BRAZILIAN SAWMILLS

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ABSTRACT

The Brazilian Forest Sector is one of the most productive in the world with a good share of the Brazilian Gross Domestic Product. The furniture sector represents about 18% of the consumption of planted wood in Brazil and employs about 35% of the workforce in the sector. They are micro and small companies that generate a lot of jobs and fix the workforce in the countryside; however, the obsolete machinery and poorly trained workforce are responsible for the low productivity and profitability of the sector. The objective of this work was to identify the main problems and point out solutions for them. The main raw material and machinery indicators were identified, as well as corrective measures for each of them. The main conclusions were that the sector must organize itself in productive poles seeking the maximum specialization or the smallest number of products per establishment.

Keywords: Wood drying defects; Band saw; Technological parameters; Cut speed; Wedge angle; Sawdust.

INTRODUCTION

In Brazil, 9.94 million hectares were planted in 2022, with 76% being *Eucalyptus* spp. with an average productivity of 32.7 $m^3\ ha^{-1}\ year^{-1}$ and 19% being *Pinus* spp., predominantly planted in the Southern region with an average productivity of 30.9 $m^3\ ha^{-1}\ year^{-1}$. The planted area for solid wood products represents 7% of the total planted area. The Brazilian Forestry Sector experienced significant growth, reaching approximately 50 billion dollars in 2022, reflecting a 6.3% annual increase. This growth contributed 1.3% to Brazil's Gross Domestic Product (GDP), making it the sixth-largest industrial activity in the country. The sector generated US$ 4.82 billion in taxes, with 663,000 direct jobs and 2.6 million indirect jobs. Brazilian exports of solid wood products totaled US$ 106 billion in sawn wood, US$ 167 billion in plywood, US$ 65 million in wood panels, and US$ 1.05 billion in furniture (Brazilian Tree Industry – IBA, 2023; SNIF, 2024).

Brazil ranks eighth globally in wood panel production with 8.5 million m^3, of which approximately 82% is exported, mainly to the USA. In 2022, 10.5 million m^2 of laminate flooring were sold, with 95% in the domestic market. During the same period, 8 million m^3 of sawn wood were produced, ranking Brazil as the 10th largest producer globally, with 40% destined for export (IBA, 2023; SNIF, 2024).

Brazil is the sixth-largest furniture producer globally, employing 57% of the workforce in the forestry sector. In 2020, Brazilian wood exports amounted to US$ 300 million in panels and floors, US$ 1.2 billion in plywood, and US$ 600 million in lumber (Brazil/MAPA, 2020; IBA, 2021).

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The wood processing sector comprises 87,000 companies, generating over 173 thousand direct jobs, mainly in the Southeast and South regions. Brazil is the ninth-largest producer of *Pinus* spp. sawn wood with 10 million m^3, with over 90% of production destined for the domestic market. The reforestation wood sector in Brazil consumes approximately 40 million m^3 annually, with 10% from *Eucalyptus* spp. and 90% from *Pinus* spp. In the plywood sector**,** 60% comes from *Pinus* spp., 40% from *Eucalyptus* spp., and in the last 15 years, only 125 industrial patents have been registered for this sector, which demonstrates stagnation and little innovation (Brazil/MAPA, 2020; IBA, 2021; TEIXEIRA & ROCHA, 2022).

In 2020, there were 18,000 furniture industries in Brazil, generating 270 thousand direct jobs and exporting $ 628 million, with wooden furniture representing over 85% of this total (ABIMÓVEL, 2021; Brazil, 2021; IEMI, 2021).

The objective of this study is to examine the key factors influencing the productivity and profitability of small and medium-sized sawmills in Brazil working with exotic species (*Eucalyptus* spp. and *Pinus* spp.) and propose improvements for their main challenges.

MATERIALS AND METHODS

Metadata from the Brazilian Forestry Sector and key countries with recognized tradition and production in furniture, post-2018, were analyzed considering technical and economic aspects.

RESULTS AND DISCUSSION

Table 1 shows the main problems with the raw material, table 2 shows the main problems with sawing and drying of wooden parts and table 3 shows the main factors that influence the machinery, end Figure 1 shows the main drying defects.

The main factors that affect log sawing are species, basic density, moisture, diameter, length, taper, piece size and log quality, variation in grain orientation, product mix, operator decision; fiber cutting direction. In relation to the machinery, the main characteristics are angles of incidence, cut, and exit; cutting speed, cutting thickness and width, total num ber of teeth and tool diameter, state and maintenance of equipment and sawing methods (BALASSO et al., 2022).

Table 1. Factors related and that influence the Sawn Wood Yield (SWY) in a Brazilian sawmill.

