



Article

Development and Performance Analysis of an Automated Flat Blade Grinding Machine for Wood Processing and Plastic Recycling Industries

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Abstract

This study presents the design, development, and experimental validation of an automated flat blade grinding machine for the wood processing and plastic recycling industries in Ecuador. The machine was engineered following the VDI 2221/2222/2225 design methodology, integrating SolidWorks-based 3D modeling and ANSYS finite element analysis (FEA) to validate critical structural components. The selected configuration includes a Type 6 alumina grinding wheel (38A-60-K-VS), a mechanical clamping system, cutting fluid cooling, and a hardwired electromechanical control system that does not require a programmable logic controller (PLC). FEA results confirmed adequate safety factors ($\eta_s > 16$; $\eta_f > 14$) for the ACME 3/4–8 power screw under operational loads. Experimental testing on blade specimens (thickness: 3 mm; length: 70 mm; steel up to 60 HRC) demonstrated that four grinding passes at a 45° inclination angle reduced mean surface roughness (R_a) from $5.39 \pm 1.83 \mu\text{m}$ (used blades) to $0.162 \pm 0.092 \mu\text{m}$, achieving values comparable to new blades ($R_a = 0.601 \pm 0.153 \mu\text{m}$): a point-estimate reduction of 97% in mean R_a relative to the used-blade condition. The automated process reduced average grinding time by approximately 30% compared to manual methods, while maintaining noise levels within the 85 dB occupational exposure limit. Operator satisfaction surveys rated the system above 4.5/5.0 across all ergonomic and usability criteria. These results validate the proposed machine as a cost-effective, locally manufacturable solution to standardize blade maintenance in small and medium enterprises (SMEs) across Latin America.

Keywords: automated control; blade sharpening; machine tool design; surface integrity; VDI 2221



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1. Introduction

The wood processing and plastic recycling industries in Ecuador are predominantly composed of small- and medium-sized enterprises (SMEs), which collectively account for approximately 7.2% of the national manufacturing GDP according to the Ecuadorian Central Bank [1]. These industries rely heavily on high-speed cutting and chipping equipment, the flat blades of which require frequent maintenance cycles. Due to the abrasive nature of lignocellulosic materials, chipper knife wear has been shown to cause productivity losses exceeding 20% in wood processing operations, requiring sharpening intervals of every

100–115 operating hours under typical industrial conditions [2,3]. In plastic recycling applications, contamination from hard inorganic materials in post-consumer plastics accelerates blade wear further, typically requiring maintenance interventions on a weekly basis [4].

A further compounding factor is technological dependency: many SMEs rely on external sharpening services typically located in major cities, which implies long waiting times, increased logistics costs, and poor process traceability. Manual and semi-automatic sharpening methods—the predominant alternative—are characterized by low precision control, leading to inconsistencies in cutting angles and loss of quality in the final product finish [5]. These operational limitations highlight the need for automated, in-house grinding solutions that are both technically accessible and economically viable for SMEs.

Research has shown that any improvement or treatment to the blade has a significant impact on production and product quality. Savescu et al. [6] demonstrated that continuous monitoring of tool wear is crucial for maintaining cutting quality and preventing workplace injuries. McGorry et al. [7] analyzed how the cutting-edge angle and post-sharpening finish affect cutting forces, significantly reducing physical effort and improving workplace safety. In this regard, Denkena et al. [8] emphasized the importance of surface roughness modelling to optimize tool performance and ensure high-quality finishes.

Previous studies on sharpening and grinding machines highlight advancements in process automation technologies. Zieliński et al. [9] demonstrated that a prototype 5-axis CNC precision grinding machine achieves repeatable surface quality in industrial blade sharpening, confirming that controlled process parameters are among the primary determinants of achievable Ra. Marchal et al. [10] analyzed cutting forces in wood machining under various process conditions, providing a comprehensive review applicable to the design and structural analysis of wood-cutting machine components. Malkin and Guo [11] established that wheel specification—particularly abrasive type, grain size, and contact geometry—is the primary determinant of achievable surface quality in grinding of hardened steels. Hardwired relay-logic control architectures represent the most practical automation entry point for wood product SMEs with limited technical personnel, consistent with the design philosophy adopted in the present work.

Despite these advances, a significant research gap remains in the development of automated grinding solutions specifically designed for the operational and economic constraints of SMEs in developing countries. Existing automated sharpening systems reported in the literature [8,9,12] rely on CNC architectures or PLC-based control systems that require substantial capital investment, specialized maintenance personnel, and reliable spare-parts supply chains—conditions that are rarely met in the wood processing and plastic recycling sectors of Latin America. Furthermore, no study to date has documented a complete engineering design process from requirements specification through structural validation and experimental performance testing for a flat blade grinding machine adapted to locally available materials and manufacturing capabilities. The absence of such documentation limits the replicability of automated maintenance solutions in industrial contexts similar to Ecuador.

In this context, this study proposes, designs, builds, and experimentally validates an automated flat blade grinding machine tailored to the industrial needs of Ecuadorian SMEs. The design follows the VDI 2221/2222/2225 methodology and integrates SolidWorks 3D modeling (2024), ANSYS (2023 R1) finite element analysis, and a hardwired electromechanical control system to achieve a low-cost, maintainable, and locally manufacturable solution. The specific objectives of this work are: (1) to apply a structured engineering design methodology to select the optimal machine configuration; (2) to validate the structural integrity of critical components through analytical calculations and FEA; and (3) to

evaluate machine performance in terms of surface roughness (Ra), grinding time, noise level, and operator satisfaction compared to the manual process.

2. Materials and Methods

The design and development process of the automated flat blade grinding machine was conducted in four sequential stages: (1) requirements specification and functional analysis; (2) conceptual design and alternative selection via morphological analysis and VDI-weighted matrices; (3) detailed mechanical design using analytical methods, 3D CAD modeling, and finite element simulation; and (4) physical prototype construction and experimental performance validation. The target workpieces were flat blades made of carbon steel, hardened steel, stainless steel, and high-speed steel (HSS) with hardness up to 60 HRC, dimensions ranging from 50 to 600 mm in length, 70–100 mm in width, and 3–20 mm in thickness. All experimental tests were conducted at the mechanical engineering laboratory of the Faculty of Mechanics at ESPOCH.

2.1. Methodological Foundation

The proposed grinding machine was designed following the structured procedure established by VDI 2221 [13], VDI 2222 [14] and VDI 2225 [15]. The VDI 2221 methodology organizes the design process into seven sequential stages grouped into four phases: (I) requirements clarification, which produces the specification; (II) conceptual design, comprising functional analysis, search for solution principles, and division into realizable modules; (III) preliminary and definitive layout development; and (IV) preparation of production documentation. The methodology has been demonstrated to be effective in streamlining the design and selection process for mechanical systems of comparable complexity [16].

The adoption of the VDI 2221/2222/2225 methodology provided three specific advantages over a design process based solely on engineering experience. First, the formal requirements specification stage (Table 1) ensured that all functional, technical, and ergonomic constraints were explicitly documented before any design decision was made; in experience-based design, these constraints are often implicit and inconsistently applied, leading to scope gaps that only emerge during manufacturing or operation. Second, the morphological analysis combined with weighted evaluation matrices (Tables 2 and 3) imposed an objective, quantitative comparison of three distinct design alternatives across sixteen criteria, whereas experience-based design typically converges on familiar solutions without systematic evaluation of alternatives. Third, the mandatory sequential validation sequence—analytical stress calculations, FEA simulation, and physical prototype testing—provided documented evidence of structural adequacy at each stage, in contrast to experience-based approaches where structural adequacy is assumed from past practice and only tested when the prototype is already built.

Table 1. List of initial specifications.

Demand/ Wishes	Parameter	Specification
D	Main Function	The machine's function is to sharpen flat blades commonly used in the plastic recycling and wood processing industries.
D	Material compatibility	Materials to be processed: Carbon steel, hardened steel, stainless steel, HSS. Maximum material hardness: Up to 60 HRC Blade dimensions supported: Length: 50–600 mm, Width: 70–100 mm, and Thickness: 3–20 mm.

Table 1. *Cont.*

Demand/ Wishes	Parameter	Specification
D	Control	The clamping process is manually controlled to block the movement of the blade, but the drive of the grinding wheel and coolant is automated, thus limiting the operator's work to only placing the blade in the machine. In addition, a certain angle greater than 45° will be set up for sharpening before the process. The use of sensors and trajectory planning is crucial for optimizing the cutting angle and surface quality, which are critical for achieving consistent sharpness in blades.
W	Environment	The machine has a chip collector that also contributes to collecting excess lubricants.
D	Maintenance	The machine is designed and built in such a way that it facilitates access to the components that require maintenance.
D	Manufacturing	The machine is planned to be manufactured in the national territory with materials offered by the local market.
D	Energy	The machine operates on the standard 220 V/60 Hz alternating current supply available in the national electrical distribution network, requiring no special power infrastructure.
W	Ergonomics	The geometry and measurements of the machine are designed in such a way that the operator has access to the machine and all its controls, and it is also planned that the operation is autonomous so that the operator is located at a safe distance, both due to the noise generated and the risk of impact from the machine.
D	Vibration control	The machine must be equipped with a vibration absorption system to prevent the wear of mechanical components and lack of precision during sharpening.

