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SCIENTIFIC PAPERS

INTELLIGENT MEASURING ELEMENT

INTELIGENTNÝ MERACÍ ČLEN

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ABSTRACT: This paper presents a comprehensive comparative analysis of two distinct intelligent measuring elements: the Wenglor P2PY105 laser distance sensor and the Balluff BTL6 magnetostrictive linear position sensor. The research addresses the critical problem of evaluating measurement accuracy and hardware integration within modern industrial control architectures. The methodology utilizes a common experimental test stand integrated with a Siemens PLC ecosystem, specifically the CPU 1515F-2 PN, ET 200SP modules (AI 4xI and CM 4xIO-Link), and HMI TP1900 Comfort. Key findings reveal a significant accuracy disparity, with the magnetostrictive sensor achieving micrometer-level precision (≥ 5 µm) and a linearity deviation of ± 200 µm, contrasted against the millimeter-level reproducibility (3 mm) of the laser Time-of-Flight system. The study further explores how intelligent diagnostics via IO-Link facilitate predictive maintenance by monitoring internal acceleration and optics contamination. These results serve as the foundational prerequisite for the optimization of an industrial robot guidance system and the implementation of robust anti-collision mechanisms.

Key words: intelligent measuring element, laser sensor, magnetostrictive sensor, PLC Siemens, IO-Link, analog output, robot guidance optimization, predictive maintenance, anti-collision systems

ABSTRAKT: Tento článok prezentuje komplexnú porovnávaciu analýzu dvoch odlišných inteligentných meracích prvkov: laserového snímača vzdialenosti Wenglor P2PY105 a magnetostrikčného lineárneho snímača polohy Balluff BTL6. Výskum sa zaoberá kritickou problematikou vyhodnocovania presnosti merania a integrácie hardvéru v rámci moderných priemyselných riadiacich architektúr. Metodika využíva spoločný experimentálny testovací stend integrovaný s ekosystémom Siemens PLC, konkrétne CPU 1515F-2 PN, moduly ET 200SP (AI 4xI a CM 4xIO-Link) a HMI TP1900 Comfort. Kľúčové zistenia odhaľujú významný rozdiel v presnosti, pričom magnetostrikčný snímač dosahuje mikrometrovú presnosť (≥ 5 µm) a odchýlku linearity ± 200 µm v porovnaní s milimetrovou reprodukovateľnosťou (3 mm) laserového systému Time-of-Flight. Štúdia ďalej skúma, ako inteligentná diagnostika cez IO-Link uľahčuje prediktívnu údržbu monitorovaním interného zrýchlenia a znečistenia optiky. Tieto výsledky slúžia ako základný predpoklad pre optimalizáciu navádzacieho systému priemyselného robota a implementáciu robustných antikolíznych mechanizmov.

Kľúčové slová: inteligentný merací prvok, laserový senzor, magnetostrikčný senzor, PLC Siemens, IO-Link, analógový výstup, optimalizácia navádzania robota, prediktívna údržba, antikolízne systémy

INTRODUCTION

In modern industrial automation, increasing emphasis is placed on the accuracy, reliability, and flexibility of measurement systems, as these parameters significantly influence the overall performance, efficiency, and safety of automated technological processes. With the ongoing development of Industry 4.0 concepts and the integration of cyber-physical systems, the role of precise and intelligent sensing elements has become even more critical. Measurement systems are no longer limited to simple data acquisition; they now serve as essential components of complex control architectures, enabling real-time monitoring, diagnostics, and adaptive decision-making.

The acquisition of accurate and high-resolution data from technological processes represents a fundamental prerequisite for their subsequent processing in programmable logic controllers (PLCs). These controllers rely on input signals from sensors to execute control algorithms and ensure proper system behaviour. Any inaccuracies or delays in measured data may lead to degraded control performance or system instability. Therefore, the careful selection and evaluation of sensing technologies is essential, particularly in applications requiring high precision and dynamic response. Modern sensor systems are expected to provide high sensitivity, stability, and robustness even in demanding industrial environments (HASSANI, DAKCERMANN, 2023).

This paper focuses on a comparative analysis of two different types of intelligent sensors used in industrial measurement tasks. The first investigated device is the contactless optical laser sensor Wenglor P2PY105, which operates based on optical distance measurement principles (WENGLOR, 2026a). Optical sensing technologies are widely used due to their high speed, non-contact operation, and suitability for precision measurements, including applications such as robotic guidance and automated inspection systems (MACHACEK et al., 2025). The second sensor is the contact guiding magnetostrictive sensor Balluff BTL6-E500-M0100-PF-S115, which utilizes magnetostrictive principles to determine position based on the propagation of mechanical waves in a waveguide (BALLUFF, 2026). Magnetostrictive sensors are recognized for their robustness, high accuracy, and suitability for absolute position measurement in industrial environments (SECO et al., 2005).