Factor	Lumber yield
Log diameter	The bigger the better
Board width	The larger the cutting number, the lower the yield
Growing stress	Produces boards with splitting, bowing and twisting
knot	The closer the canopy, the greater the number of knots
Gran	Gran reverse produces boards with bow and warping
Taper	Inverse correlation, less than 1 cm m^{-1} does not interfere
Cutting humidity	The more humid, the easier sawing
Wood density	Negative correlation (greater fiber wall thickness)
Conifers	SWY from 55% to 65%
Hardwoods	SWY from 45% to 55%
Species from the Amazon	SWY of 35% mainly due to taper

Lumber yield (RMS)

Wood yield is the ratio between the volume of sawn wood and the volume of bole wood. It varies according to the species, diameter, length, taper, tortuosity, width and thickness of the piece and number of cuts in the log. Among the species, the main factors are density, arrangement of anatomical elements and moisture content. Regarding equipment, the main factors are splitting techniques, type of equipment, saw sharpening and machine operator experience (POPADIC et al., 2019; SANTOS et al., 2019; SILVA et al., 2022).

Log or trunk diameter

The larger the diameter of the log, the greater the yield of sawn wood. The volume lost with chips and edgings is smaller in percentage compared to the volume of logs. Furthermore, efficiency also improves because less time is spent managing the log (POPADIC et al., 2019; SMAJIC et al., 2021).

Cut numbers

The greater the number of cuts a log undergoes, the lower its yield, with saw thickness being the main factor influencing yield (ORLOWSKI et al., 2022; THOMAS & BUEHLMANN, 2022).

Growth stress

Growth stress is generated during tree growth at cell maturation in the cambium zone. These forces produce tensile stress in cells near the cambium, while cells near the pith are in compression. This contrast generates a residual stress distribution with equilibrium at approximately two-thirds of the radius. The growth stress is related to the growth rate of the tree, so the higher the growth rate, the greater the growth stress, the greater the losses due to the splitting of the log tip and the sawn piece. The transverse grain reduces growth stress cracking. There is nothing else you can do (log heating, steaming, retaining grid) to reduce this tension, any of these techniques will only delay the crack. A decision must be made whether the loss of wood due to growth stress is offset by the greater volume produced by a given species (pioneer or early secondary) than another slower growing species that does not have growth stress (late secondary or climax). Radial cutting minimizes growth stresses in species prone to collapse by drying but incurs greater losses in logs less than 40 cm in diameter due to distortion related to growth stresses. Tangent cuts, made with a simple band saw, are not suitable for woods with high growth stresses, such as eucalypts. After the removal of a shore, the remaining block is deformed by bending, due to the new accommodation of the growth stresses. Therefore, it is recommended to rotate the log 180^o after removing one board, for small logs, and two boards, for logs with diameters greater than 60 cm (BALASSO et al., 2022; FRANÇA et al., 2020).

knot

There are no knots on the base log and the higher the tree height, the greater the probability of finding knots; in the lower part there are loose knots, coming from dead branches retained by the trees, near the crown are live knots and cause greater problems, depreciating the sawn pieces because they reduce the natural beauty and mechanical resistance of the wood. The knots increase the density of the wood and, consequently, the forces required for cutting, and as a result, they require a greater cutting angle of the saw. The trees accept very well (without affecting productivity) pruning of up to 30% of the crown (BALASSO et al., 2022; CÁCERES et al., 2018).

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Grain

Grain is considered straight when it occurs parallel to the longitudinal axis of the tree, transversal deviates from the longitudinal axis as reversed or inclined, if its inclination is to the right or left. These orientations influence the physical and mechanical properties of the wood as well as its texture. Straight grain provides better looking parts but causes greater twisting and collapse. Reverse grain reduces wood yield as it increases warpage and makes drying difficult, but improves mechanical properties, reduces twisting and collapse. The cross structure of the microfibrils gives the wood high axial rigidity, in addition to high resistance to collapse and rupture, which allows for an efficient conduction of water from the roots to the crown and an erect growth of the plant (BOSSU et al., 2018; COELHO et al. al., 2020; FRANÇA et al., 2020; MENDIS et al., 2019; RAVENSHORST et al., 2020).

When cutting against the grain direction, the number of teeth should be larger and the throat diameter smaller. When cutting in favor of grain, the diameter of the saw blade should be larger, and the angle of the hook should be smaller. Cutting against the grain, at a 90º angle to the grain, requires up to five times more force, therefore consumes more energy (CURTI et al., 2018; SILVA et al., 2022).

Taper

Taper is the reduction in the diameter of the log from the base to the top of the tree. The tree is considered taper when it presents a decrease of one cm per meter in diameter. The taper is inversely related with the stand density. Usually the first log (base) has larger taper than the others (BALASSO et al., 2022; SANTOS et al., 2019; ULAK et al., 2022).

