layer and thus the density profile with high resolution in the thickness direction.

The configuration in which the transmitter and receiver are on the same side (Fig. 20.39a) has the advantage that the cover layer can be analyzed quickly and well on one side, since the distance with the radiation travels in the material is very small. On the other hand, there is a disadvantage in that the opposite surface layer can only be inspected to a limited extent, especially in the case of thick panels, since the radiation passes through the material twice and is strongly attenuated. The version in which the transmitter and receiver are mounted on different sides (Fig. 20.39b) has the restriction that one cover layer cannot be examined in such detail so rapidly, but the radiation passes through the board only once. As a result, thicker plates can be measured and the attenuation is similar for every place in the board.

In some cases, a static detector is used to measure the mass per unit area, and both signals are used to calculate the density profile, and in-line density profile measurement has become the standard equipment in modern MDF-lines. The results are available without any time delay, but only an average value over a board length of several meters is obtained.

Off-Line Measurement
Density profiles are also measured in the laboratory on standard samples measuring 50 mm by 50 mm. In the first step, the average gravimetric density (kg/m^3) is determined from the external dimensions (m^3) (width, length, height) and mass (kg).

The radiation direction is then not in the thickness direction but in the plane of the board (Fig. 20.40). The wood samples are moved through a narrow collimated X-ray beam and, at intervals of less than one-hundredth of a millimeter, the transmission through the sample is determined. Taking in consideration the density-dependent attenuation, the density profile is then determined.

20.6.6 Board-weight Measurement

The board weight is determined after the hot press, after the diagonal saw/trimming unit or behind the star cooler. The state of the art is currently the mechanical scale (Fig. 20.41) installed under a separate conveyor belt or rollers weighing each board (100% surveillance).

Modern high production speeds mean that the classical mechanical scale cannot be used for thin board, 1.2 s being needed for an accurate measurement.

Its production processes become faster and faster, finding time for weighing is increasingly a challenge, and the trend is to determine the board weight by determining the mass per unit area using a contactless method such as a radioactive source or X-ray. The board weight is calculated as the product of the mass per unit area and the board area. Taking the thickness into account, the density over the board width can be calculated. Another reason for choosing a contactless scale

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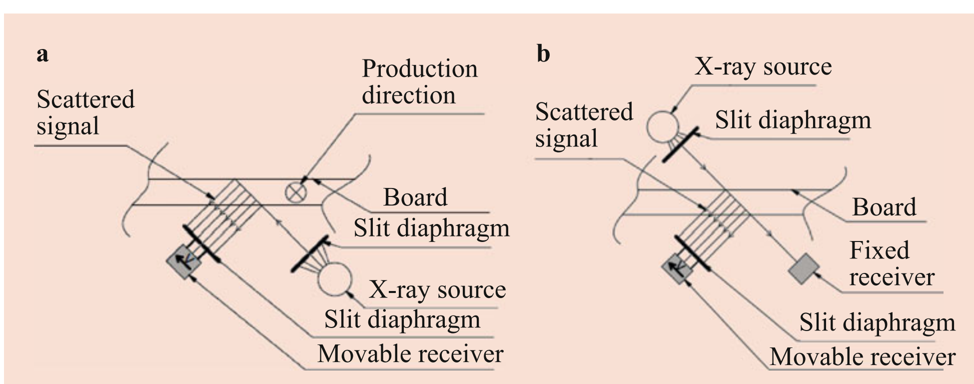

Fig. 20.39 Online density profile measurement: (**a**) receiver and source on the same side of the board, and (**b**) receiver and source on different sides of the board