The main objective of this work is to compare the selected sensors in terms of their technical parameters. In addition, attention is paid to their integration into industrial control systems, specifically focusing on communication interfaces, signal processing methods, and compatibility with a Siemens PLC test stand. The ability to reliably acquire and process sensor data is a key factor in ensuring effective automation and control.

A comprehensive evaluation and analysis of these intelligent measuring elements is essential, as the results will form the basis for optimizing the guidance system of an industrial robot. The correct selection of sensors directly affects positioning accuracy and system performance. The outcomes of this study are expected to provide valuable insights into the advantages and limitations of the investigated sensing technologies and contribute to improved design and implementation of advanced industrial automation systems.

MATERIAL AND METHODS

The paper analyzed the technical specifications and operational characteristics of two types of intelligent measuring elements (Fig. 1) (BALLUFF, 2026) (WENGLOR, 2026a) and the components of the control system test stand (Fig. 2) (SIEMENS, 2026a) (SIEMENS, 2026b) (SIEMENS, 2026c) (SIEMENS, 2026d).

Fig. 1 Intelligent measuring element P2PY105 (left), BTL6 (right)
Obr. 1 Inteligentný merací člen P2PY105 (vľavo), BTL6 (vpravo)

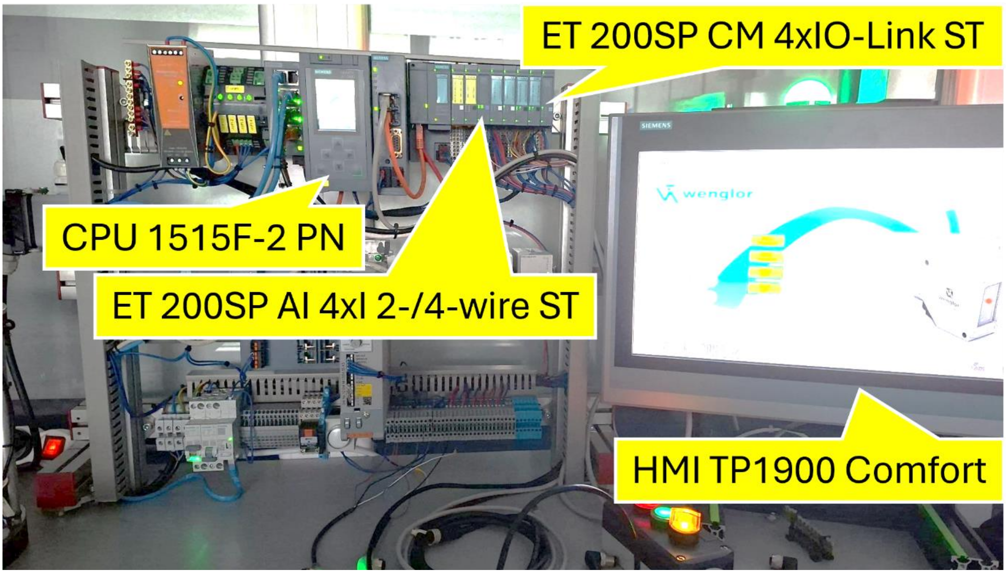

Fig. 2 Siemens PLC test stand
Obr. 2 Testovací stend Siemens PLC

Intelligent measuring elements and their test stand: The construction of the sensor test stand (Fig. 3) consists of an aluminum profile on which both analyzed sensors are firmly mounted. The measurement takes place using a common moving carriage, which is equipped with a position magnet required for the Balluff magnetostrictive sensor, and at the same time, this carriage serves as a reflective surface for the optical beam of the Wenglor laser sensor. A reference scale is attached to the aluminum profile, which enables precise visual verification of the actual physical position of the carriage and subsequent comparison with the data from the sensors.