Wood density and wood moisture

High density woods tend to have smaller lumens and thicker cell walls, so they are stronger, take longer and require greater amounts of energy to saw when dried below the fiber saturation point (FSP). When wood is dried below the FSP, there is a submicroscopic reduction of spaces and, consequently, an approximation between the microfibrils of the cell wall, which leads to an exponential increase in the stiffness and strength of wood to the fourth power. Water works as a lubricant between the wood and the saw, so the denser the wood, the higher water storage. When dry, the higher the density, the higher the cutting energy must be, the saw diameter and the number of teeth must be larger, the tooth throat smaller and the feed and cutting speed low rake angle (CURTI et al., 2021; GAO et al., 2021; GUEDES et al., 2020; IVANOVSKIY, 2021; SILVA et al., 2022).

Conifers x Hardwoods

Hardwoods are harder, denser, and more resistant to fungi and insects than conifers, so they naturally last longer and are more valuable. In conifers a yield of 40% to 60% is acceptable, while in hardwoods the yield varies from 30% to 50%. Conifers have a less tortuous shape, and sapwood is always usable. Eucalypts trees have high growth stresses, responsible for cracks at the ends of logs and boards, knots and other defects that contribute to greater losses (BALASSO et al., 2022; SILVA et al., 2022; THOMAS & BUEHLMANN, 2022).

Cutting direction

There are three basic types of 90-0º cutting (longitudinal plane, the cut is perpendicular to the grain, but the table movement is parallel to the grain); 90-90º (axial, saw and table move perpendicular to the grain); and 0-90º (radial or tangential plane, the cut is parallel to the grain, but the table movement is perpendicular).

The 90-0° type or longitudinal cut is found in processes conducted by planer and in cuts of boards, in the direction parallel to the fibers or longitudinally. Bandsaw work is a typical case of 90-90° cutting and cutting forces will vary depending on the type of cut. The cutting force is minimal when the cut is parallel to the grain or 0° and increases up to 90°. When cutting in the 0–90° cutting direction, lateral cutting becomes more influential when the cutting width is decreased (CÁCERES et al., 2018; CURTI et al., 2021; MASCIA et al., 2020; MEULENBERG et al., 2022).

Tangential cut

The cut is with the grain at an angle ranging from 0 to 45° in relation to the orientation of the wood, the movement of the wood can be twice greater than in the radial cut because there is greater storage of water, however the resistance is greater. Tangential cuts consume less energy and are more productive and efficient, recommended for logs with a diameter of up to 40 cm, generally it does not cut logs with less than 16 cm in Brazil due to the low yield, it produces boards with more uniform thicknesses, but because it incorporates the pith show more and greater cracking (increased growth stress on pith), cambering, bowing, bending, twisting, stiffening, collapsing, shrinking, worse appearance, and reconditioning. The increase in temperature and/or feed rate tends to aggravate these defects. Deformations are easier to correct in the tangential system (MASCIA et al., 2020; RAVENSHORST et al., 2020).

Radial cut

Radial cuts look better because the radius can be at 90° with the grain, the grain orientation angle varies from 45 to 90°, there is less movement of the wood and they are recommended for logs with diameters greater than 40 cm, but they consume more energy. Because they dry faster than tangential cuts, they cause more collapse, bowing and buckling (MASCIA et al., 2020; RAVENSHORST et al., 2020).

The rays can be problematic in radial cutting. When the rays line up with the saw, the cut is smooth. When perpendicular to the saw, the rays compress and smash, producing wood with a rough surface. Tangential cuts are indicated for carpentry (structural parts) because they present greater resistance, and radial cuts for carpentry because they present better appearance.

Bow (Figure 1A)

Bow is the bending of the edges of the pieces in the longitudinal direction, that is, the length of the piece. The bow increases from bark to pith and with the diameter of the tree. The bow is greater in radial cuts when compared to tangent cuts and decreases with the correct drying of the wood (BALASSO et al., 2022; WIEDENBERCK et al., 2019).

Cup (Figure 1B)

Cupping is the deformation where the sides of the boards try to come together. It occurs in the transition of juvenile wood under compression, which expands and the other side under tension contracts, causing channeling, being more frequent in tangential cuts. Cupping has a good correlation with the anisotropic index and increases with wood drying, ratio between tangential and radial contractions (WIEDENBERCK et al., 2019).