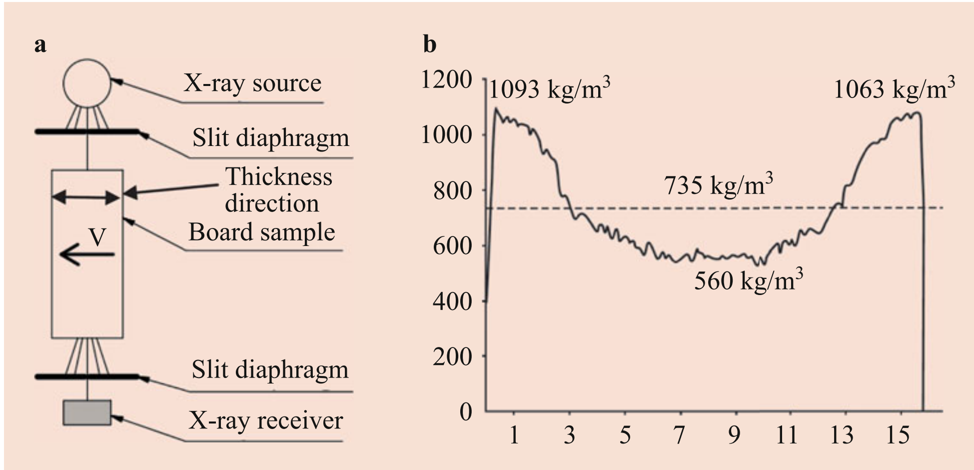

Fig. 20.40 Density profile: (**a**) Setup of an off-line density profile measurement, and (**b**) typical density profile of a wood-based panel

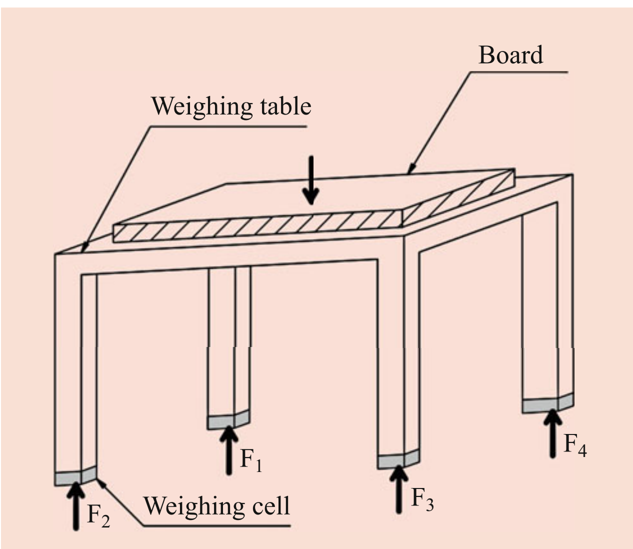

Fig. 20.41 Principle of a board scale

in new projects is the limited available space. The use of X-ray gauges also provides a saving of online construction costs.

To determine the weight of the board by X-ray, there are two possibilities: measuring in one or several representative tracks and then calculating an average or measurement of the whole width by a high precision X-ray scale. The latter is a more reliable and a high precisions option. For more detail see Sect. 20.6.2.

20.6.7 Fiber and Particle Measurements

Off-Line Measurement

The measurement of fiber length and size generally requires some preparation. Fibrous material produced under pressure and heat in a refiner is not free-flowing, and the simplest method for measuring the fibers is using tweezers and a tape measure. The sample size is very low and the method takes into account only the length of the fibers and is unsuitable for highly varied and knotted wood fibers. Therefore, in the laboratory two separation methods are used: the dry sieve and the Bauer-McNett process. Sieving for the measurement of chips in the laboratory is also used in the production of fiber boards. The Bauer-McNett process provides a sort of screening, but it is used only in the paper industry, and the fibers are deposited in successive vessels with different sieves. Neither of these methods considers the morphology of the fibers. The sieving methods cannot be used for a full characterization of the fibers, because only the fiber width can be determined [133]. In addition, they have a small size spectrum and are elaborate and time-consuming [134]. In contrast, optical methods have the advantage that they can usually cover the large spectrum of wood fibers from dust to fiber bundles. The most accurate but time-consuming method is the single viewing of the fibers with the microscope. An easier and faster method is to scan with a flatbed scanner [135] or to photograph in an air stream (Fig. 20.42a) or in the flat plane (Fig. 20.42b). The greatest advantage of measuring in a defined plane is that the objects are aligned and no error can therefore arise in the length and width measurement [136]. However, all laboratory systems have the disadvantage of measuring only a very small quantity compared with the total production quantity. Representative sampling is a challenge in all laboratory methods.