Table 2. Technical evaluation matrix for conceptual solutions according to VDI 2225.

Alternative Solution			1		2		3		Ideal Solution	
Nº	Evaluation Criteria	g	p	gp	p	gp	p	gp	P	gp
1	Security	3	3	9	3	9	3	9	4	12
2	Energy Efficiency	2	3	6	2	4	2	4	4	8
3	Principal Axis Stiffness	3	2	6	2	6	2	6	4	12
4	Machine Stability	3	2	6	3	9	3	9	4	12
5	Machine Weight	1	3	3	3	3	3	3	4	4
6	Operability	2	3	6	3	6	1	2	4	8
7	Productivity	3	3	9	3	9	3	9	4	12
8	Product Quality	4	2	8	2	8	3	12	4	16
9	Maintenance	3	2	6	1	3	1	3	4	12
10	Ergonomics	3	3	9	3	9	3	9	4	12
	Maximum Score		26	68	25	66	24	66	40	108
	Technical Value Xi		0.6351		0.6149		0.6081		1	

Table 3. Economic evaluation matrix for conceptual solutions according to VDI 2225.

Alternative Solution			1		2		3		Ideal Solution	
Nº	Evaluation Criteria	g	p	gp	p	gp	p	gp	p	gp
1	Cost of Materials	4	3	12	1	4	2	8	4	16
2	Manufacturing Cost	3	2	6	2	6	2	6	4	12

Table 3. Cont.

Alternative Solution			1		2		3		Ideal Solution	
3	Cost of Components	2	2	4	1	2	1	2	4	8
4	Cost of technology	3	3	9	1	3	1	3	4	12
5	Maintenance Cost	3	3	9	3	9	3	9	4	12
6	Energy Consumption	2	3	6	2	4	2	4	4	8
Maximum Score			16	46	10	28	11	32	24	68
Technical Value Yi			0.6739		0.413		0.4674		1	

2.2. Initial Specifications

In the first stage, it was necessary to define the specifications of the grinding machine, considering the functional, technical, economic, and characteristic requirements specified by the user. The following recommendations from companies, manufacturers and researchers have also been revised. Technical studies have determined that factors such as material compatibility, the quality of the blade steel, the absence of protective coatings, and inadequate cooling during sharpening all adversely affect the durability of the edge [17]. In addition, assembly errors, vibrations, and misalignments during operation also contribute to early wear [18]. Ergonomics in sharpening operations has also been extensively studied [7], analyzing how the cutting-edge angle and post-sharpening finish affect cutting forces, significantly reducing physical effort and improving workplace safety. Vézina and Chatigny [19] emphasized the importance of training to ensure a safer and more efficient grinding process. In the industrial sector, Savescu et al. [6] demonstrated that continuous monitoring of tool wear is crucial for maintaining cutting quality and preventing workplace injuries.

2.3. Functional Analysis

The functional analysis of the blade grinding machine is developed to understand and logically structure the functions to be performed. It begins with the elaboration of the black box diagram, as shown in Figure 1, in which the system is presented abstractly, and the variables (matter, energy and signals) of input and output are defined; it is a widely used technique that serves to understand the transformation of the variables after applying the process.

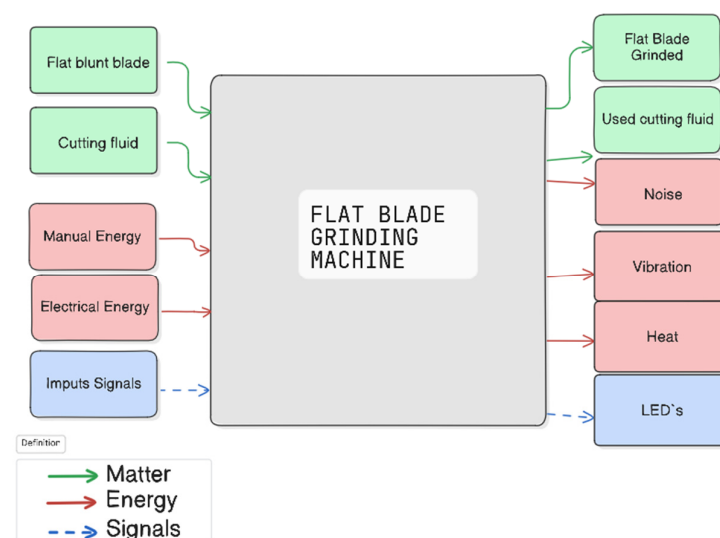


Figure 1. Black Box Diagram. Source: Authors.

Building upon the functional architecture shown in Figure 1, the machine operates as a semi-automatic sharpening center. The system processes matter (blunt blades and cutting fluid), energy (electrical and manual for setup), and signals (operator inputs) to produce a precisely ground blade. The machine integrates a 3 HP grinding spindle, a 2 HP motorized traversal system for feed control, and a 0.5 HP cooling system. This configuration allows for the restoration of blades up to 65 cm by maintaining critical cutting angles through an adjustable holder.

Figure 2 presents the sequence of operations diagram, which provides a structured and chronological representation of the complete grinding cycle. This diagram was developed as an intermediate step between the black box model and the Function Structure analysis, allowing each operation to be identified as a key transformation or control action within the system [9].

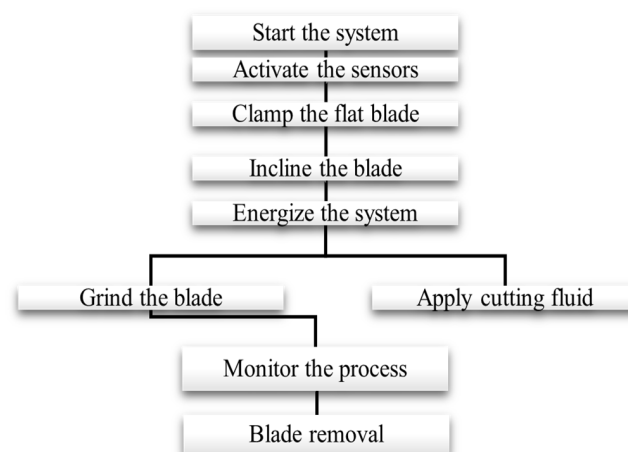


Figure 2. Sequence of operations. Source: Authors.

The sequence begins with the system startup, which initializes the control system and activates the sensors responsible for monitoring process conditions throughout the cycle. Once the system is ready, the operator performs the preparation stage: clamping the flat blade onto the machine frame and inclining it to the required grinding angle. With the blade secured and positioned, the system is energized, triggering two simultaneous parallel processes: grinding the blade and applying the cutting fluid. These two operations run concurrently, as continuous lubrication is required from the moment the grinding wheel contacts the blade surface to prevent thermal damage and premature wheel wear. Both processes are governed by a monitoring stage, which monitors the operating conditions and triggers visual indicators, or emergency stops if anomalies are detected. The cycle concludes with blade removal, returning the system to its initial standby state.

This sequential and parallel structure forms the basis for identifying the functional requirements of each subsystem: clamping, inclination, driving, cooling, control, and monitoring, which are mapped in detail in the Function Structure diagram presented in the next section.

2.4. Functions Structure

Figure 3 presents the functional flowchart of the blade grinding machine, which presents the operational logic, energy inputs, material flows, control systems, and resulting outputs. The diagram is structured into four main blocks: preparation, main process, control and monitoring, and outputs. The process begins with the manual and electrical energy inputs that activate mechanical preparation stages. After that, the machine can clamp, set up the inclination angle and energize the electromechanical actuators. The next

stage is the grinding operation, supported by a cooling and refrigerating subsystem using a cutting fluid. A control system governed by sensor inputs monitors the process conditions and triggers visual indicators (green, yellow, and red LEDs) to signal operation status, component failures, or emergency stops. The flowchart is a clear interpretation of how energy and materials are transformed during the grinding process, and it is a helpful tool to the designer as a methodological basis for analyzing the functional behavior and evaluating the performance of the proposed machine system.