Arching (Figure 1C)

Arching are distortions that occur in the wood in relation to the original plane of the surface. Tangential cuts reduce arching and cups. There is no correlation between the log diameter and the arching. Arching occurs

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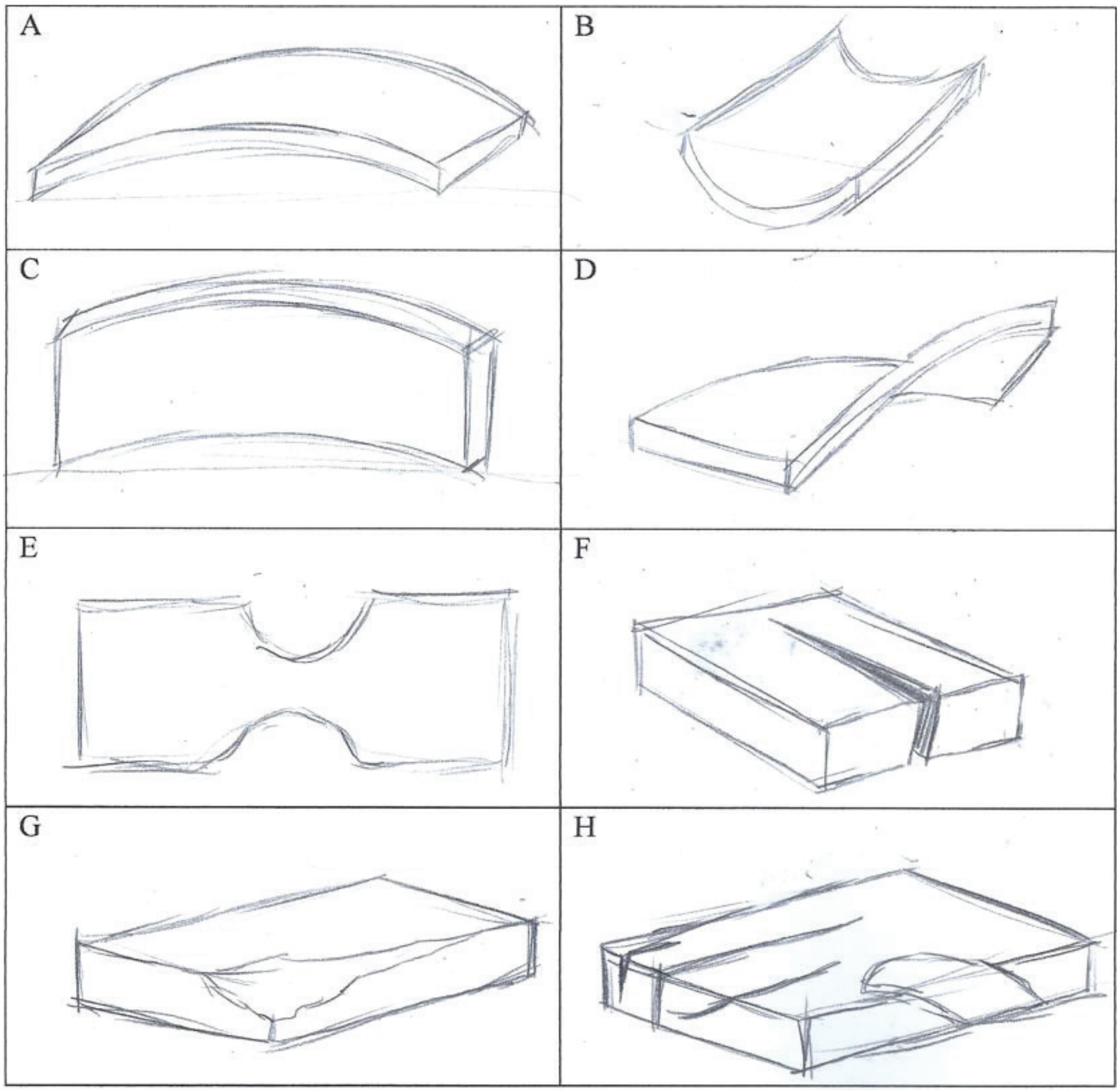

Figure 1. Main defects that occurred during wood drying: A = Bow; B = Cup; C = Arching; D = Twist; E = Collapse; F = End splitting; G = Wane; H = 1 = Checks 2 = Shake, 3 = knot.

shortly after unfolding and increases after drying (ANANIAS et al., 2020; BALASSO et al., 2022; WIEDENBERCK et al., 2019).

Twist (Figure 1D)

The board is distorted in two or more planes. The twist is the result of several factors that add up to a single piece, that is, different shrinkage, spiral grain, growth stress and transition from juvenile to adult wood, consequently they are larger near the pith, very accelerated drying programs and cuts tangential tend to have greater amounts of twist (ANANIAS et al., 2020; WIEDENBERCK et al., 2019).

Collapse (Figure 1E)

Collapse is an abnormal and irregular contraction that manifests itself during capillary water removal. The exit velocity of water is greater than the velocity of air entering the space left by it. In this way, cells can be sucked in by capillary forces, resulting in their collapse. The main cause is capillary tension. The factors that most contribute to this are: diameter and thickness of the fibers, juvenile wood that has fibers with thinner cell walls and less mechanical resistance, which causes collapse at high temperatures at the beginning of drying. Hygroscopic extractives also contribute to collapse. Any technique (preheating, increasing drying time, reducing temperature or increasing relative humidity) that reduces the rate of drying reduces the rate of collapse (ANANIAS et al., 2020; BALASSO et al., 2022; WIEDENBERCK et al., 2019; YANG & LIU, 2018; YUNIARTI et al., 2020).

