

Article

Multi-Objective Optimization of an Impact Pruner to Enhance Pruning Quality and Reduce Energy Consumption: A Case Study of *Larix principis-rupprechtii* in Coniferous Plantation Forests

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Abstract

This study conducts a multi-objective optimization of an impact pruner for coniferous plantation trees, using Prince Rupprecht's larch (*Larix principis-rupprechtii* Mayr) in North China as a case study. The objective is to establish an impact cutting mechanics model and to construct an impact cutting platform. This study utilizes the Box–Behnken principle, with the cutting speed (v), cutter wedge angle (β), and cutting clearance (L) as influencing factors and the cutting energy consumption (Y_1), total equipment energy consumption (Y_2), and specific cutting area (S) as evaluation indexes. The cutting parameters were optimized using a mathematical model for multi-objective optimization. The experimental results indicate that the factors influencing target Y_1 were ranked as β , L , and v , while the factors influencing target Y_2 were ranked as β , v , and L , and the factors influencing target S were ranked as L , β , and v . Field tests demonstrated that the optimization reduced the cutting energy consumption by up to 16.90% and improved the cutting quality by up to 19.28%. These gains directly translate to improved operational efficiency and economic value in forestry management. The optimal parameters corresponding to these improvements are $v = 2.15 \text{ m} \cdot \text{s}^{-1}$, $\beta = 20^\circ$, and $L = 5 \text{ mm}$, resulting in $Y_1 = 36.10 \text{ J}$, $Y_2 = 3351.01 \text{ J}$, and $S = 3.45$. These results demonstrate the feasibility and efficiency of the impact pruning method for *Larix principis-rupprechtii* in coniferous plantation forests. By combining mechanism analysis with multi-objective optimization, this study proposes a solution that can improve the pruning quality of coniferous plantation trees, reduce the energy consumption of impact pruning machines, enhance tree health, and serve as a measure to prevent pests and diseases, contributing to the advancement of artificial forest plant protection technology.



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Keywords: impact pruner; multi-objective optimization; impact cutting mechanism; mechanical properties; precision forestry

1. Introduction

Plantation forests may play a major role in the production of wood as well as the provision of other ecosystem services [1]. Because of its quick growth, favorable timber quality, tolerance to low temperatures and strong winds, and ability to improve soil conditions,

Prince Rupprecht's larch (*Larix principis-rupprechtii*) has become an important coniferous plantation species in northern China [1,2].

Given the importance of *Larix principis-rupprechtii* in the ecological environment and forestry economics, robotic pruning equipment to optimize growth health and timber quality is critical [3]. Currently, robotic pruning equipment research is in the exploratory and experimental stages [4]. Ueki et al. [5] created an electric climbing pruner by analyzing Japanese lumberjacks' climbing techniques and combining vertical and spiral climbing strategies. Gui et al. [6] studied active and passive fall prevention strategies to design an electric tree-climbing pruner that can successfully protect pruners from falling accidents. Ajay et al. [7] presented a non-contact pruning method using a UAV with a laser head attached. Megalingam et al. [8] developed Amaran, an unmanned robotic coconut tree climber and harvester that achieved a maximum climbing height of 15.2 m in field tests. Dubey et al. [9] designed a low-cost coconut tree climbing and harvesting robot with Arduino-based automatic and manual control functions. Although the research and development of mechanized pruning equipment are steadily developing, research on the cutting mechanism and cutting performance of plant branches is still relatively limited, which limits the process of mechanized equipment research and development.

The choice of the cutting process has a direct impact on the cutter's cutting quality and operating efficiency [10]. Currently, the most popular cutting methods in forestry equipment are sawing, reciprocating, and impacting. Sawing equipment completes the cutting by spinning a circular saw, which is typically used for shrub plants such as caragana (*Caragana korshinskii* Kom.) or woody plants such as banana plants (*Musa* spp.) [11,12]. There are also tiny cutters for mulberry trees (*Morus alba* L.) [13]; however, saw-cutting equipment is rarely used for trimming operations on tall tree-type species. Reciprocating pruning equipment cuts a branch with the shear of the cutter as it cycles back and forth. Reciprocating cutting is generally employed in crop harvesters for sesame (*Sesamum indicum* L.), soybean (*Glycine max* L.), wheat (*Triticum aestivum* L.), and other crops, and it is difficult to apply to tall tree trimming operations [14–16]. As a result, impact cutting may be the solution to future pruning problems in plantation forests of coniferous plantation forests.

For process and efficiency optimization, it is essential to comprehend how plant stems deform when subjected to machine action [17]. Due to variations in plant species and growing conditions, it is currently challenging to apply standardized methodologies for evaluating the mechanical properties of plant stalks [18]. To arrive at the desired individual parameter values, experimental or modeling methods are frequently utilized in the research of crop mechanical properties. Mohsen Azadbakht et al. [19] studied the effect of mowing height and moisture content on the cutting energy consumption of canola (*Brassica napus* L.) under impact cutting, and the height, moisture content, and cutting speed with the lowest cutting energy were obtained through experiments. Song et al. [20] studied the cutting performance of sisal (*Agave sisalana*) under impact cutting and investigated the effect of the cutting speed and cutter tilt angle on the cutting energy consumption and stress under impact cutting, and the experiments determined the cutting parameters to reduce the energy consumption and improve the cutting quality. Tian Kunpeng et al. [21] analyzed the effects of bionic cutters and traditional cutters on the cutting performance of corn stalks (*Zea mays* L.) and concluded that bionic cutters have a stronger cutting ability and cutting quality. Gan Hao et al. [22] investigated the differences in energy consumption of lawnmowers cutting arable grasses with different structures of cutters and concluded that serrated cutters are more efficient in cutting mechanical energy. Sunil K. Mathanker et al. [23] studied the effects of cutting speed and cutting angle on sugarcane (*Saccharum* spp.) cutting energy consumption under impact linear cutting and obtained the optimal combination of cutting speed and cutting angle. Johnson et al. [24] investigated the cutting

energy characteristics of *Miscanthus × giganteus* stems under different blade oblique angles and cutting speeds, further confirming that the tool angle and cutting velocity are important factors affecting cutting energy. Ghahraei et al. [25] conducted cutting tests on kenaf stems (*Hibiscus cannabinus* L.) and analyzed the effects of the knife angle and cutting conditions on the cutting force and cutting energy, providing an additional reference for parameter selection in impact cutting. Li et al. [26] investigated the cutting performance of apple branches (*Malus domestica*) at different branch diameters and moisture contents to explore the effect of each cutting parameter on the cutting force. Tong et al. [27] experimentally studied the relationship between the cutting power, severance rate, cutting efficiency and ratio of cutting speed to feed rate in apple branch cutting. In addition, some scholars have also studied the force mechanism of crop stalks in the harvesting process using three-dimensional modeling. Wang et al. [28] investigated the force model of the cutter and the sugarcane root system by establishing a sugarcane cutting model based on the coupled algorithm of the finite element method and smoothed particle hydrodynamics [28]. Li et al. [29] bundled soil and corn stover into a composite and established a finite element model to investigate the soil–root interaction model of corn stubble cutting. Guo et al. [30] established a discrete element model of banana bunch stems (*Musa* spp.) and investigated their shear, tensile, compression, and bending. The mechanical properties of banana bunch stems were investigated to provide a basis for the development of banana post-harvest machinery. Zhao et al. [31] combined discrete element modeling with mechanical tests to study the deformation mechanism of cotton stalks (*Gossypium hirsutum* L.) during the uprooting process and investigated the effects of various factors on the deformation of cotton stalks.

Overall, the above studies indicate that the cutting speed, cutter geometry, cutting position, and plant material properties are key factors affecting the cutting force, cutting energy consumption, and fracture morphology. Among these studies, the works of Azadbakht et al. [19], Song et al. [20], Mathanker et al. [23], Li et al. [26], and Tong et al. [27] are particularly relevant to the present research because they directly address the influence of cutting parameters on energy consumption, cutting force, or cutting performance. In addition, the numerical and modeling studies by Wang et al. [28], Li et al. [29], Guo et al. [30], and Zhao et al. [31] provide useful references for understanding tool–plant interaction mechanisms.

Despite extensive research on cutting mechanics and performance optimization for various crops, several research gaps remain. As summarized in Table 1, previous studies have predominantly focused on single-objective optimization—specifically, minimizing the cutting energy consumption of pruning equipment—while neglecting the critical aspect of cross-section quality. Furthermore, Prince Rupprecht’s larch (*Larix principis-rupprechtii*) is a coniferous tree species with a complex and dense tissue structure, holding significant ecological and economic importance in northern China. However, existing research on cutting energy consumption has primarily concentrated on herbaceous plants and woody fruit trees, with limited attention given to the impact cutting of coniferous tree species such as *Larix principis-rupprechtii*. The interaction effects among key cutting parameters (cutting speed, cutter wedge angle, and cutting clearance) and their simultaneous impact on both energy consumption and pruning quality have not been systematically investigated.

Impact pruners can be used in challenging operating situations, such as mountains, and are quick and effective when faced with trimming operations in coniferous plantation forests [32]. Currently, impact cutting is more frequently used on stone and metal material [33–35], while research on the mechanical response and pruning performance of coniferous plantation tree species under impact cutting remains limited. This lack of studies has resulted in an insufficient theoretical basis and parameter support for the optimal design of related pruning equipment. To address this gap, this study focuses on *Larix*

principis-rupprechtii as the research object and systematically investigates the following aspects, with the main contributions summarized as follows:

(1) For the first time, research on the cutting mechanism and performance optimization of impact pruning was conducted for *Larix principis-rupprechtii*, an ecologically and economically important tree species, thereby extending the application of impact cutting technology to the pruning of coniferous plantation trees. A cutting mechanics model was established to elucidate the influence mechanisms of the cutting speed (v), cutter wedge angle (β), and cutting clearance (L) on the cutting process, providing a theoretical foundation for subsequent parameter optimization.

(2) An impact cutting test platform was designed and constructed to systematically investigate the effects of three key parameters—cutting speed (v), cutter wedge angle (β), and cutting clearance (L)—on the cutting energy consumption (Y_1), total equipment energy consumption (Y_2), and specific cutting area (S). Single-factor experiments were conducted to identify the influence trends of each parameter on the evaluation indexes, providing essential data for multi-objective optimization.