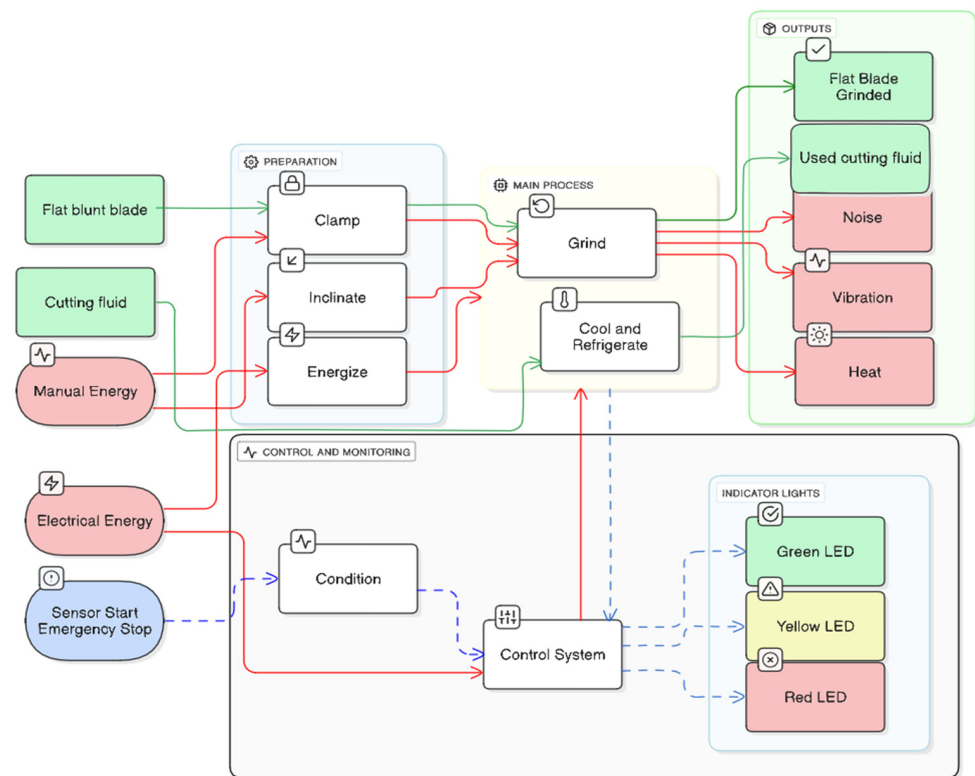


Figure 3. Structure for the design of the grinding machine. Source: Authors.

The sequence of operations presented provides a well-structured basis for the functional analysis of the blade sharpener. This approach is widely used by mechanical designers as each step in the process can be identified as a key transformation or control action of the system. The process begins with the initial activation and continues until the delivery of the final product, in this case, the sharpening blade. From this sequence, the Function Structure analysis was developed to map the specific objectives of each component or subsystem, presenting its roles, inputs, outputs, and interactions within the grinding process. This analysis is critical for the identification of different solution carriers that can be treated as possible alternative solutions.

2.5. Development of Conceptual Solutions

Once the Function Structure has been defined, conceptual solutions are generated and selected by VDI 2222 [14]. This standard provides a procedure for developing technical principles to implement each of the identified functions. Figure 4 illustrates the combination of solution carriers, applying the morphological analysis of Zwicky [20]. Three combinations of solutions were generated based on the defined functions.

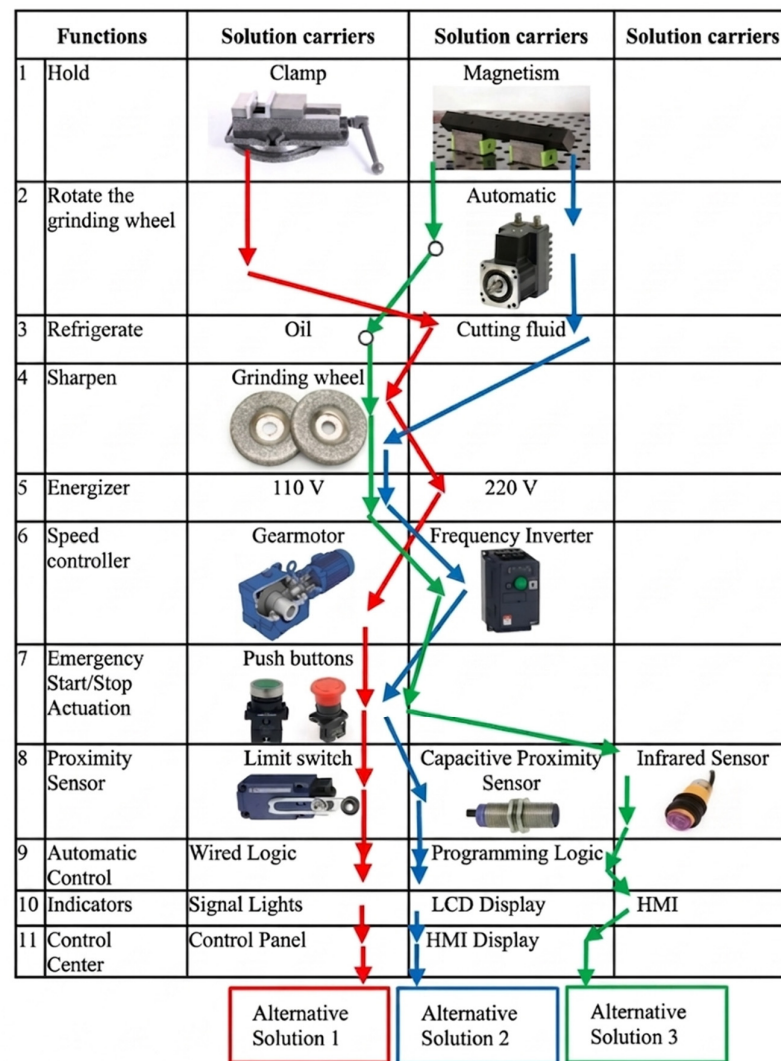


Figure 4. Morphological matrix of Zwicky. Source: Authors.

2.6. Technical and Economic Evaluation According to VDI 2225

After defining conceptual solutions through morphological analysis, a technical and economic evaluation of each design alternative was conducted according to VDI 2225. This evaluation was carried out using weighted matrices. Several technical and economic criteria were weighed and scored. Each solution generated from the morphological matrix was analyzed based on these attributes, assigning a score (p) from 1 to 5 (with 5 being the most favorable) and a weight (g) from 1 to 5 (with 5 being the most critical). Tables 2 and 3 show the results of the evaluation.

Following the weighted evaluation, Alternative Solution 1 emerged as the optimal design configuration, achieving the highest scores in both the technical ($X_i = 0.635$) and economic ($Y_i = 0.674$) assessments, as shown in Tables 2 and 3. This result confirms that the selected concept offers the best balance between functional performance and cost-effectiveness among the three alternatives considered.

The selected configuration integrates the following components and subsystems: (1) a mechanical clamping system to securely hold the blade during grinding; (2) a manual rotation mechanism for precise inclination angle adjustment prior to the grinding cycle; (3) cutting fluid as the cooling and lubrication medium to prevent thermal damage to the blade edge; (4) a cup-type grinding wheel as the tool for material removal; (5) a 220 V/60 Hz power supply, consistent with the national electrical distribution network;

(6) a gearmotor for controlled speed reduction in the grinding wheel drive; (7) push-button actuation for cycle start and emergency stop functions; (8) limit switches for automatic travel restriction and carriage reversal at stroke ends; (9) a hardwired pilot light system as a visual process status indicator; and (10) a centralized control panel housing all electrical and control components.

This configuration was selected not only for its technical and economic merits, but also for its compatibility with locally available materials and components, ease of maintenance by non-specialized personnel, and robustness under the operating conditions typical of Ecuadorian SMEs. The detailed mechanical design of this concept is developed in the following section.

2.7. Mechanical Design

The mechanical design phase focused on thoroughly specifying components and structural elements, which began after the optimal conceptual or alternative solution was selected. The designer must consider several standard engineering procedures during the design process, starting with analytical calculations performed using equations commonly applied in the mechanical design of components, such as those related to stress, deformation, torque transmission, and fatigue criteria, to ensure the correct dimensioning of each part. Additionally, the engineering software SolidWorks was employed to create detailed 3D models of all components, allowing verification that their geometry enabled proper assembly and functional integration of the entire machine. Finally, finite element analysis (FEA) was conducted using ANSYS to assess the strength, deformation behavior, and safety margins of critical components under simulated operating conditions. Complementary to these procedures, technical catalogs were consulted to define the materials for manufactured parts and select suitable commercial components consistent with design requirements.

2.7.1. Grinding Wheel Selection

The grinding wheel is one of the most critical components of the machine, as it directly determines the surface quality, material removal rate, and thermal load imposed on the blade during the sharpening process. The selection was based on three primary criteria: compatibility with the target blade materials (carbon steel, hardened steel, stainless steel, and HSS up to 60 HRC), geometric suitability for flat surface grinding, and availability in the local market.