In-Line Measurement

According to Feddersen [137], an overall energy of approximately 1520 kWh is required to produce 1m^3 MDF, of which 81.3% is thermal and 16.7% electrical consumption, the

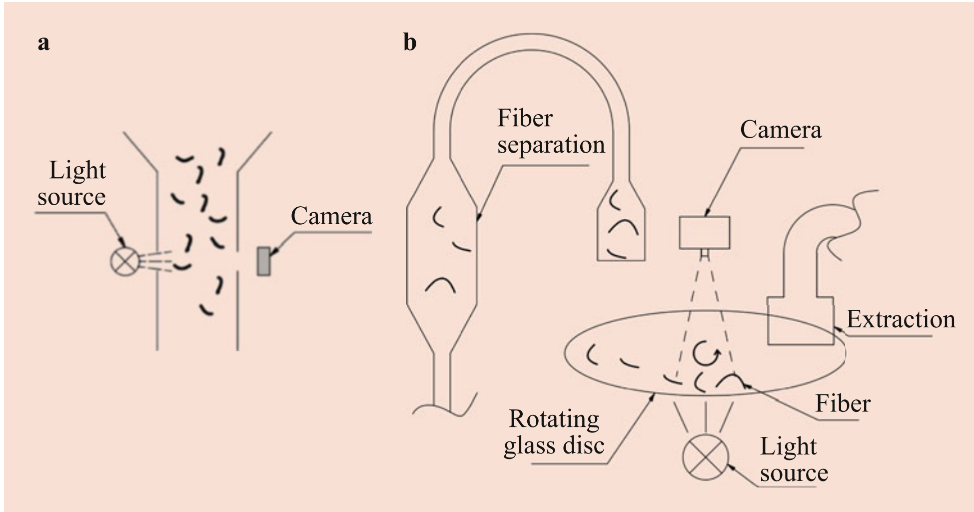

Fig. 20.42 Principle of image analysis in (**a**) an air stream, (**b**) a defined flat plate

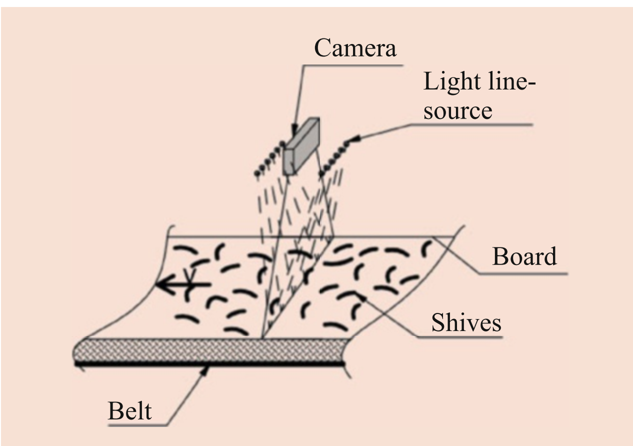

Fig. 20.43 Principle for optical control of fiber quality

greatest consumer of electrical energy being the refiner with approximately 60% [137]. This means that, considering solely the electrical energy, the defibration of the wood chips in the refiner is the largest single electrical load in the production of MDF boards. 80–110 kWh per tonne of fibers for laminate flooring with only a coarse fiber separation and up to 170 kWh for furniture boards with finely divided fibers, i.e., the fiber quality depends on the grinding energy of the refiner. The quality parameter to be set is the space between the two grinding disks. In principle, the larger the grinding disk spacing, the smaller is the electrical energy input and the coarser are the fibers or the fiber bundles (shives).

Despite the high energy consumption, it is surprising that until only a few years ago the fiber quality was determined visually as a standard test method. A fiber sample is taken from the production several times a day and is assessed visually. As a rule, this procedure results in production with safety reserves and thus wastes more than 5% electrical energy. In the production process, the control of fiber quality is very subjective and error-prone. However, the lack of suitable measurement methods for objectively and continuously analyzing and evaluating the quality of the fibers produced meant that the possibilities for optimizing the defibration process were limited and unstable.