(3) A prediction model was developed using response surface methodology, followed by multi-objective optimization aimed at simultaneously minimizing cutting energy consumption (Y_1) and total equipment energy consumption (Y_2) while maximizing pruning quality quantified by the specific cutting area (S). This multi-objective strategy effectively addresses the inherent trade-off between energy efficiency and cutting quality in pruning operations, avoiding performance imbalances that would result from single-objective optimization.

(4) The impact pruner was redesigned based on the multi-objective optimization results, and field tests were conducted to validate the applicability of the optimized cutting parameters under practical pruning conditions. This validation provides experimental support for evaluating the performance of the proposed optimization framework in coniferous plantation forests.

Table 1. Representative studies related to cutting performance and the optimization objectives of this study.

Research Material	Material Type	Test Platform	Features
Canola stalk [19]	Herbaceous plant	Impact cutting	Research objective: Minimize cutting energy consumption by optimizing cutting height and moisture content. Limitation: Single-objective optimization only; cutting quality not considered; parameter interactions ignored.
Energy cane [23]	Herbaceous plant	Impact cutting	Research objective: Minimize cutting energy consumption through optimization of cutting speed and cutting angle. Limitation: Single-objective optimization only; cutting quality not considered; no analysis of parameter interactions.
Sisal [20]	Herbaceous plant	Rotary impact cutting	Research objective: Reduce cutting energy consumption and improve cutting quality by optimizing cutting speed and cutter tilt angle. Limitation: Cutting quality only qualitatively described; lacks systematic multi-objective optimization framework.
Apple branch [26]	Woody fruit tree	Universal cutting	Research objective: The study investigated the effects of branch diameter and moisture content on cutting force. Limitation: It was limited to single-parameter analysis focusing exclusively on cutting force, while energy consumption and pruning quality were not considered.

Table 1. Cont.

Research Material	Material Type	Test Platform	Features
Apple branch [27]	Woody fruit tree	Custom cutting	Research objective: This work examined the relationship between the cutting speed/feed rate ratio and the cutting power/severance rate. Limitation: The optimization was restricted to a single objective (cutting power), and pruning quality was not addressed.
Larix principis-rupprechtii—this study	Coniferous timber tree	Impact cutting RSM	Research objective: This study establishes a multi-objective optimization framework that simultaneously minimizes cutting energy consumption Y_1 and total equipment energy consumption Y_2 while maximizing pruning quality quantified by specific cutting area S. Innovations: (1) Introduces multi-objective optimization to address the inherent trade-off between energy efficiency and pruning quality. Unlike single-objective approaches that optimize only one criterion at the expense of the other, multi-objective optimization simultaneously considers both conflicting objectives to find a balanced solution. (2) Employs response surface methodology to systematically analyze parameter interactions, enabling the identification of optimal parameter combinations where energy consumption is minimized without compromising pruning quality. (3) Achieves field-validated results with 16.90% energy reduction and 19.28% quality improvement, demonstrating that multi-objective optimization effectively resolves the energy–quality dilemma in practical pruning operations.

By integrating mechanistic analysis with multi-objective optimization and field validation, this research provides a systematic framework that advances intelligent and sustainable phytoprotection for plantation forestry. Optimized mechanical pruning enhances tree health as a preventive measure against pests and diseases, while the established parameter framework supports future integration with smart detection systems—contributing to the design of precision pruning machinery that balances operational efficiency and wood quality within sustainable agriculture.

2. Materials and Methods

2.1. Structure and Principle of Impact Climbing Pruning Equipment

Figure 1a depicts the structure of the impact pruner [30]. The clamping arm is held by a cylinder (SMC Corporation, Tokyo, Japan) to offer the holding force to fix the pruner to the trunk. The cutting mechanism consists of five cutters to complete the branch-cutting operation. It is powered by a hydraulic motor (Danfoss A/S, Nordborg Denmark) to supply climbing power. Both the ascending and pruning phase and the braking and falling phase are separate parts of the task.

In the ascending pruning stage, the hydraulic motor propels the pruner higher and increases its cutting speed. The pruner then uses increased speed and body inertia to cut the branches. The hydraulic engine slows down and brakes after the cutting is finished, and the pruner then slowly slides down to the earth.

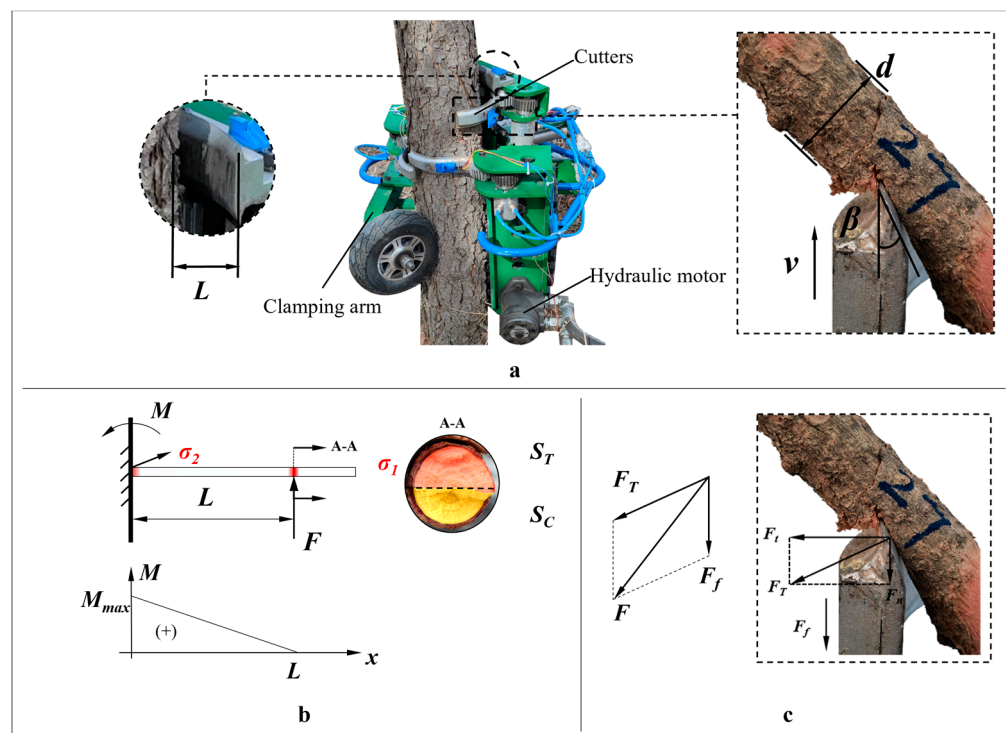


Figure 1. Impact Climbing pruner: (a) impact climbing pruner; (b) branch stress analysis; (c) cutter stress analysis. The colored regions in panel (a) are used to distinguish the main structural components, and A–A indicates the cross-section used for stress analysis.

2.2. Mechanism Analysis of Impact Cutting Process

The impact pruner can be optimized with the help of the analysis of the impact cutting principle, which also serves as a reference for cutting tests [36]. To study the impact cutting principle, the following analysis will be paired with branch growth factors and impact pruner cutting parameters.

The impact pruner's total work W_0 during the pruning operation stage consists of the following: the work G required to ascend to the pruning position and overcome gravity; the kinetic energy E required to move the pruner; and the work Y required to cut the branches. With that said:

$$W_0 = G + E + Y \quad (1)$$

The work required to defy gravity is connected to the pruning height in the equation above, the work required to cut a branch is related to the branch's material issue, and the pruner's kinetic energy is proportional to the climbing speed. The pruning machine needs increase its cutting speed when in impact pruning mode. Consequently, the cutting speed is a crucial factor that influences the cutting process and is also crucial for research on impact cutting.

As seen in Figure 1b, the branch is used as the study's focus when the cutter comes into contact with it. At this point, the branch can be roughly modeled as a cantilever beam and could be considered as a cylindrical cantilever beam with a cross-sectional diameter of d . When the cutter cuts the branch, the internal branch and the branch root will each be subject to the action of the cutting force F_n and the partial force F along the velocity direction, respectively, to generate stress effects. The equation below can be used to determine the size of the internal stress σ_1 :

$$\sigma_1 = \frac{F_n}{S_T} \quad (2)$$

where σ_1 is the stress applied to the branch (Pa); S_T is the area of the stressed part (m^2), defined as the effective contact area between the cutter face and the branch material that bears the normal force F_n , and its magnitude is related to the cutter wedge angle β and the instantaneous depth of cut.

The cantilever beam is under the force F . The cutter–trunk clearance L is the separation between the point of action and the cantilever beam’s root. The cantilever beam’s root is subjected to a bending moment M , and the bending moment diagram is depicted in Figure 1b. The following equation can be used to determine the stress σ_2 that is applied at the root:

$$M_{\max} = F_n L \quad (3)$$

$$W = \frac{\pi d^3}{32} \quad (4)$$

$$\sigma_2 = \frac{M_{\max}}{W} \quad (5)$$

where $M_{\max}$ is the maximum bending moment applied to the cantilever beam ($\text{N}\cdot\text{m}$); W is the section bending coefficient (m^3); L is the cutter–trunk clearance (m); d is the branch diameter (m); and σ_2 is the stress on the root of the branch (Pa).

Due to the varying placements of the F action points, σ_1 and σ_2 will change differently when the cutter cuts at various clearances L . When the cutter makes contact with the branch, the cutting force F is generated, and the cutter begins cutting the branch as a result. The stresses σ_1 and σ_2 are applied to the branch at both the cutting portion and the root when the cutter cuts into the interior of the branch.

As shown in Figure 2, under the combined effects of F_n , σ_1 , and σ_2 , the branch may exhibit different fracture modes during impact cutting: (a) complete severance by the cutter, resulting in a relatively smooth and uniform cross-section; (b) internal tissue fracture after the cutter penetrates the branch; (c) root fracture caused mainly by the bending stress σ_2 ; and (d) splitting caused by the combined effects of the internal stress σ_1 and bending stress σ_2 .