End spliting (Figure 1F)

There are three types of end spliting that can appear in the wood due to drying problems: 1) Upper cracks: they occur at the ends of the board, caused by the fast drying of these board in relation to the others; 2) Surface cracks or vibrations: generally occur in the wood radii or resin channels, along the entire side of the piece, they occur due to the low relative humidity in the surface layers of the piece, drying it quickly, while the internal layers are left with moisture above 30%, preventing retraction of the most superficial layers, causing tissue rupture; and 3) Internal or alveolar cracks: they can result from superficial cracks that have closed on the surface, or they can be ruptured by traction of the internal layers. Surface and top end spliting occur in the initial stages of drying, due to the drying gradient, while internal cracks manifest at the end of the process, usually associated or in the extension of surface end spliting. They increase with the drying of the wood and are more frequent when the drying program is extremely fast. End spliting due to growth stress increase from the bark to the pith. These end spliting have a positive correlation with the diameter of the logs, and with the temperature and drying speed, and are greater for tangential cuts (because they dry faster), but do not interfere with radial cuts (BALASSO et al., 2022; FRANÇA et al., 2020; WIEDENBERCK et al., 2019; YUNIARTI et al., 2020).

Wane (Lack of corner on one side of the board) (Figure 1G)

It occurs mainly in tangential cuts; the correction is made by reducing the width of the board until the defect is eliminated.

Superficial spliting (felling, shake and knot) (Figure 1H)

Surface hardening is the manifestation of tension in dry wood, in which the surface fibers are subjected to compressive stresses and the internal ones under traction. It occurs in the transition from juvenile to adult wood and can worsen due to very rapid and uneven drying. It cannot be recovered by reconditioning (ANANIAS et al., 2020; WIEDENBERCK et al., 2019).

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Clearance angle or free angle (α)

It is the gap between the cut surface and the part to be cut, reducing friction, favoring the advancement of the part. Increasing the rake angle decreases front wear and cutting-edge strength. It should be enough so that the back of the tooth does not touch the wood after cutting, avoiding friction and heat generation. Large clearance angles decrease the forward force of the wood (less contact of the wood with the non-cutting parts of the blade), but increase the tooth decay tendency, as they are linked to small wedge angles. On the other hand, small clearance angles allow for larger wedge angles and stronger teeth but may lose stability in the cut due to contact of the back of the tooth with the wood. The clearance angle should be decreased when the material is hard (high density) or to reinforce the cutting-edge. The angle of incidence should be increased when the wood is of low density or easily hardened. The positive angle facilitates dust evacuation but weakens the wedge, while the negative angle makes the tool more rigid, sacrificing dust evacuation (FRAGASSA et al., 2019; GAO et al., 2021; LI et al., 2018; PINKOWSKI et al., 2018).

Tangential clearance angle

It is the clearance angle seen by the rake surface. Its function is to allow the tool to remain free along the length of the cut in its path through the wood in the direction of

Table 2. Influence of the type of cut on sawn wood yield (SWY).

Factor	Tangential cut	Radial cut
Growing tension	180º turn with each piece cut	It is more suitable
Productivity	Higher	Lower
Diameter	16 a 40 cm	40 cm
Precision	Less accurate	More accurate
SWY	Major (fewer log cuts)	Minor
Board thickness	More uniform	Less uniform
End spliting	Major and most frequent	Smaller and less frequent
Board drying	Faster	Slowe
Defects quantity	More defects	Less defects
Warping	Bigger (easier fix)	Smaller
Cup	Major	Minor
Crook	Major	Minor
Wane	Major (board of smaller width)	Minor
Twist	Major	Minor
Bow	Major	Minor
Checks	Major	Minor
Shrinkage	Major	Minor
Collapse	Minor	Major
Appearance	Worst	Best
Reconditioning	Worst	Best
Energy consumption	Small	Large

movement of the saw, the smaller the gap, the smaller the roughness of the surface of the part. It varies from 25° for soft materials, up to 45° for harder materials. The greater the angle, the lower the feeding force (FRAGASSA et al., 2019; MEULENBERG et al., 2022).

Radial clearance angle

It is the gap angle seen by the gap surface of the tooth. It makes the beginning of the tooth greater than the end, thus allowing space for the tooth to run free in the relative movement caused by the advancement of the wood over the saw. It varies from -1° for thicknesses around 20-40 mm, to -2° for 80-100 mm (FRAGASSA et al., 2019; MEULENBERG et al., 2022).