A Type 6 cup-shaped grinding wheel was selected, as this geometry allows the abrasive face to contact the blade's surface at a controlled inclination angle, which is essential for achieving consistent edge geometry across the full blade width. The abrasive material selected was aluminum oxide (38A), which is the standard choice for grinding ferrous materials and hardened steels due to its friability—the tendency to fracture and expose fresh cutting edges during use—which maintains cutting efficiency and reduces heat generation at the tool–workpiece interface [11,21]. A grain size of 60 was chosen as a compromise between the material removal rate and surface finish quality: coarser grains (lower number) remove material faster but produce rougher surfaces, while finer grains yield smoother finishes at lower removal rates. The K hardness grade (medium) was selected to ensure that the wheel releases worn abrasive grains before excessive heat builds up, preventing glazing of the wheel surface. The vitrified bond type (VS) was preferred for its rigidity, porosity, and resistance to cutting fluids, making it compatible with the wet grinding process implemented in this machine. The complete specifications of the selected grinding wheel are summarized in Table 4.

Table 4. Grinding wheel specifications.

Characteristic	Value
Shape	Type 6 (cup)
Abrasive	38A (Alumina)
Grain Size	60
Hardness Grade	K
Bond Type	Vitrified (VS)
Dimensions (mm)	127 × 50.8 × 31.8
Edge Width (mm)	10
Back Face Thickness (mm)	13

The selected wheel dimensions (127 × 50.8 × 31.8 mm) provide a sufficient abrasive surface area for blades up to 100 mm in width, consistent with the design specification range of 70–100 mm (Table 1). The 10 mm edge width ensures uniform contact along the blade bevel, while the 13 mm back face thickness provides structural rigidity to withstand the grinding forces without deflection. The maximum operating speed of the wheel was verified against the spindle motor speed (3450 rpm), confirming safe operation within the manufacturer's recommended peripheral velocity range of 20–25 m/s [21].

2.7.2. Power Screw and Nut Design

The design verification of the power screw was performed following the theory of Power Screws [21]; by applying different stress equations, safety factors, and torques, the following results were obtained using a single-start ACME 3/4–8 thread in horizontal loading conditions with a 29° thread angle (half-angle $\alpha = 14.5^\circ$). The AISI 1018 low-carbon steel was selected to manufacture the power screw due to its good machinability, ductility, and moderate tensile strength, making it suitable for shafts and transmission components and the standard structural steel ASTM A36 was selected for the nut due to its high weldability and toughness.

For the analytical design, the following parameters and assumptions were adopted, representing typical operating conditions for lubricated steel–bronze screw systems and taking into account the mechanical properties of the material: friction coefficient $\mu = 0.15$, lead $l = 3.175$ mm, mean diameter, $d_m = 17.2$ mm, core diameter $d_c = 15.40$ mm, core area $A_c = 186.3$ mm², polar moment of inertia $J = 1.42 \times 10^5$ mm⁴, thread mean radius $r = 7.7$ mm, yield strength, and small eccentricity $e = 3$ mm. These properties were assumed to model assembly misalignment. The mechanical properties of the AISI 1018 steel were $S_y = 372.32$ MPa (54 ksi), ultimate tensile strength $S_{ut} = 441.26$ MPa (64 ksi), endurance limit, $S_e = 132.38$ MPa ($0.3 \times S_{ut}$) and alternating stress component for fatigue: 10% of mean stress.

The total axial load F was determined using Equation (1) as the sum of four load components: the motor weight ($W_{motor} = 230.54$ N obtained from the manufacturer's datasheet of the selected gearmotor, rated mass 23.5 kg); the carriage weight ($W_{carriage} = 252.91$ N), determined from the mass properties of the SolidWorks assembly model of the grinding carriage, with a total mass of 25.8 kg (including frame, linear guides, and fittings); the blade weight ($W_{blade} = 7.85$ N, corresponding to the maximum blade mass within the design range: 600 mm × 100 mm × 20 mm, $\rho = 7850$ kg/m³); and the frictional resistance ($f_r = \mu \times N$, where $\mu = 0.15$ is the kinetic friction coefficient of the linear guide system and N is the normal force component on the guide rails).

$$F = W_{motor} + W_{blade} + W_{carriage} + f_r \quad (1)$$

$$F = 706.25 \text{ N}$$

The torque required to move the load was calculated using Equation (2), which considers the mean diameter, lead, friction coefficient, and thread geometry. These parameters allow the efficiency of the screw and the power required by the drive motor to be determined.

$$T = \frac{F \cdot d_m}{2} \cdot \left(\frac{l + \pi \mu d_m \cos \alpha}{\pi d_m - \mu l \cos \alpha} \right) \quad (2)$$

$$T = 1.14 \text{ N.m}$$

The axial stress σ on the screw core was calculated using Equation (3):

$$\sigma = \frac{F}{A_c} \quad (3)$$

$$\sigma = 3.79 \text{ Mpa}$$

The shear stress τ induced by torque was obtained using Equation (4):

$$\tau = \frac{T \cdot r}{J} \quad (4)$$

$$\tau = 0.062 \text{ Mpa}$$

The bending stress σ_b generated at the root of the thread is calculated using Equation (5):

$$\sigma_b = \frac{32 F \cdot e}{\pi \cdot d_c^3} \quad (5)$$

$$\sigma_b = 19.2 \text{ Mpa}$$

The equivalent von Mises stress σ_m combined the effect of shear and normal stresses σ_a in the screw and was estimated using Equation (6):

$$\sigma_m = \sqrt{(\sigma_a)^2 + 3\tau_{max}^2} = \sqrt{(\sigma + \sigma_b)^2 + 3\tau_{max}^2} \quad (6)$$

$$\sigma_m = 23.0 \text{ Mpa}$$

The static safety factor η_s was calculated using Equation (7).

$$\eta_s = \frac{S_y}{\sigma_m} \quad (7)$$

$$\eta_s = 16.2$$

Finally, the fatigue safety factor (modified Goodman) η_f , for an alternating component of 10% (conservative approach), was calculated using Equation (8).

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} = \frac{1}{\eta_f} \quad (8)$$

$$\eta_f = 14.8$$

The ACME 3/4–8 screw exhibits low combined stresses and very high safety margins ($\eta_s > 16$, $\eta_f > 14$), confirming a robust configuration. The moderate torque demand ($T = 1.14 \text{ N.m}$) ensures energy efficiency and long service life under cyclic operation.

2.7.3. Gearmotor and Drive System Selection

The required output speed for the lead screw was determined based on the desired linear traversal velocity of the grinding carriage ($v = 0.05 \text{ m/s}$) and the screw lead

($l = 3.175 \text{ mm/rev}$), yielding a target output speed of $n_{out} \approx 945 \text{ rpm}$. Considering a gear transmission efficiency of 92%, a commercially available gearmotor with the following specifications was selected: rated power $P = 0.37 \text{ kW}$ (0.5 HP), output speed $n = 1400 \text{ rpm}$ with a 1:1.5 reduction ratio ($n_{out} \approx 940 \text{ rpm}$), nominal output torque $T_{nom} = 3.78 \text{ N}\cdot\text{m}$, and IP54 protection class, operating at 220 V/60 Hz. The selected torque provides a safety factor of 3.3 over the analytically required torque ($T = 1.14 \text{ N}\cdot\text{m}$) for the horizontal traversal under maximum axial load ($F = 564.99 \text{ N}$) and then applies a safety factor, ensuring reliable operation under variable load conditions.

The rated power was determined through an analytical torque requirement study. For the traversal system, the axial load was calculated as the sum of component weights and frictional resistance (f_r). A safety factor of 3.3 was applied to the required torque to select a 0.5 HP (0.37 kW) gearmotor, ensuring reliability under variable cutting loads. The grinding spindle utilizes a 3 HP motor to maintain constant peripheral speed during material removal.

For the grinding wheel spindle, a dedicated three-phase induction motor ($P = 0.75 \text{ kW}$; $n = 3450 \text{ rpm}$; 220 V/60 Hz) was selected, providing a peripheral grinding speed of $v_s = 22.9 \text{ m/s}$. This falls within the recommended operating range of 20–25 m/s for alumina (38A) wheels grinding hardened steel, consistent with the wheel manufacturer's specification for the selected Type 6 cup wheel [11,16].

2.7.4. Structural Fasteners and Blade Holder System

Using the finite element software ANSYS to simulate static conditions, it was possible to assess the stress distributions and safety factors for the fasteners anchoring the motor base and structural frame, as seen in Figure 5a. Additionally, the same analysis was conducted on the blade holder system seen in Figure 5b to check its stiffness, as the sharpening process requires that the blade does not move and a flat surface can be obtained.