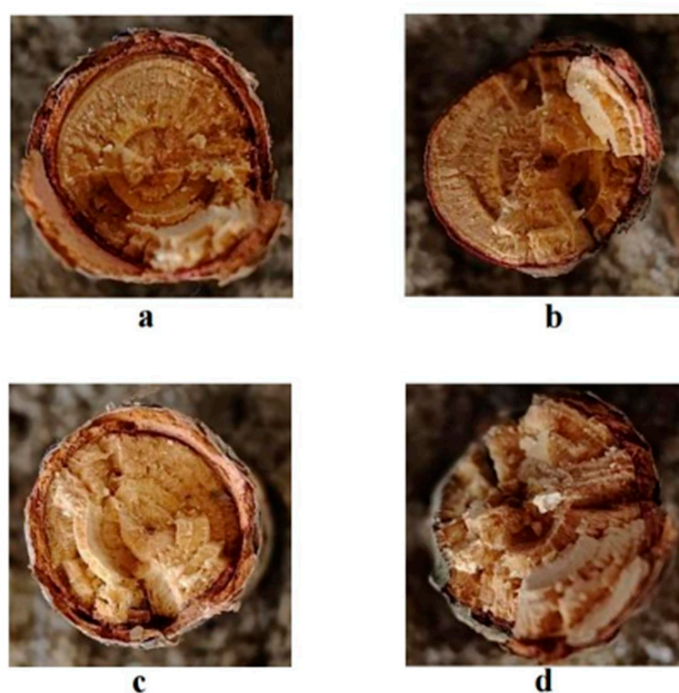


Figure 2. Branch breakage patterns under impact cutting: (a) complete cutter severance; (b) internal tissue fracture; (c) root fracture; and (d) splitting fracture.

The amount of force needed to cut the branch off is known as the cutting force. When a cutter with a speed of v cuts into a branch from the inside, the cutter and the branch are subject to forces of friction and contact. These two forces combine to produce the cutting force. The cutting force proves the crucial indicator of material deformation, fracture features, and the extent of material loss [37]. On the other hand, the amount of cutting force has an influence on the energy consumption and effectiveness of the pruning machinery.

As seen in Figure 1c for the pruning cutter and branch interaction process, the cutter is considered as the study's object. During the cutter and branch interaction, the load on the cutter can be assumed to be evenly distributed at this time. To make the analysis more straightforward, the load is equivalent to the force acting perpendicular to the cutter surface, in which case the cutter force is denoted by the letter F_T . The following equation can therefore be used to determine the force in the direction of the cutting speed and the tangential direction of the speed of the force, respectively:

$$F_n = F_T \sin \beta \quad (6)$$

$$F_t = F_T \cos \beta \quad (7)$$

where F_T is the cutter–branch interaction force (N); F_n is the normal component force of F_T along the velocity direction (N); F_t is the tangential component of F_T force along the velocity (N); and β is the cutter wedge angle ($^\circ$).

Here, the force required by the cutter to overcome friction is equivalent to F_f , which simplifies the analysis. The parallelogram rule can then be used to combine the force generated by the cutter as it cuts the branch to obtain:

$$\vec{F} = \vec{F}_T + \vec{F}_f \quad (8)$$

where $\vec{F}$ is the combined cutter force vector (N); $\vec{F}_T$ is the cutter–branch interaction force vector (N); and $\vec{F}_f$ is the cutter–branch friction force vector (N).

Equation (8) shows that the cutter wedge angle β has an influence on the cutting force $\vec{F}$'s size.

In conclusion, the presentation of the cutting results depends on the cutting speed v , cutter wedge angle β , and cutting clearance L during the impact cutting process. It is required to develop a mathematical model of the aforementioned factors to enhance the impact pruner's efficiency.

2.3. Structure and Principle of Impact Cutting Test Platform

As illustrated in Figure 3, an impact high-speed branch-cutting platform was constructed to mimic the action of the pruner, in conjunction with the impact cutting process mechanism. The platform for impact cutting is powered by an AC motor. The power is transmitted to the in-line slider-crank mechanism by the reducer, and the frequency converter adjusts the speed of the AC motor. The in-line slider-crank mechanism will translate the crank's rotation into the movement of the slider. The slide block is made up of two slide blocks, and the cutter is mounted to the outer slide block. The force sensor is connected between the two slide blocks. When the cutter cuts the branch, its force is communicated to the slider, which reacts by collecting data from the force sensor.

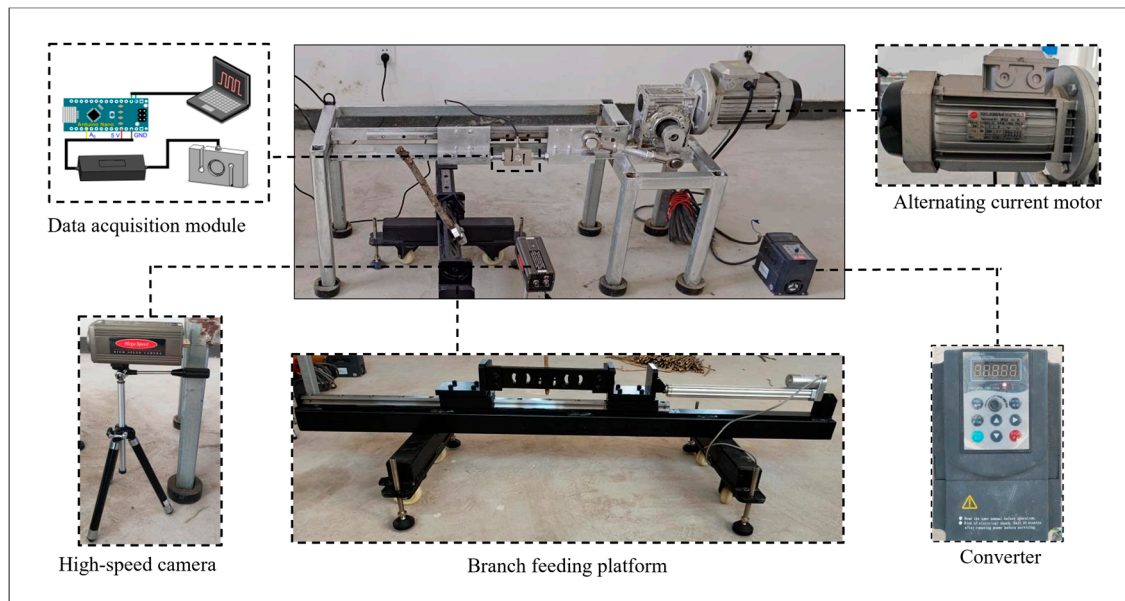


Figure 3. Impact cutting test system.

The accuracy of the test findings can be increased by simulating the branch angle, branch diameter, and other objective elements on the branch feeding platform. This will bring the test conditions closer to those of a forest test site.

The crank-slider system regulates the cutting speed. The in-line slider-crank mechanism's transmission principle is depicted in Figure 4 for clarity. When the motor provides the crank with an angular velocity ω , the crank rotates to drive the connecting rod, which then transmits the motion to the slider, giving it a horizontal translational speed of v . When crank 1 is perpendicular to the direction of the slider, the speed instantaneous center P24 (belonging to slider 4 and crank 2) coincides with the instantaneous center P23 (belonging to crank 2 connecting rod 3), according to the analysis of the kinematic principle of the crank slider by the velocity instantaneous center method. This means that the speed v_s of the slider is the same as the end speed v_T . Therefore, the spatial position of the in-line slider-crank mechanism at this time could be set as the cutting position, and the slider's speed can be equal to the cutting speed v . By altering the motor speed, the impact test bench can realize the regulation of the cutting speed.

The cutting speed to determine the equation is as follows [38]:

$$v = \omega r \quad (9)$$

$$\omega = \frac{\pi n}{30} \quad (10)$$

$$n = \frac{60f}{p} \quad (11)$$

$$v = \frac{2\pi r f}{p} \quad (12)$$

where v is the cutting speed ($\text{m} \cdot \text{s}^{-1}$); ω is the angular velocity ($\text{rad} \cdot \text{s}^{-1}$); r is the crank length (m); n is the rotational speed ($\text{r} \cdot \text{min}^{-1}$); f is the frequency (Hz); and p is the number of motor pole pairs.

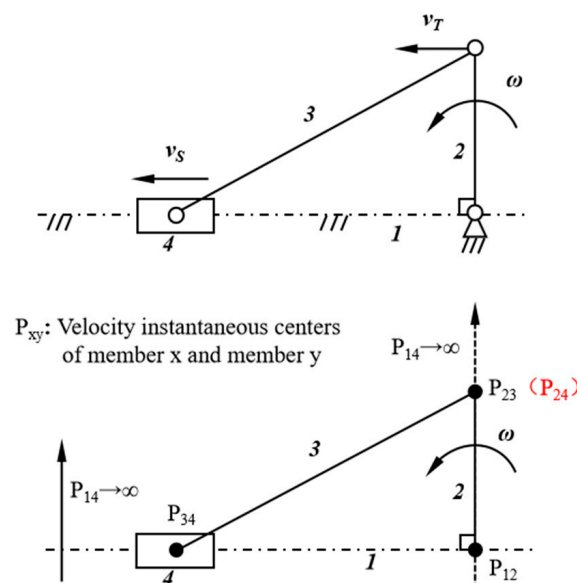


Figure 4. Principle of crank-slider mechanism.

2.4. Experimental Design

The cutting speed v , cutter wedge angle β , and cutting clearance L were selected as the key optimization parameters through a structured two-step procedure combining theoretical prioritization and experimental screening. First, based on the established impact cutting mechanics model (Section 2.2) and a review of the relevant literature, a broader set of potential factors was considered. Among these, v , β , and L were theoretically prioritized because they directly and independently govern three fundamental physical processes: the kinetic energy input, cutting force decomposition, and bending moment governing the fracture mode, respectively. Subsequently, preliminary single-factor experiments were conducted to empirically verify the significance of these theoretically prioritized factors against other candidates (e.g., cutter thickness, branch moisture content within a typical range). The results confirmed that v , β , and L exhibited the most pronounced and statistically interpretable effects on the evaluation indexes (Y_1 , Y_2 , S), while the influence of other factors was comparatively negligible. Therefore, this integrated theoretical and empirical rationale led to the selection of v , β , and L for the subsequent systematic investigation using response surface methodology.

2.4.1. Evaluation Indicators

Energy consumption is crucial for the creation and improvement of cutting mechanisms [39]. In order to assess the influence pruner's performance, this study employed the cutting energy consumption Y_1 and the equipment's total energy consumption Y_2 as indicators.

There is a rolling friction interaction between the track and the tree stems during the ascent of the impact pruner. Regarding the track and the trunk as ideal rigid bodies, the rolling friction does not work. According to this mechanical model, the total energy consumption Y_2 is mostly made up of the following components: the kinetic energy E of the machinery, the work done by overcoming gravity W , and the energy consumption Y_1 for cutting branches.