In order to continuously monitor the fiber quality in modern MDF production, the in-line optical control of the formed fiber mat by means of an imaging method is used (Fig. 20.43). Via a line camera with an incident light system, the surface of the passing fiber mat is continuously inspected over a width of approximately 400 mm. It is not necessary to inspect the entire fiber mat width of up to 2800 mm to statistically evaluate the fiber quality. Technically, inspection over the entire width of the mat is possible, but it would significantly increase costs. A cross-beam construction is the basic feature of the measurement system. The field of view of the camera is protected by a closed tube against dirt and dust. The system is equipped with an automatic height adjustment, so that the camera and lighting unit always follow the mat height, which changes, for example, depending on the mat moisture and product. This ensures that the surface to be inspected is always exactly in the focus of the camera. The system also has an automatic light control system to compensate for brightness effects from different digester conditions or from different types of wood. Every 3 s an image with 2048 × 4096 pixels with a resolution of 100 µm transversely and longitudinally to the production direction is analyzed, which means that 100 pixels can be resolved on a 1 mm^2 mat surface, so that fiber bundles (shives) can safely be recognized in an area as small as 0.2 mm^2. Since the fibers are not isolated in the measurement position, the separation of the fiber bundles depends solely on a different gray value compared to the average gray value of the entire fiber mat. As a rule, the shive is a brighter object than the single fiber.

A photograph taken by the line camera forms the basis for the identification of the relevant objects. The first processing step eliminates existing textures, which can be placed over the original image, due to the movement of the fiber mat in the production direction through the press belt of the pre-press. In order to reconcile clear quality standards with the customer across all locations, all the parameters are related to a reference surface area of 1 m^2. In a second step, a threshold image is generated, which only displays these particles that lie above a parameterizable grayscale threshold value. This is a relative threshold that is recalculated for each captured image. In a third step, the selection is further reduced to those objects that have a minimum size and eccentricity determined by the plant operator. In this way, the shive values can be determined in-line in the fiber mix on the mat surface via the three parameters of gray value, area, and eccentricity. Various key figures, such as their respective area, the circumferences, the lengths, and the widths, are calculated for the objects found. In addition, the eccentricity of the objects as a measure of their deviation from the circular shape and the angle at which the shives are deposited on the mat surface can be calculated. In the end, a class division is achieved as a simplified classification similar to that achieved by the sieving method. The class divisions can be adjusted in order to meet the respective fiber productions. As trends visualized over time, the changes per class are directly readable.

The distance between the refiner discs or the cooking conditions in the digester can now be adjusted automatically in a control circuit on the basis of the measured values and fixed tolerances. The controller has a set-point specification per recipe (fiber quality) with upper and lower tolerance limits for an acceptable number of shives per square meter of a defined size class. The inspection system transfers the current actual values for the shive numbers to the controller via an OPC interface. The controller fits the grinding disc space so that the current shive number always lies within the defined tolerance window. With the realized automated regulation of the refiner as a function of objectively measured values of the fiber quality, a long-cherished wish of the wood-based material manufacturers has been fulfilled.

Application Benefits

With the help of a fiber inspection system, the cooking and refining process can be finely tuned and the energy consumption and fiber quality can be optimized and a saving potential of up to 10 kWh savings potential per tonne of wood can be expected. Due to the possibility of manipulating the fiber sizes, the producers of MDF boards can produce targeted fiber qualities. Internal standards can be set up and the customer requirements can be specified so that a permissible number of shives per size class per square meter of surface is determined. In the event of a complaint, objective indicators are available indicating whether the fiber quality is sufficient or insufficient.

20.6.8 Temperature and Gas-Pressure Measurements

Temperature and gas pressure are the dynamic variables used to maximize production capacity and achieve the desired density profile in wood-based panels. An exact knowledge of the two variables is an essential part of the press program. To minimize press times, a rapid hardening of the adhesive is striven for, but the degree of adhesive hardening can differ in the different mat layers [138]. To avoid blisters when the press is opened, the compound of wood particles and resin must be stronger than the sum of the restoring forces of the compressed mat and the internal gas pressure from the evaporation of water and wood components [139].

The steam movement toward the mat center is, according to Gefahrt [140], called the boiling wave and is important for the temperature development and the plasticization of the wood particles. Due to a gas pressure gradient from the mat center to the mat edges, the boiling wave moves at different speeds in the center and edge areas from the surface layer to the core layer. Evaporation of the boiling wave needed for heat transport only occurs at the appropriate evaporation temperature associated with the gas pressure, and this accounts for the different temperature levels between panel edge and panel center.

Two different systems are available: PressMAN™ and ContiLog, with its successor EasyLog. All these systems can measure the gas pressure and the temperature in the hot press and, in the case of the EasyLog sensor, also in the subsequent condition or cooling phase. The Pressman is designed as a repeatable measurement system and the Conti- and EasyLog as one use components.