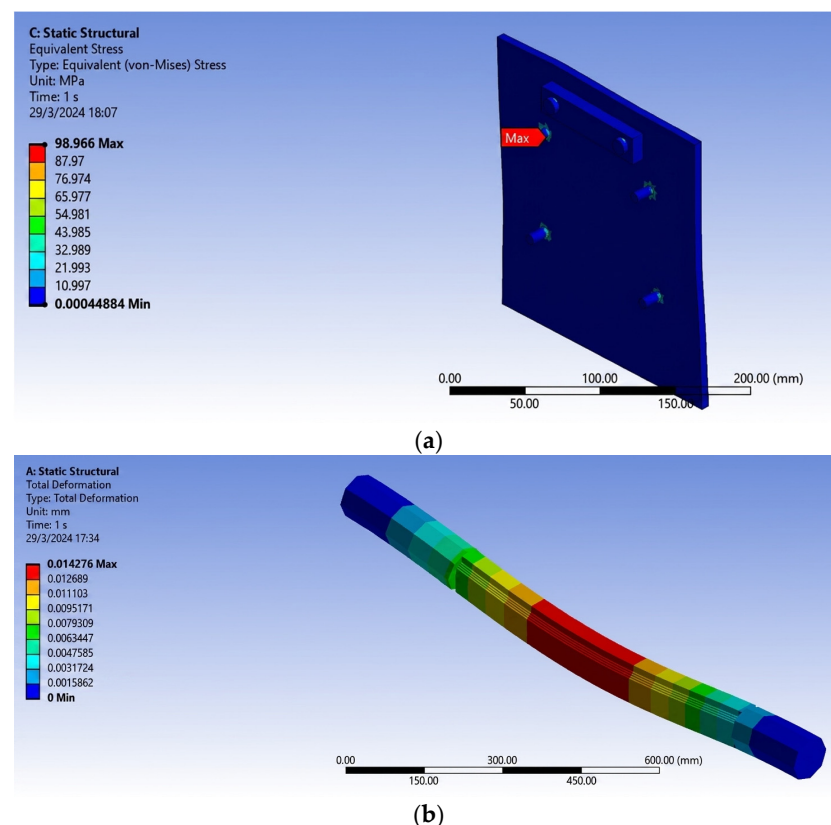


Figure 5. Static simulation results: (a) fasteners and (b) blade holder system. Source: Authors.

In all models, fixed support boundary conditions were applied at the bolt–frame contact surfaces, constraining all degrees of freedom. For the motor base fasteners ($M10 \times 1.5$), the applied load combines the motor weight (230.54 N) with the tangential grinding reaction force (~ 196 N, derived from $P = 0.75$ kW at $n = 3450$ rpm). For the structural frame bolts ($M8 \times 1.25$), the load comprises the carriage assembly weight (252.91 N) and the horizontal grinding reaction forces. For the blade holder system, the tangential grinding force (196 N) was applied perpendicularly to the clamping surface together with the blade self-weight (7.85 N). All models used tetrahedral meshing with elements refined to 2 mm in high-stress zones, with bonded contact between bolts and plates, and convergence verified at less than 3% variation in von Mises stress between successive refinements. The material properties assigned were ASTM A36 ($E = 200$ GPa, $\nu = 0.3$, $S_y = 250$ MPa) for frame components and AISI 1018 ($E = 200$ GPa, $\nu = 0.29$, $S_y = 372$ MPa) for the power screw. Table 5 presents the numerical FEA results for all simulated components.

Table 5. Summary of FEA results for critical machine components.

Component	Max Von Mises (MPa)	Max Deformation (mm)	Material S_y (MPa)	Safety Factor (η_s)
Motor base fasteners ($M10 \times 1.5$)	98.57	0.082	250 (ASTM A36)	>2.5
Structural frame bolts ($M8 \times 1.25$)	74.22	0.061	250 (ASTM A36)	>3.4
Blade holder system	0.614×10^{-1}	0.028	250 (ASTM A36)	>4.1
Power screw (ACME 3/4–8)	23.0	N/A	372 (AISI 1018)	16.2

The tangential grinding force was estimated using the specific grinding energy approach. For alumina wheels grinding hardened steel (up to 60 HRC), specific grinding energy values in the range $u = 20$ – 40 J/mm³ are reported for conventional surface grinding [11]. Using the conservative upper bound ($u = 40$ J/mm³), the material removal rate for the tested blade geometry (contact width $b = 10$ mm, depth of cut $a_e = 0.05$ mm, and table speed $v_i = 0.05$ m/s) yields $Q = b \times a_e \times v_i = 0.025$ mm³/s. The tangential grinding force is then $F_t = u \times Q / v_c$, where $v_c = 22.9$ m/s is the wheel peripheral speed, giving $F_t \approx 0.044$ N. This value is negligible compared to the static weight components (motor: 230.54 N, carriage: 252.91 N), confirming that the dynamic grinding force does not govern the structural design of the carriage, blade holder, or frame for the tested blade geometry and operating parameters. For larger blades within the design range (up to 600 mm $\times$ 20 mm), the contact area and grinding force could be substantially larger, and a more detailed force analysis would be required, as noted in the Limitations paragraph in Section 4.

Mesh convergence was verified for each model by progressively refining the element size from 8 mm (coarse) to 4 mm, 2 mm, and 1 mm in the zones of highest stress concentration, recording the maximum von Mises stress at each refinement level. Convergence was achieved when the change in von Mises stress between successive refinements fell below 3%. This criterion was satisfied at a global element size of 4 mm with local refinement to 2 mm in high-stress zones for all three components.

The FEA results confirm that stress levels in all critical components remain well below the material yield strength limits, with safety factors exceeding 2.5 for all fastener configurations (Table 5). The maximum deformation in the blade holder system (0.028 mm) is negligible relative to the dimensional tolerances required for grinding quality, confirming that the clamping mechanism provides adequate stiffness to achieve a flat, consistent grinding surface.

2.8. Automation

The automation aspect focuses on the grinding and lubrication processes. Thus, the start of the process controls the movement of the grinding wheel and its moving table, the lubrication pump, and, for safety, an emergency stop is considered.

As shown in Figure 6, the implemented automation system consists of a hardwired control system based on electromechanical components, including relays, push buttons, pilot lights, limit switches, and a central control panel. This configuration enables autonomous control of the grinding wheel start-up, table movement, and lubrication system, ensuring a safer and more efficient grinding process. The operator's only function is to position the blade and activate the cycle start signal. The operating logic does not depend on programmable controllers (PLCs), which simplifies maintenance, reduces costs, and ensures robust operation adapted to the local industrial environment. The operating cycle proceeds as follows: (1) the operator positions the blade and activates the cycle start push button; (2) the main contactor energizes both the grinding wheel motor and the lubrication pump simultaneously; (3) the carriage traverses the full stroke guided by limit switches that reverse the table direction at each end; (4) upon completion of the preset number of passes, the carriage returns to the home position and the system de-energizes automatically. This hardwired architecture is consistent with the practical automation needs of wood product SMEs with limited technical personnel, for which relay-logic systems represent the most accessible entry point.

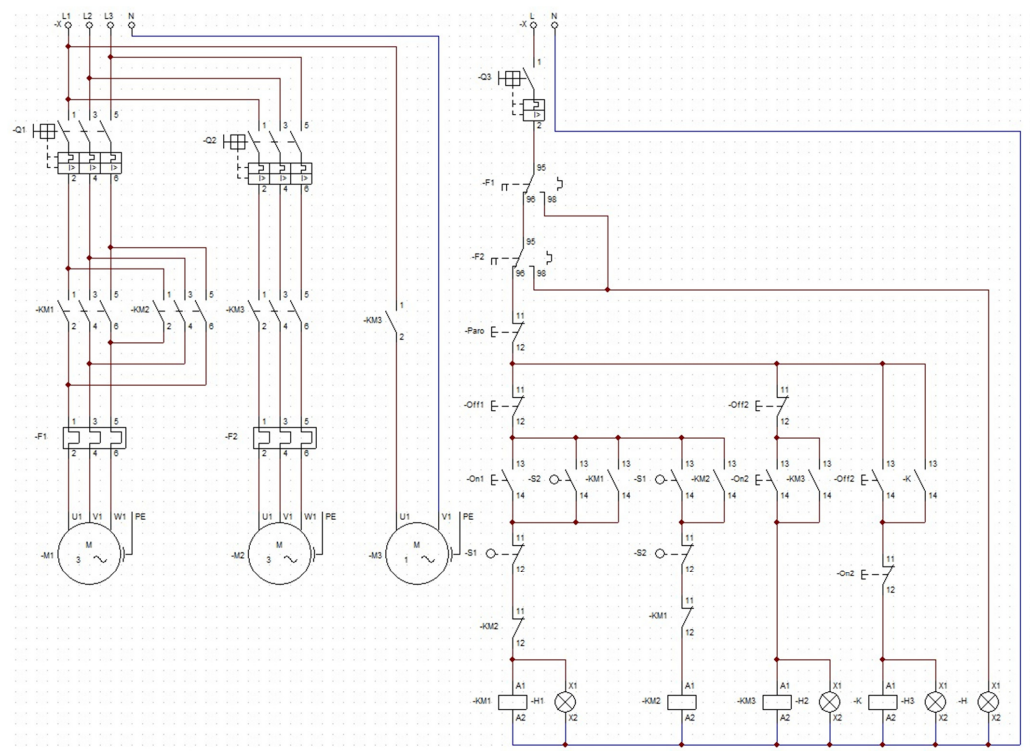


Figure 6. Wired Automation System. Source: Authors.