The work performed by the cutting force when cutting branches accounts for the majority of the cutting energy consumption Y_1 . In this study, a force–time curve is used to represent the cutting force signal from the impact cutting process that is captured in

real-time by the force sensor. By combining the force–time image, the cutting energy consumption Y_1 is determined.

The force–time curve of the cutting force used in the test is depicted in Figure 5. The impact pruner weighs 41.25 kg [32] and operates at a constant cutting speed v in the test. The following equation is used to compute the energy consumption:

$$Y_1 = v \int F(t) dt \quad (13)$$

$$Y_2 = Y_1 + E + W \quad (14)$$

$$E = \frac{1}{2}mv^2 \quad (15)$$

$$W = mgh \quad (16)$$

where Y_1 is the cutting energy consumption (J); Y_2 is the total energy consumption (J); E is the kinetic energy of the equipment (J); W is the work done to overcome gravity (J); v is the cutting speed ($\text{m} \cdot \text{s}^{-1}$); $F(t)$ is the time-varying force function (N); m is the mass of the equipment (kg); g is the local gravitational acceleration ($9.8 \text{ N} \cdot \text{kg}^{-1}$); and h is the pruning height (m).

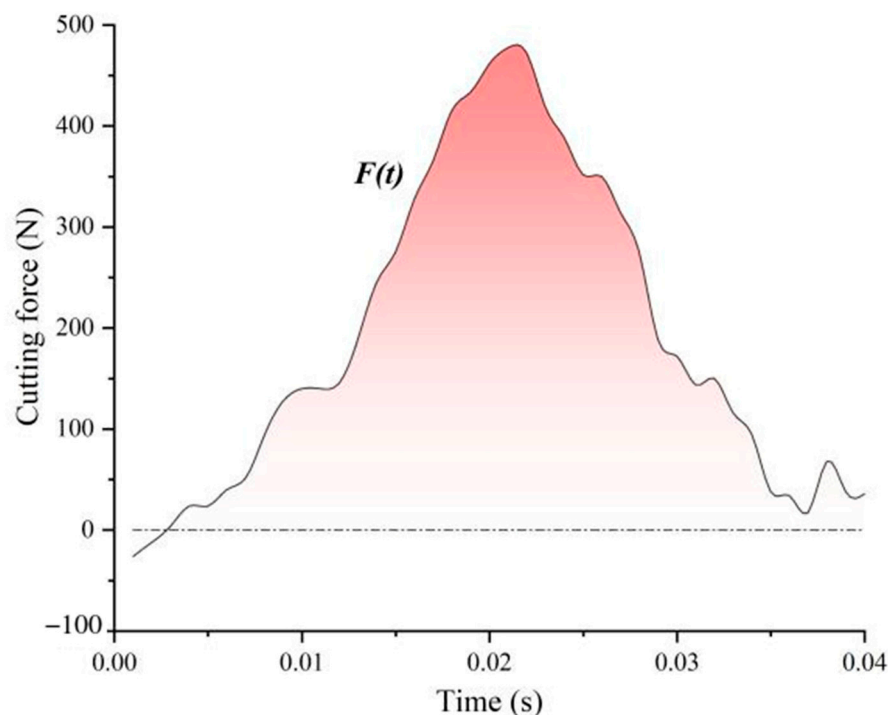


Figure 5. Force–time curve. The shaded region represents the positive portion of the force–time curve used for calculating cutting energy in combination with the cutting speed.

The enhancement of pruning quality in the *Larix principis-rupprechtii* pruning procedure contributes to the rise of tree height [40]. For *Larix principis-rupprechtii*, better pruning can significantly increase wood quality as well as the straightness of the trunk and the length of the knot in the trunk.

The specific cutting area S was thus added in this study as a third assessment metric to maximize each cutting parameter in terms of pruning quality. As indicated in Table 2, the percentage of the branch’s cross-sectional area that the cutter actually cut throughout the test was separated into five rankings and given a name for a specific cutting area. Various grades signify various pruning qualities. The quality of the pruning improves with rank.

Table 2. Rank of specific cutting area.

Rank	0	1	2	3	4
Percentage	0%	0–25%	25–50%	50–75%	75–100%

2.4.2. Test Parameters

It can be seen from the theoretical analysis of Equations (13) and (14) that the cutting speed v has a significant influence on the energy consumption Y_1 , Y_2 and that different cutting speeds also have different effects on the degree of branch fracture cross-sectional damage. Therefore, understanding the impact of the cutting speed on the branch-cutting parameters is crucial for the development of equipment. Cutting speed is a significant characteristic of impact pruning equipment. The upper limit was determined with reference to the operational capability of the pruner and practical safety considerations. Previous field tests of the same impact pruner model recorded a maximum achievable climbing speed of $v_{\max} = 4 \text{ m}\cdot\text{s}^{-1}$ [32]. To ensure operational safety and to prevent potential damage to the tree bark during high-speed impact, a conservative upper limit of $2.5 \text{ m}\cdot\text{s}^{-1}$ was adopted for this study. The lower limit was based on preliminary experimental observations of cutting effectiveness. At speeds below $1 \text{ m}\cdot\text{s}^{-1}$, the impact energy was often insufficient to cleanly sever the target branches (15–30 mm in diameter), resulting in incomplete cuts and reduced pruning efficiency. As a result, the cutting speed range in this investigation is set to:

$$1 \text{ m}\cdot\text{s}^{-1} \leq v \leq 2.5 \text{ m}\cdot\text{s}^{-1}$$

It is evident that varying the cutter wedge angle will alter the contact force F_T between the cutter and the branch. The magnitude of the component force F_n in the branch will change as a result of the change in F_T from Equation (6), which will also affect the size of the internal stress σ_1 loaded by the cutter on the interior of the branch. Changes in F_T will alter how much energy is required to cut the branch, and changes in σ_1 will impact how the branch breaks in the cross-section, affecting the quality of pruning. In agricultural and forestry cutting tools, a wedge angle ranging from 15° to 35° is commonly employed, as it represents a practical compromise between cutting sharpness and the structural durability of the cutter edge [41]. Within this spectrum, an angle below 15° , while sharper, may lead to rapid edge wear or chipping under impact loading, whereas an angle exceeding 35° would significantly increase the required cutting force and promote undesirable crushing of the branch tissue. Therefore, to systematically investigate the effect of β across this practically relevant and representative spectrum, its range was set as:

$$15^\circ \leq \beta \leq 35^\circ$$

In the above range, the gradient $\Delta\beta = 5^\circ$.

The adjustment of the cutter–trunk clearance L results in a change in σ_2 and has an impact on the branch fracture mode, as illustrated in Equation (5). As a result of varied fracture modes, the cutting energy requirements and pruning fracture cross-sectional quality will vary. In addition, various fracture techniques will result in different types of stubble, which will result in varying degrees of knots inside the trunk. Knots, which can be divided into live knot and dead knot varieties, are frequent material flaws in the wood. Living branches create live knots, which work in harmony with the tree. Dead branches give rise to dead knots, which have tubular cells that are structurally distinct from those in the stem [42].

Figure 6 depicts a 5- to 6-year-old *Larix principis-rupprechtii*, which grows with the live knots depicted inside the trunk when pruning stubble is left on the tree for an excessively

long time. As a result of localized deformation and deviation of the wood fibers from the longitudinal axis of the stem axis, knotting significantly reduces the stiffness and strength of the wood, creating zones of mechanical weakness [43].



Figure 6. Example of knot formation in *Larix principis-rupprechtii*. Excessively long pruning stubs may become embedded during subsequent stem growth, forming knots and reducing stem quality.

The purpose of pruning is to promote healthy tree development and high-quality wood [44]. In order to prevent the formation of knots, it is vital to investigate how the clearance between the cutter and the trunk affects the goal value. In operational practice, this translates to keeping the pruning stub short. A common target is to maintain a stub length under 20 mm to facilitate proper wound closure. The cutting clearance L has been chosen as the parameter in this paper. In order to maximize tree health and wood quality, the cutting clearance is specified to be:

$$5 \text{ mm} \leq L \leq 15 \text{ mm}$$

In the above range, the gradient $\Delta L = 5 \text{ mm}$.

2.4.3. Test Materials

Larix principis-rupprechtii trees that have undergone winter pruning have been proven to have greater vigor [45]. As a result, the test materials were collected from the Mulan State Forest Farm in Chengde City, Hebei Province, in December 2024. With a high topography in the northwest and a low topography in the southeast, the Mulan State Forest is situated at the intersection of the Da Hinggan Ling Prefecture Remainder, the Inner Mongolian Plateau, and the Yanshan Remainder. Its elevation ranges from 750 to 2067 m. The region's geographic coordinates range from $116^{\circ}32' \text{ E}$ to $118^{\circ}14' \text{ E}$ and $41^{\circ}35' \text{ N}$ to $42^{\circ}40' \text{ N}$. The forest is situated where the Yanshan Remainder, the Inner Mongolian Plateau, and the Daxinganling Remainder meet. The main tree species in this region include *Larix principis-rupprechtii*, *Pinus sylvestris* var. *mongolica*, *Pinus sylvestris*, *Pinus tabulaeformis*, and *Quercus mongolica*.

In plantation management, a common silvicultural goal is to remove branches while they are still relatively small (typically before exceeding 20–30 mm in diameter) to minimize wood defects and promote clear bole development. This study targets a branch diameter relevant to this operational window. To obtain representative samples, a purposive sampling strategy was employed. Specifically, healthy, dominant 5- to 6-year-old *Larix principis-rupprechtii* trees within a designated, uniformly managed stand were selected. From each tree, multiple straight, defect-free branches with a target diameter of approximately 15 mm were collected from the mid-canopy height (6–8 m), which corresponds to a primary zone for early formative pruning. A sufficient number of branches were collected to satisfy the requirements of the full experimental design, including all factor-level combinations and replicates specified in Section 2.4.5.

From this sample pool, standardized test specimens with a mean diameter of 15 mm and a length of 0.3 m were prepared. When the moisture content of the gathered *Larix principis-rupprechtii* branches was assessed in accordance with GB/T 1927.4-2021, and it was discovered to be between 6 and 11% [46].