Wedge angle (β)

It is formed by the metal tip of the tooth and determines its resistance. The thinner or sharper it is, the easier it is to cut and break. It must be large enough to give the tooth the necessary rigidity. The greater the density of the wood, the greater the angle of cut. The larger the cutting angle, the more aggressive the tooth, the faster the cut and the worse the finish. Aggressive blades are suitable for softwoods but will not last when cutting hardwood. The force or energy consumed to cut the wood increases with increasing density, cutting thickness, wedge angle, decreasing the angle of attack and increasing cutting speed, when cutting parallel to the fibers. The greater the penetration depth, the smaller the cutting angle, generating thicker powder and thus decreasing cutting efficiency. A larger cutting angle generates finer powder, providing greater cutting efficiency. It is affected by cutting speed, feed and saw design (GAO et al., 2021; MEULENBERG et al., 2022; PINKOWSKI et al., 2018; SVOREN et al., 2022).

Lead angle or Exit angle or Hook angle (ϒ)

They vary according to the thickness of the piece, the larger, the faster and easier the feeding, in practice they vary from 8 to 20º**;** smaller angles allow better control and are used for denser woods. Cutting forces decrease with increasing angle of attack. Large rake angles (powder) allow higher feed rates and are suitable for sawing soft wood, teeth with small angles are used in blades intended for sawing dense wood at low feed rates. High feed speeds require larger rake angles than at lower speeds, they can be positive (acute angle), null (shallow) or negative (obtuse). The smaller the hook angle, the better the quality of the sawn part. In practice, 15 to 25º is used for both soft and dense wood; for agglomerates and laminates from 5 to 15º; from 0 to 5º for plywood type veneers and negative for two-face melamine agglomerate. The rake angle has a greater impact on the roughness or quality of the part than the feed rate. These angles (α, β and ϒ) are complementary. The rake angle influences the force and power required or cut, the surface finish and the heat generated. The greater the angle of inclination, the less bending work of the powder. The angle of inclination depends on: a) the strength of the tool and the material to be machined; b) the amount of heat generated by the cut; c) the forward speed. The negative angle is used to cut difficult-to-machine materials and in interrupted cuts, requiring greater machining force and power, in addition to generating more heat in the tool. Increasing the rake angle in the positive direction decreases the cutting-edge resistance in the negative direction, one degree in cutting effort, decreases the power by approximately 1%. The rake angle should be increased in the negative direction when the machined material is hard and when higher cutting-edge strength is required, such as interrupted cutting and rough surface machining. The angle of inclination in the positive direction should be increased when the material is soft or with low stiffness (CÁCERES et al., 2018; FRAGASSA et al., 2019; PINLOWSKI et al., 2018; ZHU et al., 2018).

Cutting speed

It has a negative correlation with wood density, cutting angle, clearance angle, wedge angle, saw diameter, tooth pitch, tooth width, thickness, height and tooth clearance. Positive correlation with feed speed, rake angle, cutting angle, friction angle and milling depth. Powder type is a function of rake angle and does not correlate with cutting speed. On a bandsaw, the cutting speed for softwood is up to 50 m s^{-1}, for hardwood 40 to 46 m s^{-1} and for extremely dense wood 30 to 35 m s^{-1}. For medium density fibreboard (MDF) the speed varies from 40 to 70 m s^{-1}. A double-cut saw reduces time by 10-12% compared to the time spent on a single-cut saw. The lower the tooth advance, the better the surface quality and the less need to sand the part, however, the tooth has a short service life. Ideally, it should be slow enough to not damage the finish, and fast enough to avoid burning the wood. There is a tendency to decrease energy consumption with increasing feed speed and decreasing cutting speed. However, with the feed rate too high and the cutting speed too low, the energy required is greater than the energy supplied by the motor. Fixing the feed rate, the greater the number of saw teeth, the lower the cutting speed (CÁCERES et al., 2018; CURTI et al., 2018; FEKIAC et al., 2022; FRAGASSA et al., 2019; GAO et al., 2021; KOLEDA et al., 2019; KOVAC et al., 2021; NASIR & COOL, 2019; PINKOWSKI et al., 2018; SVOREN et al., 2022).

Feed speed

It is the distance traveled per unit of time between the tool and the wood. For breakout operations, feed speeds are between 15 to 100 m min^{-1} depending on the saw model. In Brazil, 17 m min^{-1} is normally used for hardwood and 22 m min^{-1} for softwood, reaching 35 m min^{-1} depending on the cutting height. Cutting power decreases with increasing feed speed. Bandsaw lateral deflection increases linearly with increasing feed speed up to a point, and exponentially thereafter. The higher the feed rate, the longer the powder length and the higher the energy consumption and the higher the roughness of the part (FEKIAC et al., 2022; FRAGASSA et al., 2019; LI et al., 2018; SVOREN et al., 2022).