With the PressMAN, a measuring tip is inserted laterally between the pre-press and the hot press into the mat and removed after the hot press. The maximum length of the measuring tip is 600 mm and the conditions in the middle of the board cannot therefore be determined.

The ContiLog or EasyLog can measure simultaneously in several positions across the board width. The measured values are transformed by wireless. In the Contilog, the sensor actively transmits the data by radio frequency, and the EasyLog transmits the data via RFID.

The ContiLog essentially consists of the components shown in Fig. 20.44.

In the production of particleboard and OSB, the ContiLog or EasyLog sensor is placed in the mat after the first core layer forming machine (Fig. 20.45) and is followed through

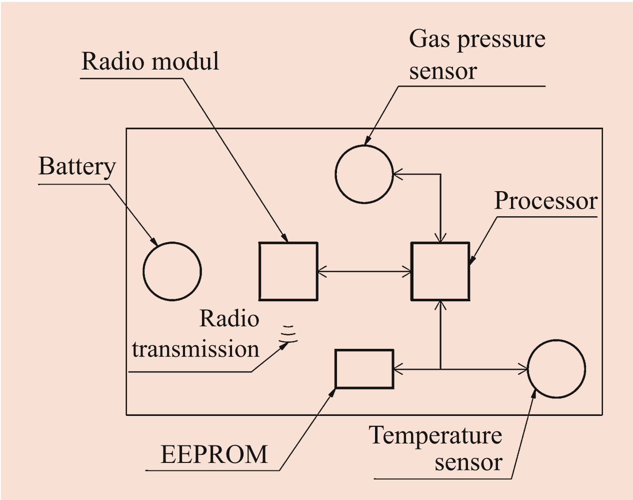

Fig. 20.44 Function scheme of the ContiLog sensor

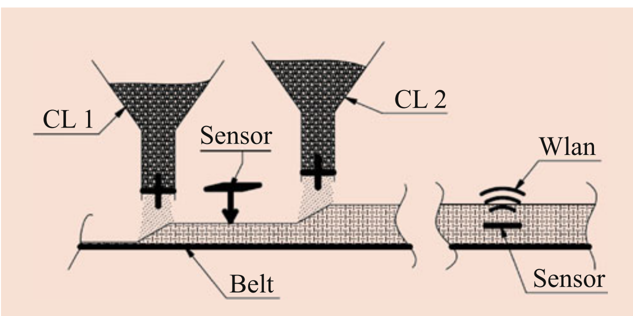

Fig. 20.45 Insertion of the sensors between the two CL forming machines

the press by a marking on the mat edge. The positions of the ContiLog sensor at the press inlet and outlet are marked for later data synchronization.

Prior to measurement, the power supply (battery) of the sensor is activated and measurement is started via the reader. For the simultaneous operation of several data loggers, each sensor has its own ID, which ensures that, after pressing, the correct sensor can be selected at any time.

The gas pressure and temperature sensors are controlled by the processor, which records the measured values, processes them, and stores them in an external memory from which they can be recalled and transmitted to the reader via the radio or RFID module. From the reader, the measured data are transferred to a PC for graphical representation.

Meyer and Thömen [139] explain the fundamental relationships of gas pressure courses in particleboard. Their results, based on measurements made with the PressMAN, up to 600 mm from the panel edge, showed a distinct horizontal gas pressure distribution in both production direction and across the width of the mat. The gas pressure was higher

Table 20.10 Maximum Contilog temperatures and gas pressures at the edge and in the center of a 38 mm particleboard

Distance from the edge (mm)	Max. temperature (°C)	Max. gas pressure (kPa)
150	109.2	24.6
1200	121.1	82.0

in MDF than in particleboard. The authors also showed a clear relation between panel thickness and gas pressure, a decrease in panel thickness leading to an increase in gas pressure.

These relationships were confirmed by measurements with the Contilog over the entire width of the mat. Table 20.10 shows the maximum Contilog temperature and gas pressure near the edge and in the center of the particleboard, determined with two ContiLogs during a 38 mm particleboard production.

Due to the higher gas pressure in the panel center, the maximum Contilog temperature was 121 °C in the center and 109 °C at the edge of the particleboard.