2.4.4. Data Acquisition and Processing

The cutting force during the cutting operation was measured using a tensile force sensor with a range of 0 to 10,000 N. To ensure measurement accuracy, the sensor was calibrated prior to the test series using standard static weights traceable to national standards. A linear calibration curve (force vs. voltage) was established with the sensor in its mounted configuration, and this calibration was verified before each test day to account for any potential drift. During operation, the sensor's transmitter amplifies and converts the signal into a 0 to 5V analog output. As shown in Figure 7, this analog signal was captured by an Arduino Nano development board and transmitted via a serial port to a PC for recording. In order to remove the effect of system error, the signal that has been gathered needs to be further processed. The force–time function $F_0(t)$ in no-load operation and the force–time function $F_1(t)$ in load operation are measured first. The error-eliminating force–time function $F(t)$ is then obtained by subtracting the function $F_1(t)$ from the function $F_0(t)$. The force–time curve was created in Origin 2018 using the function $F(t)$ to estimate the energy consumption.

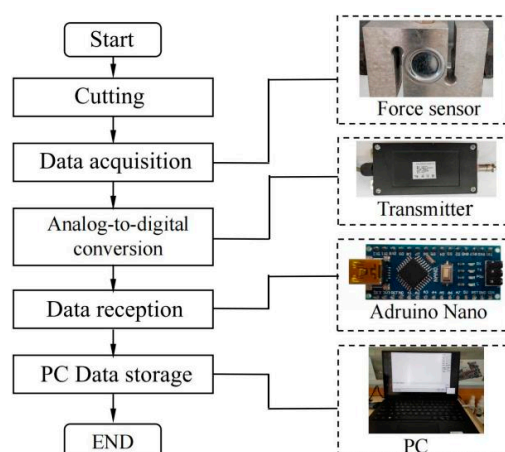


Figure 7. Data acquisition process.

Both the branch fracture section and the branch-cutting procedure were photographed using a digital camera. Lableme 5.5.0 software was used to mark the cutting area in the branch fracture section, the percentage of the cutting area was determined by counting the pixel points, and Table 2 was used to determine the specific cutting area S rank.

2.4.5. Experimental Arrangements

The influence of the cutting speed v , cutter wedge angle, and cutting clearance L on the cutting energy consumption Y_1 , total energy consumption Y_2 , and specific cutting area S were first investigated using a one-factor test to confirm the appropriateness of the factors chosen. Table 3 displays the test factors and levels. The tests were administered three times to each test group, and the results were averaged.

Response surface analysis, which was developed based on the findings of single-factor analysis and in accordance with the Box–Behnken principle, was used to acquire more precise optimization parameters and to identify the interactions between parameters. In the multifactor test, the cutting energy consumption Y_1 , total energy consumption Y_2 , and

specific cutting area S were employed as targets along with the cutting speed v , cutter wedge angle, and cutting clearance L as test factors. Table 3 lists the test variables and levels. The experimental data obtained from this design were used to construct a predictive model.

Table 3. Single-factor test levels.

Level	v	β	L
1	1	15	5
2	1.15	20	10
3	1.3	25	15
4	1.45	30	
5	1.6	35	
6	1.75		
7	1.9		
8	2.05		
9	2.2		
10	2.35		
11	2.5		

2.4.6. Regression Modeling and Multi-Objective Optimization

In order to mathematically describe the relationship between the factors and the response variables, a quadratic polynomial regression model was fitted to the experimental data. This model form is standard in response surface methodology as it can effectively capture potential curvilinear responses and factor interactions within the design space. The indicator regression model's basic formulation is as follows:

$$Y = A_0 + \sum_{i=1}^{n=3} A_i X_i + \sum_{i=1, j=1}^{n=3, m=3} A_{ij} X_i X_j \quad (17)$$

where Y is the test indicator response value; A_0 is the intercept; A_i is the linear coefficient; A_{ij} is the quadratic or interaction coefficient; and X_i is the factor coding value.

In order to determine the ideal parameter combination for the impact pruner, a multi-objective optimization process was used in conjunction with the regression model of Y_1 , Y_2 , and S .

3. Results and Discussion

3.1. Single-Factor Results and Analysis

Single-factor tests were conducted to preliminarily evaluate the effects of the cutting speed (v), cutter wedge angle (β), and cutting clearance (L) on the cutting energy consumption (Y_1), total equipment energy consumption (Y_2), and specific cutting area (S). The results provide a basis for identifying the main variation trends of each factor and for designing the subsequent response surface experiments.

3.1.1. Effect of Cutting Speed on Evaluation Indexes

Figure 8 depicts the cutting speed's influence on the optimization goal. The energy consumption of Y_1 and Y_2 initially increased and then gradually declined as the cutting speed v increased; Y_1 exhibited an overall lowering trend, while Y_2 showed an overall increasing trend. While the level of the specific cutting area S initially steadily rises and then gradually falls, total energy consumption rises. This demonstrates that, in line with conventional wisdom, the higher the cutting speed, the greater is the equipment's total energy consumption Y_2 ; additionally, as the cutting speed increases, the pruning quality initially increases before declining at $v = 1.6 \text{ m} \cdot \text{s}^{-1}$ when the pruning quality was at its

highest, as demonstrated by evaluation level 3. Equation (14) can be used to determine that the cutting speed is equal to the equipment's climbing speed and that the greater the cutting speed, the more kinetic energy the equipment needs, and thus, the greater is Y_2 . The trend of changes in Y_2 are affected by Y_1 , so when $v > 1.7 \text{ m}\cdot\text{s}^{-1}$ or so, Y_1 is decreased when Y_2 also decreases. At greater ($v = 2.5 \text{ m}\cdot\text{s}^{-1}$) or lesser ($v = 1 \text{ m}\cdot\text{s}^{-1}$) cutting speeds, the energy consumption Y_1 and Y_2 and the specific cutting area S are, however, lower. As described in the mechanical analysis in Section 2.2, the branch-cutting process can be simplified as a cantilever beam subjected to a concentrated load. When the cutting speed is low ($v < 1.7 \text{ m}\cdot\text{s}^{-1}$), as in Figure 9, the internal structure is damaged, and the branch is severed by the cutter's cutting action. However, as the cutting speed increases, the specific cutting area S expands, the branch pruning quality gradually improves, the cutting force F works over a wider region, and the energy consumptions Y_1 and Y_2 rise. The aforementioned conclusions are consistent with the working circumstances of impact cutting equipment. The branch breaks at the root, between the root and the cutting position, as shown in Figure 9; when the cutting speed is greater ($v > 1.7 \text{ m}\cdot\text{s}^{-1}$), the cantilever beam is struck by load F , and the root of the branch is the first to be destroyed under the stress, which means $\sigma_2 > [\sigma]$ ($[\sigma]$: the allowable stress of the internal organization of the branch). At this point, the pruning energy consumption Y_1 does not represent the energy W_1 needed to destroy the branch's internal structure, but rather, the energy W_2 needed to stress the branch as a result of the torque M produced by the load F . The test findings show that this energy is less than that needed to damage the branch's internal structure, which indicates that $W_1 > W_2$. In the meantime, the branch splitting is severe in this instance, and the pruning was done poorly.

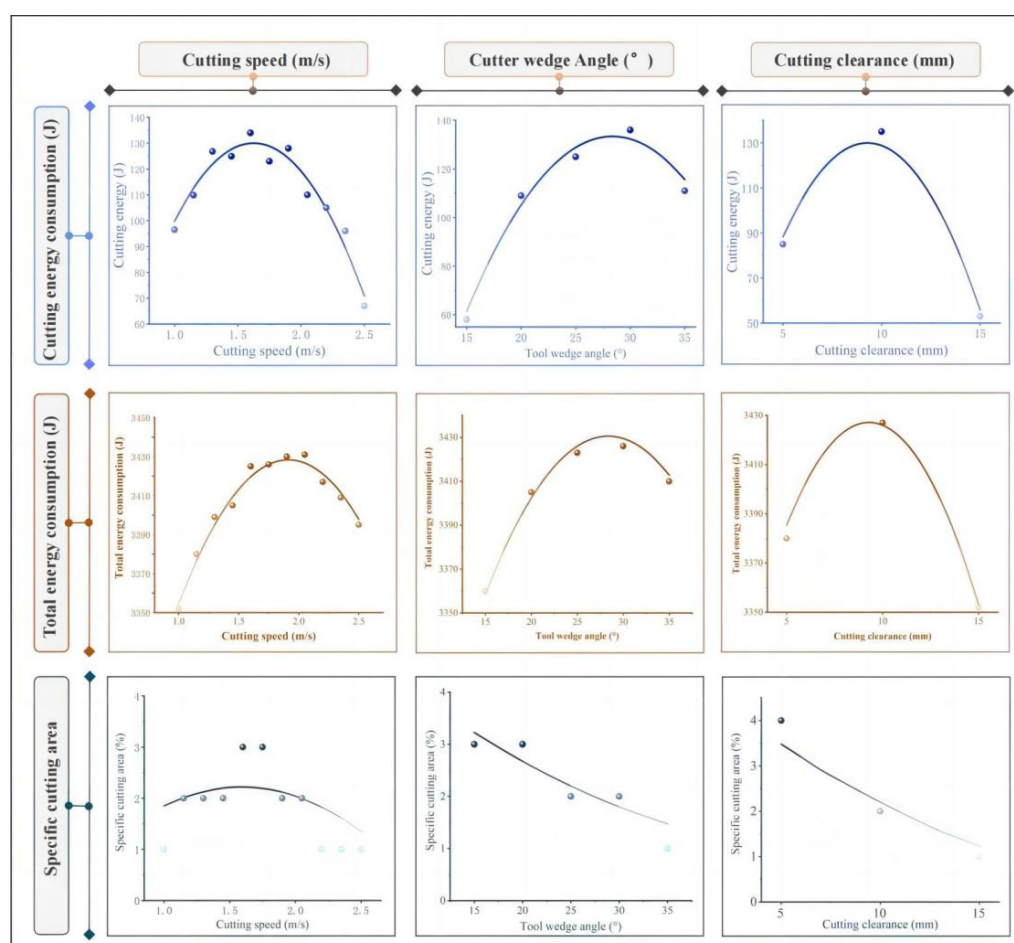


Figure 8. The influence of cutting parameters on the index.