Wide blade width (≥ 63.5 mm)

The wide blade (≥ 63.5 mm) features the bottom of the teeth throat must be at least five mm away from the flywheel. They are limited to straight cuts or primary cuts. In general, it is recommended to use the widest blade your saw will allow 10 mm wider than the width of the wheel or flywheel. Greater thickness excessively tensions the saw. The shape and arrangement of teeth originate in six basic ways. The thicker, the stiffer the blade. For wide blades there are three basic types of teeth: 1) C or N: with a wide throat and good rigidity, it is used in operations to cut any type of wood; 2) P or O: allows the powder to be divided more easily and is used for all types of wood; and 3) Special, it has a very wide rake angle and throat space, so it is suitable for soft woods. Wider blades produce less noise, can be faster, can cut wider parts, and cuts are straighter and thinner. The grounding or fixing of the tooth should be 45 to 60% of the total size of the tooth. Narrow blades (≤ 50.8 mm or 2 inches) are used for secondary cutting such as contours or indentations (FRAGASSA et al., 2019; SYSALA et al., 2019).

Tooth

When choosing the type of tooth, consideration should be given to the throat capacity, adequate lateral stability and cutting geometry. Tooth geometry affects cut variation (instability), surface finish, cut thickness, and energy consumption. Tooth pitch, tool angles, throat area, and radial and tangential clearance angles will determine variations in cut, surface finish, cut thickness, and power consumption. Crosscuts require more teeth than longitudinal cuts. Saws of the same diameter with more teeth tend to consume more energy, produce smoother cuts, generate more dust. When the wood is high density, the saw diameter and the number teeth should be larger, the tooth throat smaller and the feed and cutting speed low rake angle (ÇAKMAK & MALKOÇOGLU, 2019; FRAGASSA et al., 2019; KOVAC et al., 2021; SILVA et al., 2022; SYSALA et al., 2019).

Tooth height

Distance between the cutting edge and the bottom of the throat, with the following characteristics: 1) softwood blades must have a higher height than for hardwood; 2) woods with a high moisture content need fewer teeth, a larger throat and the feed and cutting speed should be lower; 3) By increasing the diameter of the saw, the cutting speed must be increased; 4) greater in repressed blades than in locked blades; 5) by increasing the width and thickness, the height of the tooth can be increased; 6) should not exceed ten times the thickness; 7) for blades with a width between 100 and 150 mm, the height can be selected based on the following criteria: 7.1) Softwood: blades with repressed teeth: height equal to one third of the pitch. Blades with locked teeth: height three and a half to four times less than the pitch; 7.2) Hardwoods: blades with repressed teeth: height three and a half to four times smaller than the pitch; blades with locked teeth: height five times smaller than the pitch. The smaller the tooth, the slower the cut, as the tooth has a small throat and cannot carry copious amounts of sawdust while working. The smaller the tooth, the finer the cut and the better the finish. The greater the number of teeth, the faster the cut. It is generally recommended to have six to eight teeth engaged in cutting. If fewer than three teeth are engaged, there is a possibility of chatter or vibration as there is a tendency to overfeed the work and each tooth is cut too deeply. Fewer teeth engaged means more teeth filled with sawdust. Both problems can be overcome to some extent by adjusting the feed rate. Once the diameter of the circular saw is fixed, the greater the thickness of the part to be sawed, the lower the number of teeth (ÇAKMAK & MALKOÇOGLU, 2019; FRAGASSA et al., 2019; SILVA et al., 2022).

Pitch of the teeth

Distance from the tip of one tooth to the adjacent. Determines the number of teeth that will act simultaneously on a sawn part. It can be constant (uniformity in everything, distance of teeth, depth of throat, angle of inclination) or variable (variation in any element, usually presents two different pitches). The most important features are: 1) cutting speed: to increase speed, you must increase the pitch; 2) Feed speed: larger pitch means, decrease the feed without decreasing the performance, but requires more frequent sharpening; 3) Profile of the teeth: the throat must have an adequate shape and depth to ensure a good removal of the sawdust, the angle of the tooth must guarantee a good cut and rigidity; 4) Type of wood: hard woods need to be cut with smaller steps than soft ones, dry woods also need smaller steps than green ones, abrasive woods need bigger steps; 5) Cutting height: it is recommended to keep at least three to five teeth working simultaneously, to distribute the efforts to remove the sawdust; 6) Width and thickness: with greater widths and thicknesses, the pitch can be increased while maintaining the rigidity of the saw, thinner cuts require a greater number of teeth per inch (ÇAKMAK & MALKOÇOGLU, 2019).

In principle, the pitch of the teeth would have no effect on the cutting force, however, saws with a large pitch (few teeth working simultaneously) can be shifted more easily in the lateral direction, increasing the width of cut and the cutting force when entering contact with the side of the blade with the wood. A step that is too large increases the strain on each tooth, quickly depleting the edge. A small step produces a smoother sawn surface but requires more energy. A small pitch necessarily implies a small tooth base and restricts the advancement of the lumber to be sawn. If the tooth tip angle and the cutting angle are large, the backs of the teeth can be strongly convex to avoid an excessively large pitch (ÇAKMAK & MALKOÇOGLU, 2019).