2.9. Machine Construction

The machine was originally modeled in 3D using SolidWorks, as shown in Figure 7a, where the geometric configuration, dimensions, and assembly constraints of all structural and functional components were defined. The 3D modeling stage allowed for the verification of spatial interferences, evaluation of the kinematic behavior of moving parts, and ensured correct alignment between mechanical subsystems before manufacturing. The final prototype of the machine, built with locally available materials and commercial

components, is shown in Figure 7b, which is consistent with the project's goal of achieving technical functionality while maintaining economic feasibility.

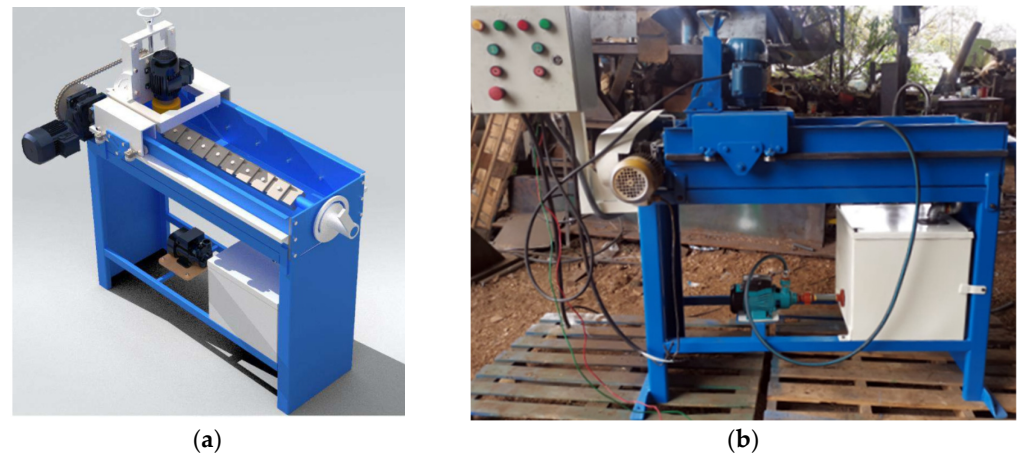


Figure 7. Machine construction: (a) 3D model and (b) final prototype. Source: Authors.

The manufacturing process diagram is shown in Figure 8. The steps were followed sequentially and demonstrated to be effective in maintaining order and control in the construction stage.

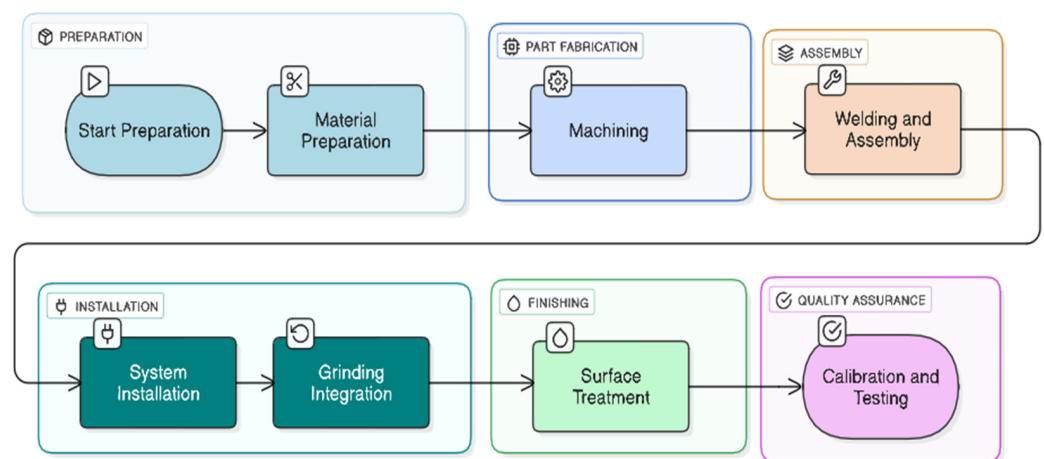


Figure 8. Machine manufacturing process diagram. Source: Authors.

The manufacturing process followed the six stages outlined in Figure 8 in strict sequential order, ensuring traceability and quality control at each phase. Starting from raw material preparation and machining of individual components, through structural welding and assembly, to system installation, surface finishing, and final calibration, each stage was completed and verified before advancing to the next. This structured approach minimized rework, facilitated the identification of dimensional deviations during assembly, and ensured that the final prototype met the geometric and functional requirements established in the design phase. The result is a fully operational machine built entirely with locally available materials and commercial components, demonstrating that the proposed design is not only technically sound but also practically replicable within the manufacturing capabilities of the Ecuadorian industrial context.

3. Results

Experimental Testing Results

The testing phase was supported by the existing literature on the subject; it can be stated that for the grinding process, regardless of the blade measurements, lubrication is necessary throughout the process due to the high temperatures generated when the grinding wheel comes into contact with the blade, and this angle must be set at 45° . It was taken into consideration that in any manual procedure, it is not possible to control the angle of inclination of the cutting edge with precision; therefore, the machine has a mechanism to adjust the inclination according to the operator's needs. A calibrated surface roughness tester (Phase II model, accuracy $\pm 0.01 \mu\text{m}$, and calibration according to ANSI B46.1) was used to measure surface roughness (Ra) before and after grinding (Figure 9).



Figure 9. The calibrated surface roughness tester.

To ensure the statistical representativeness of the surface characterization, a systematic sampling strategy was implemented for each specimen. Three distinct measurement points were established along the longitudinal axis of the blade: one at the center and two at 15 mm from each end. At each point, five consecutive readings were taken, totaling 15 measurements per specimen and 60 measurements per test condition ($n = 4$). Following ANSI B46.1 standards, the measurement direction was set perpendicular to the grinding marks to capture the maximum profile variations. The mean Ra values reported in Table 6 represent the average of these 60 data points, accounting for potential pressure variations along the traversal path.

Table 6. Roughness of the test blades.

Nature of the Blade	Passes	Inclination	Mean Ra (μm)	SD (μm)	95% CI (μm)	CV (%)
Used Blade	—	—	5.390	1.831	2.48–8.30	34.0%
New Blade	—	—	0.601	0.153	0.36–0.84	25.5%
Sharpened Blade	1	0°	1.485	0.203	1.16–1.81	13.7%
	2	0°	1.126	0.189	0.83–1.43	16.8%
	3	0°	1.037	0.164	0.78–1.30	15.8%
	1	45°	0.553	0.145	0.32–0.78	26.2%
	2	45°	0.491	0.089	0.35–0.63	18.1%
	3	45°	0.326	0.105	0.16–0.49	32.2%
	4 *	45°	0.162	0.092	0.02–0.31	56.8%

* The fourth pass was performed exclusively at 45° because the Ra trend after three passes at that inclination ($0.326 \mu\text{m}$) had already surpassed the new-blade reference quality ($0.601 \mu\text{m}$), justifying further optimization. At 0° inclination, the Ra after three passes ($1.037 \mu\text{m}$) remained substantially above the new-blade reference, indicating that this configuration cannot achieve the target surface finish irrespective of additional passes; a fourth pass was therefore not conducted.

To validate the efficiency of the machine, tests were conducted on blade specimens of 3 mm thickness and 70 mm length (carbon steel, 60 HRC) under two variable conditions: inclination angle (0° and 45°) and number of grinding passes (1 to 4). For each condition, four specimens were tested ($n = 4$) to obtain a mean Ra value and its standard deviation

(SD). The 95% confidence interval (CI) was determined using the *t*-distribution with three degrees of freedom ($df = n - 1 = 3$), applying Equation (9), where $t^*(0.025, 3) = 3.182$ is the critical *t*-value for a two-tailed test at 95% confidence. All collected data are presented in Table 6. As a reference baseline, four new blade specimens of the same geometry were also measured ($Ra = 0.601 \pm 0.153 \mu\text{m}$); these were uncoated carbon steel flat blades sourced from a single local supplier, representative of the blades currently used in the SME operations for which the machine was designed, and are not intended to characterize the surface finish of commercially manufactured blades in general.

$$CI = \bar{x} \pm t^* \times \frac{SD}{\sqrt{n}} \quad (9)$$

Also, the coefficient of variation (CV) was calculated as $CV (\%) = (SD/\text{mean } Ra) \times 100$, providing a normalized measure of dispersion independent of the magnitude of *Ra*.