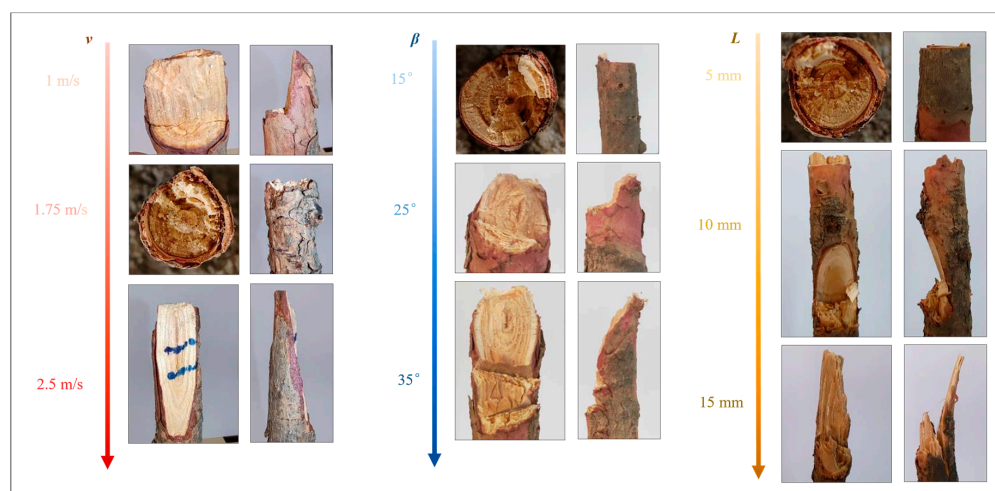


Figure 9. Cutting quality.

3.1.2. Effect of Cutter Wedge Angle on Evaluation Indicators

Figure 8 depicts how the cutter wedge angle affects the evaluation indexes. Y_1 and Y_2 first rise and then fall as the cutter wedge angle rises, while S progressively declines. The results of the analysis above are consistent with the changing trend of Y_1 and Y_2 being the same when the cutting speed is constant. Equation (6) shows that the normal component force F_n of the cutting force damaging the internal tissue of the branch gradually increases as the cutter wedge angle increases, but the torque M generated by load F on the root of the branch at this time is insufficient to damage the branch, which means $\sigma_2 < [\sigma]$. The definitional equation for work is:

$$W = Fs \quad (18)$$

where W is the work done by the object (J); F is the applied force (N); and s is the displacement in the direction of the force (m).

F_n increases, W rises, and energy consumptions Y_1 and Y_2 grow as well, while the branch diameter remains constant, which represents the distance of work done. When the cutter wedge angle $\beta > 30^\circ$, the force F causes a torque M at the branch's root when applied to the root stress, which means $\sigma_2 > [\sigma]$, and the branch breaks at the position between the root and the cutting site, as shown in Figure 9. At this point, the torque M generated by the load F is causing the branch to be stressed to the point of destruction, which means that $Y_1 = W_2$, and as a result, both Y_1 and Y_2 are decreasing in energy consumption.

According to Figure 9, when the wedge angle β of the tool increases, the specific cutting area S gradually decreases, and the pruning quality becomes worse. The smaller the tool wedge angle β , the sharper the cutter is, that is, the smaller the F_n , the easier the cutting process is, and vice versa. Similarly, the smaller the tool wedge angle β is, the larger the cutting area S , the better the pruning quality, and vice versa.

3.1.3. Effect of Cutting Clearance on Evaluation Indicators

Figure 8 depicts the impact of the cutting clearance on the assessment index. When the cutting clearance progressively increases, Y_1 and Y_2 initially rise and then fall, and S gradually falls. The test results demonstrate that when the cutting clearance gradually increases, the pruning energy consumption Y_1 and total energy consumption Y_2 change trends are similar, and the maximum values are reached when the cutting clearance $L = 9$ mm. The specific cutting area S gradually decreases, and there is an optimal cutting quality $S = 4$ at the cutting clearance of $L = 5$ mm. As observed in Figure 9, when L gradually increases, the fracture surface from the cut-off gradually changes to cut-off and split and eventually becomes entirely split according to the fracture cross-section of the branch. The quality of

pruning gradually deteriorates until it transforms to total cleavage. The branch fracture changes from the cutter cutting off the branch ($Y_1 = W_1$) to the cutter partially cutting off and stress fracture ($\sigma_1 > [\sigma]$, $Y_1 = W_1 + W_2$) and then finally changes to the branch being completely broken by the stress effect ($\sigma_2 > [\sigma]$, $Y_1 = W_2$) at the same time the quality of the fracture surface deteriorates. The boundary position where the cutting mode switches from cutter severance to stress fracture is at the cutting clearance $L = 10$ mm.

In conclusion, the analysis above demonstrates that when the branch fracture mode is the cutter cutting branch ($Y_1 = W_1$), the quality of pruning is better ($S = 4$) and that it is worst ($S = 1$, $S = 0$) when the branch fracture mode is splitting ($Y_1 = W_2$). Figure 10 displays a plot of the stress–time variation during the cutting process. As the cutting process proceeds, S_T decreases and σ_1 increases from Equation (2). According to Equation (5), the band area in which σ_2 is located is affected by the cutting gap L and the branch diameter d , independent of the other factors. When the branch fracture process happens in the (a) region ($\sigma_1 < [\sigma]$, $\sigma_2 < [\sigma]$), the branch fracture mode is complete cutting by the cutter, which results in the highest energy consumption and specific cutting area $S = 4$; when the fracture process occurs in the (b) region ($\sigma_1 < [\sigma]$, $\sigma_2 > [\sigma]$), at this time, the branch fracture mode is the root fracture, there is the lowest energy consumption, and the specific cutting area $S = 1$ –2; when the branch fracture process occurs in the (c) region ($\sigma_1 > [\sigma]$, $\sigma_2 > [\sigma]$), the branch fracture mode is complete cleavage, the energy consumption is medium, and the specific cutting area $S = 0$; when the cutting process occurs in the (d) region ($\sigma_1 > [\sigma]$, $\sigma_2 < [\sigma]$), the branch fracture mode is the cutter partially cutting, partially fracture, the energy consumption is medium, and the specific cutting area $S = 2$ –3.

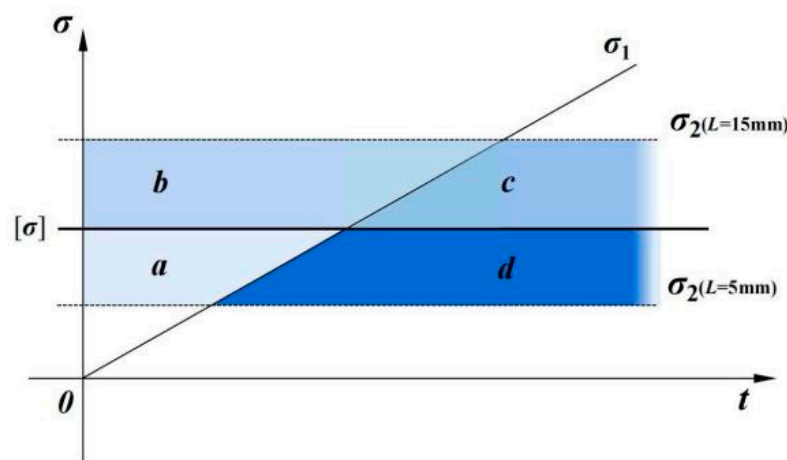


Figure 10. Stress–time curve.

According to the mechanism of impact cutting concluded from the test results, from the perspective of energy consumption, we prefer that the process take place in the (d) region; from the perspective of pruning quality, we prefer that the process take place in the (a) region. In order to guarantee cutting quality while minimizing energy consumption, we should generally make sure that the branch breakage mode is skewed as much as possible toward the way the cutter cuts the branch.

From the above analysis, it can be seen that the closer to the t -axis, or the larger $[\sigma]$, the band region contained in σ_2 is, the higher the cutting quality is and the lower the cutting energy consumption is. From Equations (4) and (5), it is known that the larger the branch diameter d is, the smaller σ_2 is; the better the physical properties of the branch, the larger $[\sigma]$ is. Therefore, the impact pruner is more suitable for the branch pruning operation with large-diameter and tough tissue.

3.2. Results and Analysis of the Multifactor Test

The multifactor test levels and results are shown in Table 4. The multifactor test was designed and analyzed using Design-expert software (Version 13.0, State-Ease Inc., Minneapolis, MN, USA). After quadratic polynomial regression fitting of the ANOVA results, a regression model can be obtained with the cutting speed v , cutter wedge angle β , and cutting clearance L as factors and the pruning energy consumption Y_1 , total energy consumption Y_2 , and specific cutting area S as the target values.

Table 4. Multifactor test levels and results.

No.	Factor			Evaluation Index		
	v	β	L	Y_1	Y_2	S
1	1.75	35	15	7.61	3334	0
2	1.75	35	5	56.44	3382	3
3	1.75	25	10	91.86	3417	2
4	1.75	25	10	61.31	3387	3
5	2.5	25	15	4.7	3426	0
6	1.75	25	10	81.31	3407	2
7	1	25	15	27.4	3291	1
8	2.5	15	10	4.1	3425	2
9	1	35	10	105	3369	1
10	1.75	15	5	6.6	3334	4
11	1	15	10	19.85	3284	3
12	1	25	5	52.94	3317	3
13	1.75	15	15	2.04	3327	3
14	2.5	25	5	8.96	3430	3
15	2.5	35	10	18.1	3439	1
16	1.75	25	10	72.3	3398	2
17	1.75	25	10	75.6	3402	2

3.2.1. Regression Modeling and Significance Testing

As can be seen from Table 5, the p -values of the response surfaces of the regression model for Y_1 , Y_2 , and S are 0.0001, 0.0001, and 0.0009 ($p < 0.01$), indicating that the regression model is highly significant. The p -values of the lack of fit terms were 0.4719, 0.4720, and 0.7510 ($p > 0.05$), indicating that the model was well fitted. The model coefficients for determining R^2 were 0.9719, 0.9747, and 0.9499, indicating that the model has a high confidence level. Therefore, this model can be used to predict the impact of cutting performance of *Larix principis-rupprechtii* branches.