Cutting height

The higher the cutting height, the lower the force and consequently the lower the energy consumption, which allows for higher feeding speed (FRAGASSA et al., 2019; GAO et al., 2021).

Chip (Dust, particles, chips and semi-continuous chips)

Each cutting tool is defined by three main angles: Dust exit, tooth tip and incidence. Powder thickness is a function of the tool rake angle, that is, a positive correlation with the rake angle and a negative correlation with the settling degree. The larger the shape, the course the chip and the worse the finish of the part. With fine powder, the wear is manifested with greater intensity on the clearance surface. In thick powder, it is evenly distributed between the exit surface and the gap surface, the tooth maintains its shape and acuity longer. The type of chip is a function of the machined material and type of tooth and has the function of dissipating the heat generated by the saw. Wetter wood produces larger and curlier chips, especially in cuts parallel to the grain. The higher the density, the longer the time to cut and the lower the dust generation. The thicker the chip, the greater the energy consumption (FRAGASSA et al., 2019; KOVAC et al., 2021; SILVA et al., 2022; SVOREN et al., 2022; ZHU et al., 2018).

Cutting parallel to the grain produces very fragmented chips and a large amount of dust, while cutting perpendicular to the grain produces continuous chips and a small amount of dust. The greater the number of teeth, the greater the amount of dust produced. When cutting against the grain direction, the number of teeth should be larger, and the throat diameter should be smaller. When cutting in favor of the grain, the diameter of the saw blade should be larger and the hook angle should be smaller (ÇAKMAK & MALKOÇOGLU, 2019; CURTI et al., 2021; SILVA et al., 2022).

CONCLUSION

Most sawmills in Brazil have low yield and efficiency due to obsolete equipment and generate large amounts of waste. A sector-focused funding program is required.

Regarding the raw material, one should try to work with few species of large diameter because the percentage of juvenile wood is reduced and the efficiency in the handling of the log's increases.

Warping and cracking are caused by anisotropy, wood moisture gradient, distorted grain, growth stress, drying stress, transition from juvenile to late wood. The correction or reduction of warping is achieved with better stacking of the boards and more conservative or less accelerated drying programs.

Regarding the machinery, to improve performance, one must reduce the thickness of the saw (reduction in sawdust losses) and increase the precision in the cutting thickness of the part to improve quality and reduce losses due to wrong measurements, this is achieved by working with the most modern equipment and choosing the ideal tooth for each species and piece produced. The great diversification of products also decreases productivity because it requires adjustments in the equipment.

The government should encourage and organize productive arrangements, such as in Ubá-Minas Gerais State, Itapetininga-São Paulo State, Guarapuava-Paraná State, Itajaí-Santa Catarina State and Cachoeira do Sul-Rio Grande do Sul State, where there is an offer of raw materials, and organize vocational courses to stimulate development in these places.

Factor	Influence
Wood moisture	Negative correlation, reduces the friction between the tool and the chip, expels the chip from the cutting region, cools the part and improves the surface finish
Density	Positive correlation, higher energy consumption
Saw diameter	Negative correlation
Cutting angle or wedge	Positive correlation with density
Angle of incidence or clearance	Distance between the cutting tool and the surface of the part to be cut, negative correction with density
Attack angle	Negative correlation with density, for large angles repressed teeth, and locked teeth for low angles
Cutting speed	Negative correlation with density, saw diameter and tooth pitch, and saw part quality. It is higher in the orthogonal cut (90-90), a positive correlation with the draft and cut angle
Feed speed	From 15 100 m min-1, in Brazil it is practiced 17 m min-1 for hard woods and 22 m min-1 for soft woods, reaching 35 m min-1 depending on the cutting height
Cutting force	Decomposed into normal and parallel, positive correction with cut density and thickness, negative correlation with moisture, cut angle and rake angle
Cutting direction	Transverse steering requires less force
Cutting thickness	Positive correlation with sawdust loss
Cut 90°-90°	Chips 1 and 2, requires higher rake angle
Circular saw clearance	1 to 2 mm of the thickness of the sawn part
Tooth	Thickness greater than that of the saw (reduces friction), in the transverse cut direction the fibers are greater than in the longitudinal cut the fibers, for low density woods it is recommended high saw speed, high cutting height and tooth throat to remove more chips, for high density woods the reverse, the smaller the thickness of the saw, the stronger the tooth must be, the greater the exit angle, the smaller the cutting angle, the clearance angle must be as small as possible
Knife and counter-knife clearance	Major cause of bending moment, bending or crushing failure
Wide band saw	Low waste generation, high cutting speed, thinner cut
Saw thickness	Positive correlation with flywheel diameter

Table 3.
Factors that influence the effort, wear and energy consumption of the saw.

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