With the data loggers, a better understanding of the temperature and gas pressure across the mat width and along the transport direction has been achieved. This information can be used to optimize the press program. An excessively high gas pressure in the panel center may cause delamination after the hot press. The reject quota can be minimized by adjustment of the gas pressure measurement at the press outlet.

20.6.9 Surface Inspection

Modern sanding and finishing lines reach production speeds, which make the visual control of the board surface almost impossible. The high requirements for the quality of the board surfaces currently require sophisticated inspection systems. Defects on the board surface are detected by multi-line grayscale or RGB color camera systems and image analysis software.

Defects on printed surfaces can be detected by pattern matching or by threshold value evaluation. The threshold value method can be used for decor papers and raw boards, whereas the pattern matching method can only be used for multicolored decors with repeating print patterns. The threshold method assumes that the errors are brighter or darker than the rest of the surface. The pattern matching method, on the other hand, indicates the differences from an original pattern.

Modern inspection systems not only detect errors but can assign these errors to specific causes in the process. The defects are classified because the focus is not only on quality control but also on process optimization.

The systems are equipped with different light sources and to detect different types of surface errors several differently directed sources of illumination are used (Fig. 20.46).

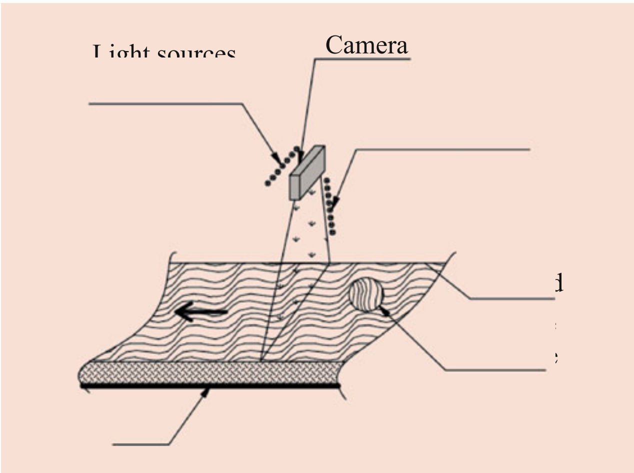

Fig. 20.46 Principle of surface inspection systems in the wood-based panel industry

The systems are able to detect locally limited defects like holes, oil stains, condensates, or rubber embeddings and large-scale defects like, e.g., chatter marks or grid lines. Different detected defects may have different degrees of relevance for the process and the quality requirements of the current production order. Depending on the type of defect, the system can trigger different actions. Minor defects can, for example, only be recorded for statistical evaluation in order to improve the production process in the medium term. Major defects may trigger warnings so that an operator is able immediately to straighten production settings. Panels with defects that affect further processing or may result in customer complaints can immediately be downgraded or rejected [141].

In raw panel production, the inspection system is located behind the hot press or after the sander. In laminated panel production, it is located behind the coating/melamine short cycle or continuous press.

The surface inspection systems make it possible to minimize complaint rates as well as to optimize the manufacturing process in general.

20.6.10 Preview and Future Trends

In times of increasing networking of industrial production systems and optimized process control based on Industry 4.0, the extraction of as much data as possible for quality control is becoming increasingly important in the production process [142]. The integration of nondestructive testing methods into production processes and the rapid return of data is of crucial importance in order to be able to guarantee the required product quality and the most efficient production possible [143].

The increasing demand for accuracy and reliability of the online measurement systems already has an effect on future trends. The near future will require 100% surveillance throughout the whole process and, as a result, the demand for the continuous availability of the measurement systems [144].

As a consequence, the general trend, which can be summarized under the keyword Big Data, can also be seen in the wood products industry. There will be an exponentially increasing data volume/flow and a need for intelligent solutions regarding high-speed signal processing, evaluation, and visualization. The immediate answer to this is more powerful data processing capacity. In the next step, all data can be combined to provide an innovative quality trending and forecast system.

However, several other factors also contribute to this development toward complexity: increasing production speeds combined with an increase in automation and plant capacity as well as more diversification to a larger range of products, increasing quality requirements and demand for cost efficiency.

Increasing complexity will also have an impact on the work and on the work conditions at the production site. For the correct handling of advanced systems, staff will require further training (operators, maintenance) and more specialists will be required to provide the expertise in the fields of measuring technology, mechanics, and electrics as well as electronics and data technology.

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