The above significance analysis shows that in the response surface model of Y_1 , β , v^2 , β^2 , and L^2 have an extremely significant effect on this model ($p < 0.01$); v , L , and βL have a significant effect on this model ($0.01 \leq p < 0.05$); and vL and $v\beta$ have a non-significant effect on this model ($p > 0.05$). In the response surface model of Y_2 , v , v^2 , β , β^2 , and L^2 have a highly significant effect on this model ($p < 0.01$); L and βL have a significant effect on this model ($0.01 \leq p < 0.05$); and vL and $v\beta$ have a non-significant effect on this model ($p > 0.05$). In the response surface model of S , β and L have a highly significant effect on this model ($p < 0.01$); βL and v^2 have a significant effect on this model ($0.01 \leq p < 0.05$); and v , $v\beta$, vL , β^2 , and L^2 have a non-significant effect on this model ($p > 0.05$). The following simplified model was obtained by removing the insignificant terms from the above model:

$$Y_1 = -740.90 + 283.04v + 29.65\beta + 50.10L - 0.39\beta L - 77.27v^2 - 0.40\beta^2 - 2.27L^2 \quad (19)$$

$$Y_2 = 2437.16 + 371.00v + 29.65\beta + 50.10L - 0.39\beta L - 88.63v^2 - 0.40\beta^2 - 2.27L^2 \quad (20)$$

$$S = 3.28 + 3.23v - 0.12\beta + 0.02L - 0.01\beta L - 1.07v^2 \quad (21)$$

Table 5. ANOVA results of evaluation indexes.

Source	Y ₁				Y ₂				S			
	SS	DF	F	p	SS	DF	F	p	SS	DF	F	p
Model	9	43,417.80	26.93	0.0001	9	48,335.73	29.98	<0.0001	9	19.89	14.73	0.0009
<i>v</i>	1	1668.69	9.31	0.0185	1	3767.12	21.03	0.0025	1	0.5000	3.33	0.1106
β	1	5892.64	32.89	0.0007	1	5892.64	32.89	0.0007	1	6.13	40.83	0.0004
<i>L</i>	1	2100.17	11.72	0.0111	1	2100.82	11.73	0.0111	1	10.13	67.50	<0.0001
<i>v</i> β	1	628.76	3.51	0.1032	1	628.76	3.51	0.1031	1	0.2500	1.67	0.2377
<i>v</i> <i>L</i>	1	55.43	0.3094	0.5954	1	55.58	0.3102	0.5949	1	0.2500	1.67	0.2377
β <i>L</i>	1	1500.40	8.37	0.0232	1	1500.40	8.38	0.0232	1	1.0000	6.67	0.0364
<i>v</i> ²	1	7953.55	44.39	0.0003	1	10,465.25	58.42	0.0001	1	1.52	10.11	0.0155
β ²	1	6832.25	38.13	0.0005	1	6831.40	38.14	0.0005	1	0.0947	0.6316	0.4529
<i>L</i> ²	1	13,558.95	75.68	<0.0001	1	13,560.14	75.70	<0.0001	1	0.0947	0.6316	0.4529
Residual	7	1254.12			7	1253.95			7	1.05		
Lack of Fit	3	543.76	1.02	0.4719	3	543.59	1.02	0.4720	3	0.2500	0.4167	0.7510
Pure Error	4	710.36			4	710.36			4	0.8000		
Cor Total	16	44,671.93			16	49,589.68			16	20.94		
R ² = 0.9719; Adjusted R ² = 0.9358					R ² = 0.9747; Adjusted R ² = 0.9422				R ² = 0.9499; Adjusted R ² = 0.8854			

3.2.2. Analysis of the Impact of Factors on Target Values

The F-value of each factor can be analyzed through Table 5 to determine the magnitude of the influence of each factor on the target value. The order of significance of cutting energy consumption Y_1 is β , L , and v ; the order of significance of total energy consumption Y_2 is β , v , and L ; the order of significance of the specific cutting area S is L , β , and v . To reduce the energy consumption of the impact pruning machine, the parameter optimization should focus on considering the influence of the cutter wedge angle β , and to improve the quality of pruning, it should focus on considering the influence of the cutting clearance L .

To illustrate how various factors affect the indicators, 3D response surface plots were created using Origin2018 software (OriginLab Crop., Northampton, MA, USA) based on the regression model of the target values. Figure 11 displays the 3D response surface map showing how each factor interacts with the goal value.

The targets Y_1 and Y_2 increase with the increase in cutting speed and then gradually decrease; when $v = 1.7 \text{ m} \cdot \text{s}^{-1}$, the energy consumption is the largest. With the increase in the cutter wedge angle, both targets show a trend of increasing and then decreasing. Energy consumption increases until it peaks at $\beta = 30^\circ$. With the increase in cutter clearance, both targets show a trend of increasing and then decreasing. Energy consumption increases until it peaks at $L = 10 \text{ mm}$. Target S shows a trend of increasing and then decreasing with an increase in the cutting speed and shows a trend of decreasing with an increase in the cutter wedge angle and cutting clearance. The cutting quality is the highest when $v = 1 \text{ m} \cdot \text{s}^{-1}$, $\beta = 15^\circ$, and $L = 5 \text{ mm}$. The change rule is the same as the results of the single-factor analysis.

The higher the cutting speed is, the higher the total energy consumption and the poorer the pruning quality, and when the cutting speed is slower, the quality of the cut is also reduced. A larger cutter wedge angle results in significant energy consumption and poorer cutting quality during pruning. However, the test discovered that cutter-edge wear is severe and cutter life is reduced when the cutter wedge angle is $\beta < 20^\circ$. When the cutting clearance is 15 mm, the energy consumption of pruning is the lowest, but the quality of pruning is poor. When the cutting clearance is 5 mm, the pruning energy consumption is lower, and the pruning quality is excellent.

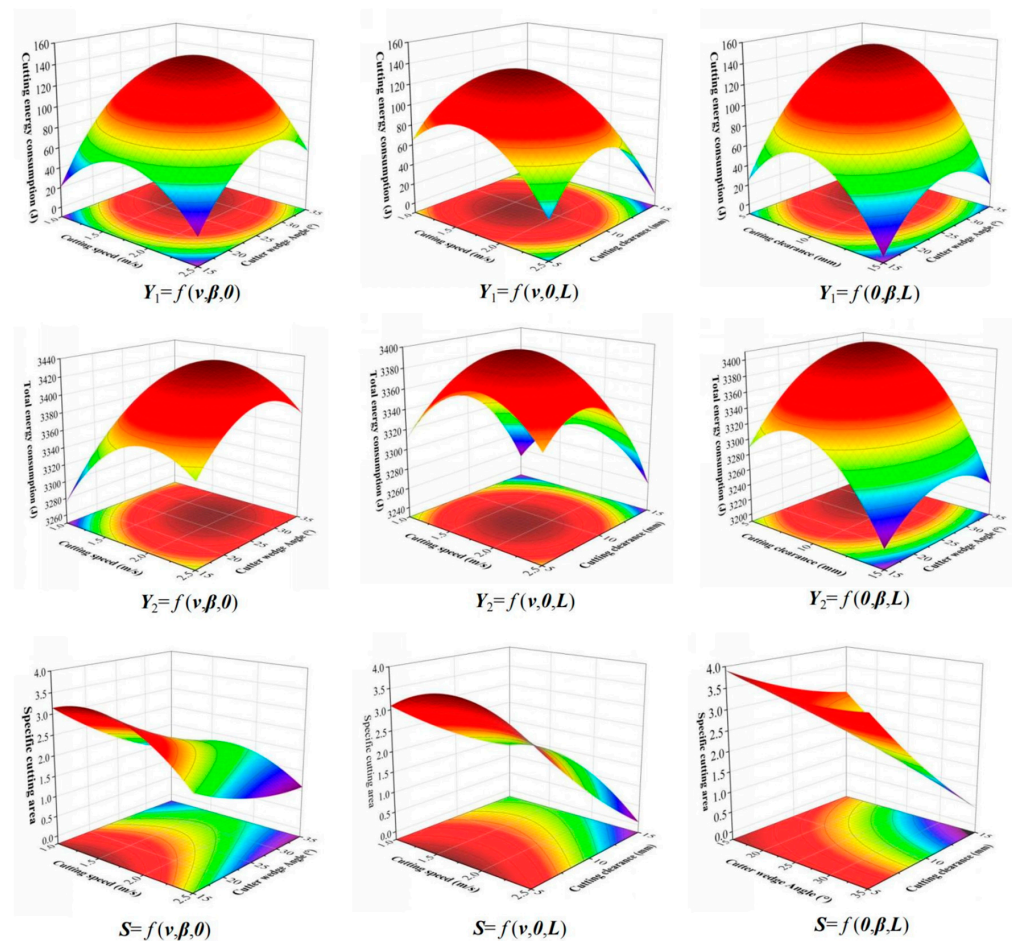


Figure 11. Effects of interaction on the target value.

4. Parameter Optimization and Testing

4.1. Parameter Optimization

In summary, there is no doubt that the minimum Y_2 and the maximum S are required to obtain the optimal cutting parameters. To find the optimal combination of parameters, multi-objective parameter optimization is performed for the model. According to the actual working condition of the impact pruner, the constraints are as follows:

$$\begin{aligned}
 1 \text{ m} \cdot \text{s}^{-1} &\leq v \leq 2.5 \text{ m} \cdot \text{s}^{-1} \\
 15^\circ &\leq \beta \leq 35^\circ \\
 5 \text{ mm} &\leq L \leq 15 \text{ mm} \\
 \min Y_1 &= f_1(v, \beta, L) \\
 \min Y_2 &= f_2(v, \beta, L) \\
 \max S &= f_3(v, \beta, L)
 \end{aligned} \tag{22}$$