The results presented in Table 6 reveal a clear and consistent trend: surface roughness decreases monotonically with an increasing number of passes, and the 45° inclination angle produces significantly lower *Ra* values than the 0° configuration across all pass counts. At 0° inclination, three passes yielded a mean *Ra* of 1.037 μm , which remains substantially higher than the new blade reference value ($Ra = 0.601 \mu\text{m}$), indicating that this configuration is insufficient to restore blade surface quality regardless of the number of passes applied. In contrast, the 45° inclination produced a progressive improvement with each additional pass, achieving $Ra = 0.553 \mu\text{m}$ after one pass, which is already comparable to a new blade, and reaching $Ra = 0.162 \pm 0.092 \mu\text{m}$ after four passes, representing a 97% reduction relative to the used blade condition ($Ra = 5.390 \mu\text{m}$). Notably, this optimal value is 73% lower than the new blade reference, indicating that the automated grinding process produces a finer surface finish than that of commercially manufactured blades.

The coefficient of variation (CV) reported in Table 6 provides a normalized measure of dispersion across conditions. For the 0° inclination, CV values ranged from 13.7% to 16.8%, indicating low and consistent variability. At a 45° inclination, CV values increased progressively from 26.2% at one pass to 56.8% at the four-pass condition. This apparent increase does not indicate process instability; rather, it reflects a statistical artifact of the CV metric: as the mean *Ra* approaches the instrument resolution limit ($\pm 0.01 \mu\text{m}$), small absolute variations become proportionally large relative to the mean. The absolute standard deviation at this condition ($SD = 0.092 \mu\text{m}$) remains well within acceptable tolerances for industrial blade sharpening, confirming process reproducibility. Four passes at 45° produced the lowest mean *Ra* measured in this study ($0.162 \pm 0.092 \mu\text{m}$), with a 95% confidence interval ($0.02\text{--}0.31 \mu\text{m}$), which is below the new-blade reference ($Ra = 0.601 \mu\text{m}$); the improvement over three passes ($Ra = 0.326 \mu\text{m}$) is consistent across all specimens. Given the sample size of $n = 4$ specimens per condition, all *Ra* comparisons reported in this section should be interpreted as point estimates. No inferential statistical tests are reported, as the available degrees of freedom ($df = 3$) would yield insufficient statistical power; formal hypothesis testing is recommended in future work with $n \geq 10$ specimens per condition.

The optimal grinding condition was therefore identified as four passes at a 45° inclination, which consistently produced *Ra* values below 0.2 μm , equivalent to a surface finish classification of N5 according to ISO 1302. It is also worth noting that the grinding process simultaneously removes surface rust from used blades, restoring the base metal surface and providing an additional corrosion protection benefit that extends the blade service life beyond that which surface roughness measurements alone reflect.

The automated control system also had a positive influence on operational performance metrics beyond surface roughness. To evaluate grinding time and noise level, both the automated and manual processes were tested using the same blade specimens

(3 mm × 70 mm, carbon steel, and 60 HRC) and the same number of passes (four per condition). For the automated process, grinding time was recorded with a calibrated digital stopwatch from cycle start to completion, and noise levels were measured with a calibrated sound level meter (IEC 61672 Class 2) positioned 1.0 m from the machine at operator ear height during steady-state operation. For the manual baseline, a single trained operator with experience in blade sharpening within the SME context used a bench-mounted angle grinder fitted with a flap disc of equivalent abrasive specification (aluminum oxide with a grain size of 60). The inclination angle was set to 45° using a protractor gauge before each pass, and the blade was ground freehand without mechanical clamping or automated table traverse. Cooling was achieved by periodic immersion in a water bath between passes, consistent with common SME practice. Grinding time was measured from contact with the first wheel to completion of the fourth pass, including angle re-verification and cooling pauses. No automated lubrication was applied.

The results, as shown in Figure 10, reveal consistent advantages of the automated system across both metrics. As shown in Figure 10a, mean grinding time was reduced from 9.20 ± 0.18 min (manual) to 6.40 ± 0.14 min for the four-pass condition and 4.20 ± 0.08 min for the two-pass condition, representing reductions of 30.4% and 54.3% respectively. The reduction in time is attributable to the elimination of manual angle resetting between passes and the continuous, mechanically controlled traverse table, which removes the pauses inherent to freehand operation. Regarding noise levels, Figure 10b shows that the automated process produced mean levels of 65.0 ± 0.73 dB (four passes) and 67.0 ± 0.85 dB (two passes), compared to 83.0 ± 1.30 dB for the manual process—a reduction of 18 dB for the four-pass condition. All conditions remained below the 85 dB 8 h occupational exposure limit established by NTE INEN-ISO 9612. Descriptive statistics for grinding time and noise level under all conditions are summarized in Table 7.

Table 7. Grinding time and noise levels.

Process	Mean Grinding Time (s)	SD (Time)	Mean Noise Level (dB)	SD (Noise)
Manual Grinding	9.20	0.18	83.0	1.30
Automated Grinding (4 passes)	6.40	0.14	65.0	0.73
Automated Grinding (2 passes)	4.20	0.08	67.0	0.85

Note: The dashed red line in Figure 10b indicates the 85 dB 8 h occupational exposure limit established by NTE INEN-ISO 9612. All conditions remain below this threshold.

Finally, a satisfaction survey was administered to the machine operator, who evaluated five ergonomic and usability criteria on a 1-to-5 Likert scale. Results are presented in Figure 10c. All criteria received ratings above 4.6, with reduction in fatigue obtaining the highest score (4.90) and safety during operation achieving the lowest score (4.60), indicating overall favorable acceptance of the machine across all evaluated dimensions.

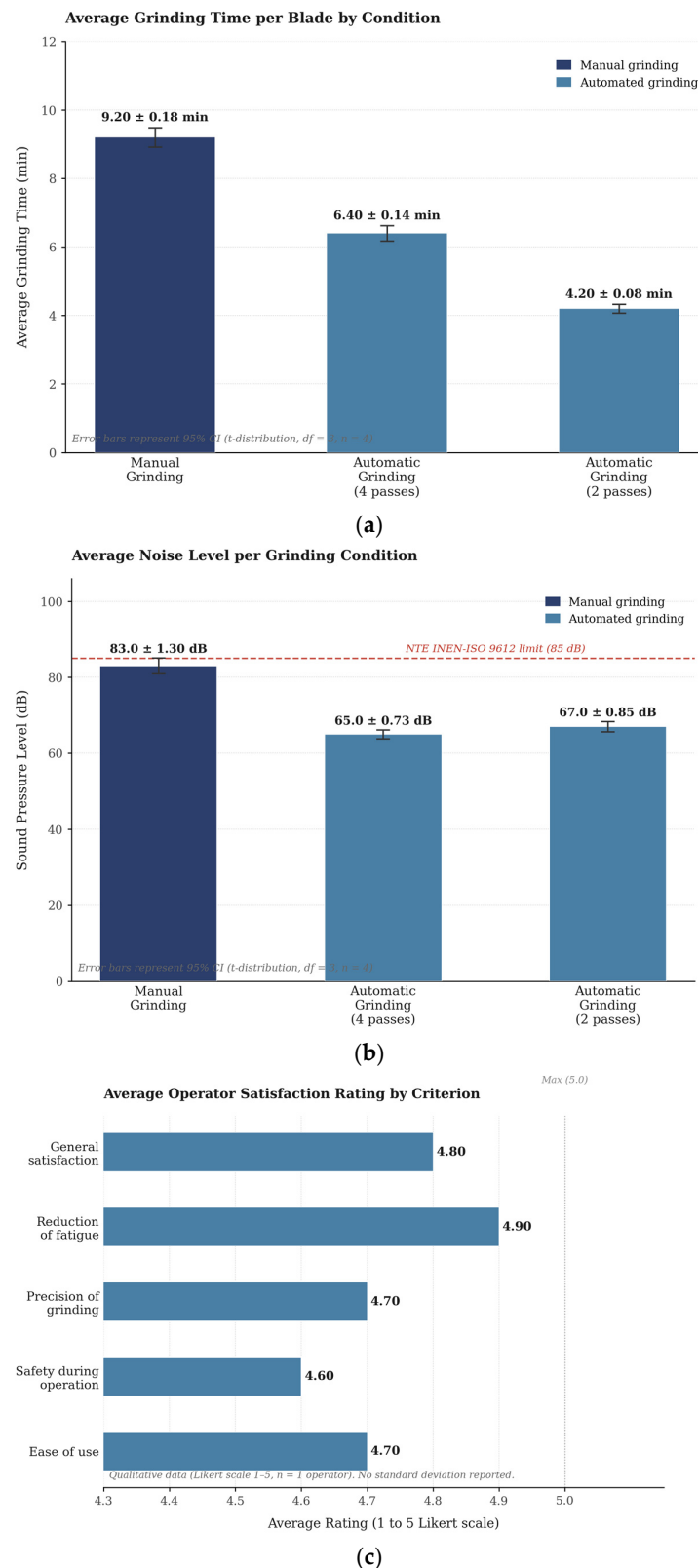


Figure 10. Performance results: (a) average grinding time per blade; (b) average noise level; and (c) average operator satisfaction rating.