The best parameter combination was obtained through Design-expert software (Version 13.0, State-Ease Inc., Minneapolis, MN, USA) optimization: $v = 1.4 \text{ m} \cdot \text{s}^{-1}$, $\beta = 15^\circ$, and $L = 5 \text{ mm}$. Under this parameter combination, the energy consumption values are $Y_1 = 24.93 \text{ J}$ and $Y_2 = 3274.48 \text{ J}$, and the specific cutting area level is $S = 4$ ($S = 3.98$). However, it should be noted that cutter-edge durability should also be considered in practical impact-pruning operations. As shown in Figure 12, the visual comparison before and after

the repeated impact cutting tests indicates that the cutter with $\beta = 15^\circ$ exhibited more obvious edge damage, including edge chipping and blunting. In contrast, the cutter with $\beta = 20^\circ$ showed only slight edge wear and still retained acceptable cutting-edge integrity for continued use. Therefore, although $\beta = 15^\circ$ provided favorable predicted values in the initial optimization, it was not selected as the final practical parameter because an excessively small wedge angle may reduce cutter durability under repeated impact loading. Accordingly, the constraint on the cutter wedge angle was modified to:

$$20^\circ \leq \beta \leq 35^\circ \quad (23)$$

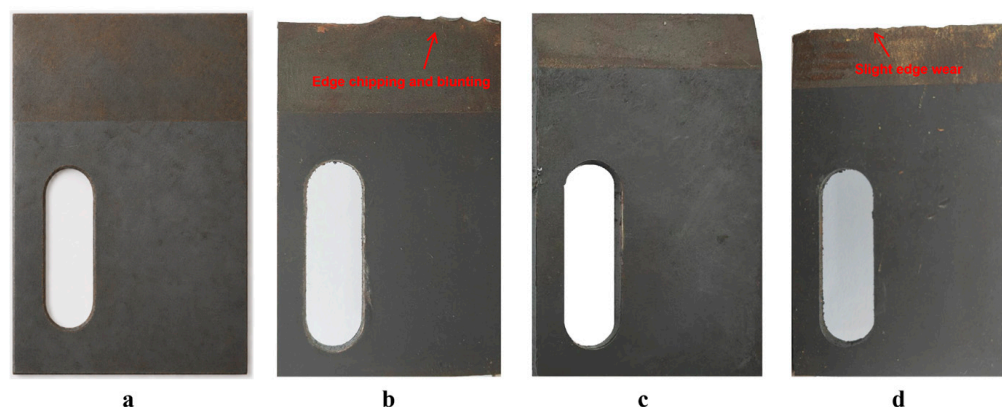


Figure 12. Comparison of cutter-edge conditions before and after repeated impact cutting tests at different cutter wedge angles. (a) $\beta = 15^\circ$ before testing; (b) $\beta = 15^\circ$ after testing; (c) $\beta = 20^\circ$ before testing; (d) $\beta = 20^\circ$ after testing. Arrows indicate typical edge-damage regions.

The parameters obtained after modification and re-optimization are $v = 2.15 \text{ m}\cdot\text{s}^{-1}$, $\beta = 20^\circ$, and $L = 5 \text{ mm}$. Under this combination of parameters, the energy consumptions are $Y_1 = 36.10 \text{ J}$ and $Y_2 = 3351.01 \text{ J}$, and the specific cutting area rank is $S = 3$ ($S = 3.45$).

4.2. Field Test

The hydraulic-driven impact pruner described in the preceding section was used for the field test to confirm the outcomes of the impact pruning equipment's functioning under ideal settings. The field test is shown in Figure 13.

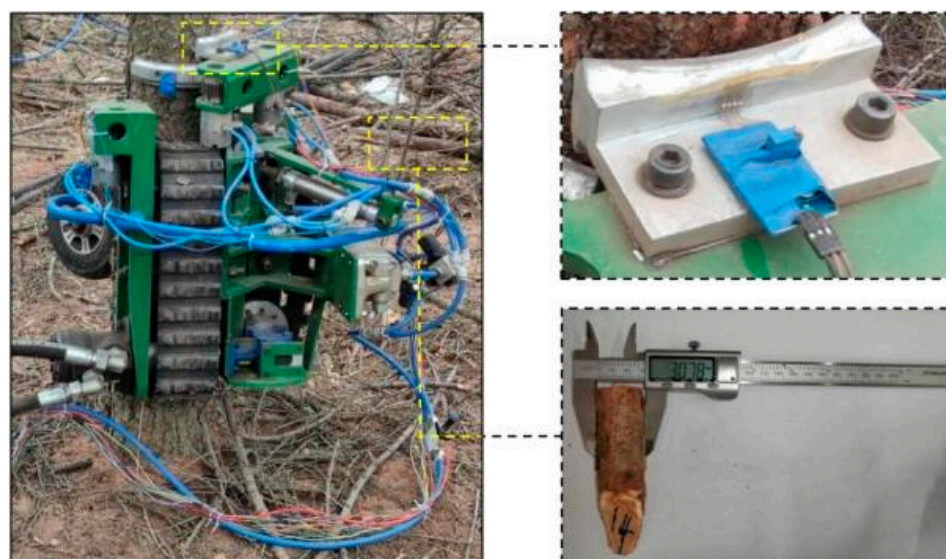


Figure 13. Field validation of the optimized impact pruner under practical pruning conditions.

4.2.1. Test Methods

The test was conducted in April 2025 in the state-owned forest of Mulan Weichang, Chengde City, Hebei Province. Five- to six-year-old *Larix principis-rupprechtii* plants to be pruned were selected as test subjects, with a climbing height of $h = 5\text{--}10\text{ m}$, a trunk diameter of $D = 150\text{--}300\text{ mm}$, and a pruning diameter of $d = 10\text{--}30\text{ mm}$.

4.2.2. Data Acquisition

The cutting energy consumption Y_1 , Y_2 , and specific cutting area S were computed using the same equation as before. As illustrated in Figure 13, a tape measure was used to measure the impact pruner's pruning climbing height; a vernier caliper was used to measure the diameter of the branches pruned; and a high-sensitivity strain gauge (RunesKee, China, Shenzhen) was used to assess the cutting force during pruning.

4.3. Test Results and Analysis

After completing the pruning tests on *Larix principis-rupprechtii* trees in the test area, branches with diameters of $d = 15, 20$, and 25 mm were selected as test samples and divided into three diameter groups. For each diameter group, 25 branch samples were collected, and 25 pruning measurements were performed. Therefore, a total of 75 branch samples and 75 field test measurements were obtained for the analysis. After calculating the average value, the Origin2018 software (OriginLab Crop., Northampton, MA, USA) was used for graphing, as shown in Figure 14. Under the three different diameters of branch pruning results, the energy consumption Y was reduced by 7.96%, 16.90%, and 14.64%, and the specific cutting area S was improved by 19.28%, 11.05%, and 5.05%, respectively. According to the results of the field test, it is known that the optimized cutting parameters are more effective in reducing energy consumption when targeting the cutting of large-diameter branches and more effective in improving the cutting quality when facing small-diameter branches. Additionally, according to the results of pruning quality, the larger the branch diameter, the larger is the S . Therefore, we can draw the following conclusion that the impact pruning equipment is more suitable for large-diameter-branch pruning work.

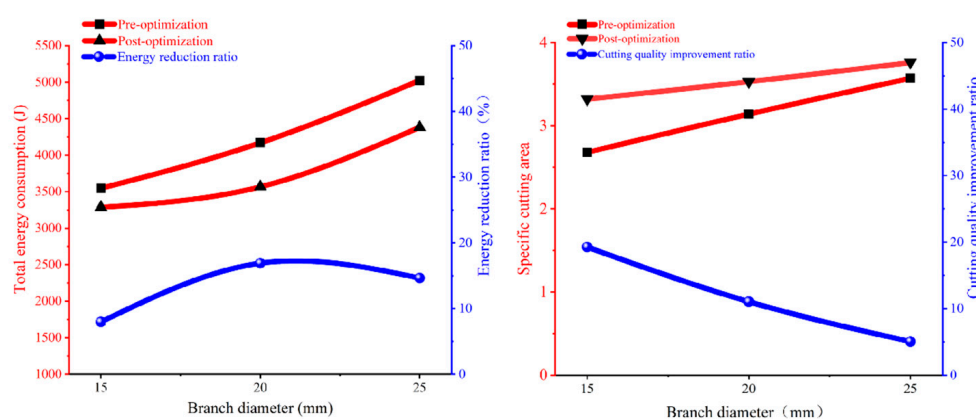


Figure 14. Test results of sample.

The reason for this result may be that when the cutting speed was approximately $v = 2\text{ m}\cdot\text{s}^{-1}$, the cutting power provided by the pruning machine was much larger than the power required to break small-diameter branches; therefore, the optimization effect was less pronounced in this group. When facing branches with larger diameters ($d = 25\text{ mm}$), the pruning quality of the impact pruner was already relatively high before optimization, so the improvement was limited. The field observations suggested that the optimized parameters reduced splitting in small-diameter branches ($d < 20\text{ mm}$). For larger branches

($d > 25$ mm), most branches could be removed with a single pruning operation, while only a small number required a second cut. These observations are consistent with the measured trends in energy consumption and specific cutting area shown in Figure 14.

4.4. Limitations of the Study

It is important to acknowledge the boundaries of this work. The findings and optimized parameters were derived from tests on a single case species, Prince Rupprecht's larch (*Larix principis-rupprechtii*), under a specific set of laboratory and field conditions. Therefore, their direct applicability to other plantation species requires further validation. Future studies should extend the proposed methodology to other major coniferous and broad-leaved plantation tree species to evaluate the universality and robustness of the impact cutting mechanics model and the multi-objective optimization framework. In addition, the assessment of pruning quality in this study was based on two-dimensional image analysis; incorporating three-dimensional wound morphology and long-term tree health indicators could further strengthen future evaluations.

5. Conclusions

This study addressed how the cutting parameters of an impact pruner can be optimized to reduce energy consumption while maintaining pruning quality for Prince Rupprecht's larch (*Larix principis-rupprechtii*) in coniferous plantation forests. To answer this question, an impact cutting mechanics analysis was combined with laboratory cutting tests, response surface modeling, multi-objective optimization, and field validation.

The results showed that the cutting speed (v), cutter wedge angle (β), and cutting clearance (L) jointly affected cutting energy consumption, total equipment energy consumption, and pruning quality. The significance ranking of the factors was β , L , and v for cutting energy consumption (Y_1); β , v , and L for total equipment energy consumption (Y_2); and L , β , and v for the specific cutting area (S). After considering both the cutting performance and cutter durability, the optimized parameter combination was $v = 2.15 \text{ m} \cdot \text{s}^{-1}$, $\beta = 20^\circ$, and $L = 5 \text{ mm}$. Field tests confirmed that the optimized parameters reduced energy consumption by up to 16.90%, improved pruning quality by up to 19.28%, and ensured that the specific cutting area remained at $S \geq 3$.

The main contribution of this study is the establishment of a multi-objective optimization framework for impact pruning that considers both energy efficiency and pruning quality. Compared with single-objective parameter selection, the proposed method provides a more balanced basis for the design and operation of impact pruning equipment. The results also indicate that impact pruning is particularly suitable for pruning relatively large-diameter branches of coniferous plantation trees. This study provides theoretical and experimental support for the development of efficient pruning machinery for plantation forest management.

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