4. Discussion

The superiority of the 45° inclination configuration over the 0° configuration can be attributed to the geometric relationship between the cup wheel face and the blade bevel at this angle, which minimizes the contact area and concentrates the abrasive action pre-

cisely along the cutting edge, reducing both surface irregularities and thermal load at the tool–workpiece interface. This behavior is consistent with the specific grinding energy framework described by Malkin and Guo [11], who established that the contact geometry between the abrasive tool and the workpiece is among the primary determinants of achievable R_a in grinding of hardened steels. The automated grinding process produced a mean R_a of 0.162 μm , which was lower than that of the new blade reference specimens tested ($R_a = 0.601 \mu\text{m}$); however, this comparison is limited to the specific blade geometry and supplier used in this study and should not be generalized to commercially manufactured blades in general, as new blades are typically produced through stamping, shearing, or production-scale grinding processes optimized for dimensional tolerances and throughput rather than edge surface quality. The ability of the automated system to achieve consistent R_a values across all four specimens under controlled inclination and feed rate conditions is consistent with the findings reported by Zieliński et al. [9], who demonstrated that precision grinding machines with controlled process parameters produce repeatable surface quality in industrial blade sharpening applications. This result confirms that the machine achieves a surface finish classification of N5 per ISO 1302, consistent with the findings by Spinelli et al. [2,3], who demonstrated that systematic sharpening operations can restore and even exceed the original cutting performance of industrially manufactured blades.

Regarding operational efficiency, the 30.4% reduction in grinding time achieved by the automated machine is consistent with the deliberate design trade-off adopted in this study: the hardwired relay-logic architecture, while limiting maximum automation potential, eliminates the need for PLC programming expertise, reduces initial investment, and ensures robust operation in environments where spare-parts availability and technical personnel are limited. This design philosophy reflects the practical constraints of the SME context targeted by this work.

The noise reduction observed a decrease of 18 dB relative to the manual process, which is technically significant and attributable to two concurrent mechanisms: the elimination of the unstable frictional contacts characteristic of manual grinding, and the continuous lubrication system that dampens vibration transmission through the tool–workpiece interface, consistent with findings reported by Savescu et al. [6].

Several limitations of this study should be acknowledged. First, the experimental sample size ($n = 4$ specimens per condition) limits the statistical power of the roughness comparisons; no inferential tests are reported, given the low degrees of freedom ($df = 3$), and a minimum of $n = 10$ is recommended for future validation studies. Second, all roughness, grinding time, and noise measurements were obtained using blade specimens of a single geometry (3 mm $\times$ 70 mm, carbon steel, 60 HRC). The machine is designed to accommodate blades ranging from 50 to 600 mm in length, 70–100 mm in width, and 3–20 mm in thickness across four material types (carbon steel, hardened steel, stainless steel, and HSS). For longer or thicker blades, the optimal number of passes, the applied grinding force, and the achievable R_a are expected to differ due to changes in contact area, thermal load, and structural deflection of the blade holder; the 45° inclination angle identified as optimal for the tested geometry may not generalize across the full design range, and future work should systematically vary blade dimensions and material to establish the operating boundaries of the validated parameters. Third, the long-term durability of the grinding wheel and mechanical components under continuous industrial use has not been evaluated; a wear analysis over a minimum of 500 operational cycles is recommended. Fourth, the operator satisfaction survey was limited to one operator, which precludes generalization; a multi-operator study using a validated scale (e.g., System Usability Scale) would provide more robust ergonomic evidence. Finally, at the optimal grinding condition ($R_a = 0.162 \mu\text{m}$), the measurement uncertainty of the Phase II profilometer ($\pm 0.01 \mu\text{m}$)

represents approximately 6% of the measured value. While the instrument's nominal range covers this Ra level, characterization of surface finishes below 0.2 μm would benefit from a higher-resolution contact profilometer (e.g., with $\pm 0.001 \mu\text{m}$ resolution) to improve the reliability of absolute Ra values at the optimal condition. The Ra = 0.162 μm result should, therefore, be interpreted as an indicative value consistent with an N5 surface finish classification, rather than a precisely characterized absolute roughness.

5. Conclusions

The design, construction, and experimental validation of the automated flat blade grinding machine demonstrated that structured engineering methodologies, locally available materials, and hardwired electromechanical control systems can be combined to produce a technically sound, cost-effective, and replicable automated maintenance solution for the wood processing and plastic recycling industries. While the machine was developed and validated within the Ecuadorian industrial context, where SMEs face similar constraints in terms of capital investment, access to high-technology equipment, and availability of specialized technical personnel, the design principles, validated operational parameters, and manufacturing approach presented in this work are broadly applicable to similar industrial environments across Latin America and other developing regions. The following specific conclusions are drawn from this work:

(1) Design methodology: The VDI 2221/2222/2225 methodology provided a structured and replicable framework for the complete design process. The selected configuration (Alternative Solution 1) scored highest in both technical ($X_i = 0.635$) and economic ($Y_i = 0.674$) multi-criteria evaluations, confirming the best balance between functional performance and cost-effectiveness among the three alternatives considered.

(2) Structural validation: FEA confirmed that all critical components operate with safety factors well above the minimum acceptable threshold: the power screw achieved $\eta_s = 16.2$ (static) and $\eta_f = 14.8$ (fatigue), while motor base fasteners, structural frame bolts, and the blade holder system maintained safety factors of >2.5 , >3.4 , and >4.1 , respectively, ensuring structural integrity under cyclic operational loads.

(3) Surface quality: Four grinding passes at a 45° inclination angle achieved $R_a = 0.162 \pm 0.092 \mu\text{m}$, equivalent to an N5 surface finish classification as per ISO 1302, representing a point-estimate reduction of 97% in mean Ra relative to the used-blade condition ($R_a = 5.390 \mu\text{m}$; $n = 4$). The measured Ra was lower than that of the new blade reference specimens tested ($R_a = 0.601 \mu\text{m}$), though this comparison is limited to the specific blade geometry and supplier used in this study; generalization to other geometries and materials within the design range requires additional experimental validation. These results demonstrate the machine's capability to restore blade surface quality to levels consistent with or exceeding the reference condition and should be confirmed with a larger sample size ($n \geq 10$) in future validation work.

(4) Operational efficiency: The automated control system reduced average grinding time by approximately 30% compared to manual methods and maintained noise levels between 65 and 70 dB, below the 85 dB occupational exposure limit established by NTE INEN-ISO 9612, improving both productivity and occupational health conditions for machine operators.

(5) Industrial applicability: The machine was designed and manufactured entirely with locally available materials and commercial components in Ecuador, demonstrating a cost-effective and replicable model for SME-oriented industrial automation applicable across Latin America.

Future Work: Future research should prioritize increasing the experimental sample size to $n \geq 10$ specimens per condition to enable ANOVA-based statistical validation and

improve the confidence of the roughness comparisons. Long-term durability testing over a minimum of 500 operational cycles is also recommended to characterize grinding wheel wear rates and assess the fatigue life of critical mechanical components under continuous industrial use. From a technological standpoint, the integration of a PLC-based closed-loop control system with depth-of-cut feedback sensors would further automate the grinding process and improve Ra consistency across blade dimensions. Additionally, experimental validation should be extended to cover the full design range of blade dimensions specified in Table 1 (up to 600 mm × 20 mm), which were not included in the present study. Finally, the ergonomic evaluation should be expanded to a multi-operator study using a validated psychometric instrument, such as the System Usability Scale (SUS), to provide statistically robust evidence of the machine's usability and acceptance in real industrial settings.

Author Contributions: S.L. conceived the research idea, led the engineering design process, and coordinated the overall study. J.V. developed the design methodology, performed the mechanical calculations, and contributed to prototype construction and experimental testing. C.T. developed the 3D CAD models and finite element simulations, conducted the experimental roughness measurements, and processed the collected data. M.Z. designed and implemented the automation and control system, contributed to prototype construction, and provided technical supervision throughout the manufacturing and testing phases. S.L. and J.V. wrote the original manuscript. S.L., J.V. and M.Z. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

Ra	Arithmetic Mean Surface Roughness (μm)
FEA	Finite Element Analysis
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
HRC	Rockwell Hardness Scale C
ACME	Standard Screw Thread Profile (29° included angle)
SME	Small and Medium Enterprise
PLC	Programmable Logic Controller
BOM	Bill of Materials
HSS	High-Speed Steel
HMI	Human–Machine Interface
RPM	Revolutions per Minute
INEC	Instituto Nacional de Estadística y Censos (National Statistics and Census Institute)
NTE	Norma Técnica Ecuatoriana (Ecuadorian Technical Standard)
INEN	Instituto Ecuatoriano de Normalización (Ecuadorian Standardisation Institute)

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