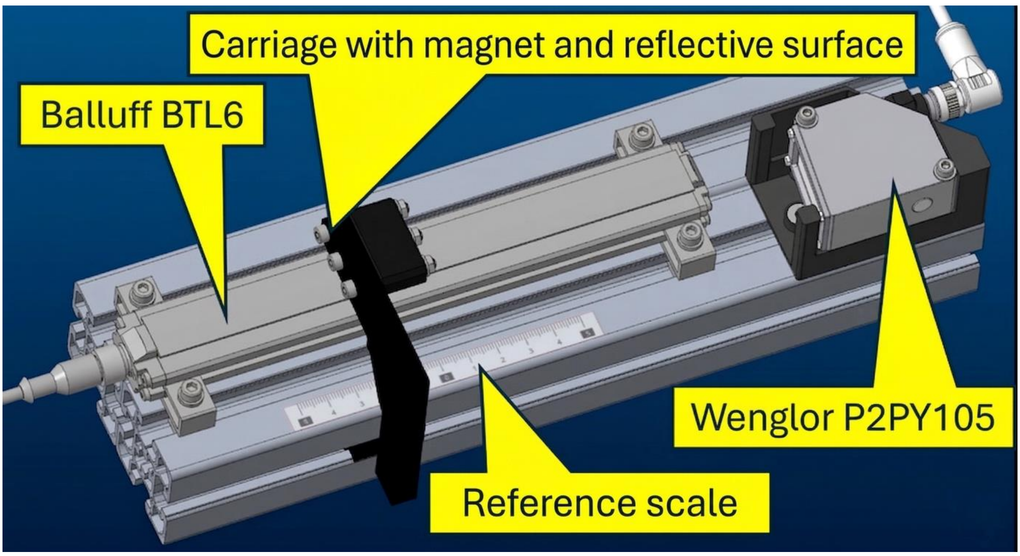

Fig. 3 Sensor test stand
Obr. 3 Stend testovania senzoru

Wenglor P2PY105 laser sensor: This sensor works on the principle of measuring the Time-of-Flight of a light beam and uses a Class 1 laser. The measuring range of this sensor is from 0 to 10,000 mm. It uses the IO-Link V1.1 digital interface with a COM3 transmission rate for communication with the PLC (WENGLOR, 2026a).

Balluff BTL6-E500-M0100-PF-S115 magnetostrictive sensor: The device in a flat profile aluminum housing uses the magnetostrictive principle. The nominal measuring length of this model is 100 mm, and it uses an analog interface with a 4 to 20 mA current output for data transmission (BALLUFF, 2026).

Siemens PLC test stand: For the purpose of analysis, the test stand consists of the following parts (SIEMENS, 2026a) (SIEMENS, 2026b) (SIEMENS, 2026c) (SIEMENS, 2026d):

- **CPU 1515F-2 PN:** A central processing unit from the SIMATIC S7-1500F series, which is designed for standard and safety (failsafe) applications. The software environment for the configuration and engineering of this PLC is STEP 7 in the TIA Portal system from version V18.
- **HMI TP1900 Comfort:** A SIMATIC HMI operator touch panel with an 18.5-inch widescreen TFT display with a resolution of 1366 × 768 pixels, which allows the display of 16 million colors and is used for operator visualization.
- **ET 200SP with AI 4xI 2-/4-wire ST module:** A compact analog input module that can process signals from 4 independent current inputs with a high resolution of 16 bits and a basic error limit of ± 0.3%. This module reads the 4-20 mA signal from the Balluff sensor.
- **ET 200SP with CM 4xIO-Link ST module:** A communication module (Master) that provides 4 ports according to the IO-Link V1.1 protocol and allows the transmission of process and diagnostic data. The module ensures the seamless connection of the Wenglor sensor.

RESULTS

Comparative Analysis of Measurement Accuracy and Physical Principles: The performance of the sensors is fundamentally dictated by their underlying physics and the temporal resolution of the processing electronics.

Wenglor Accuracy Analysis (Optical Time-of-Flight): The Wenglor P2PY105 utilizes the Time-of-Flight (ToF) principle. While this enables a long measuring range (up to 10,000 mm), its precision is inherently limited by the speed of light ($c \approx 3\times10^8$ m/s). To achieve high resolution, timing electronics must resolve picosecond increments; a mere 1-picosecond timing error equates to a ~0.3 mm deviation. Consequently, the sensor achieves a reproducibility of 3 mm in "Precision mode," making it better suited for long-range detection than micrometer-level tasks. (WENGLOR, 2026a).

Balluff Accuracy Analysis (Magnetostriction): The Balluff BTL6 utilizes mechanical (ultrasonic) wave propagation along a waveguide. These waves travel significantly slower than light (~2800 m/s). This lower velocity allows the same timing electronics to achieve much higher temporal resolution relative to distance. A 1-picosecond timing error in this context results in a negligible sub-micrometer deviation. Thus, the sensor achieves a repeat accuracy of ≤±0.002% (≥±5 µm) and a linearity deviation of ±200 µm, making it superior for high-precision linear positioning. (BALLUFF, 2026).

Table 1 Comparison of key parameters of measuring elements for PLC integration
Tabuľka 1 Porovnanie kľúčových parametrov častí merania pre integráciu PLC

Parameter	Wenglor P2PY105	Balluf BTL6-E500-M0100
Measuring principle	Laser (Time-of-Flight)	Magnetostrictive (Linear)
Working range	up to 10,000 mm	100 mm
Reproducibility	3 mm (in Precision mode)	≥ ±5 μm
Interface for PLC	IO-Link V1.1, 2x switching output	Analog, 4...20 mA
Value on error	Digital diagnostic messages	Error current 3,6 mA
Data transmission type	Digital (bidirectional)	Analog (unidirectional)

Data integration into the Siemens PLC test stand requires a different approach for these intelligent measuring elements (Fig. 4). The Balluff magnetostrictive sensor is connected to the analog input module (AI 4xI) of the ET 200SP system, which processes a continuous signal and converts it with a 16-bit resolution (SIEMENS, 2026b). The device does not provide additional digital data in standard operation, but in the event of an error (for example, if the carriage with the magnet leaves the measuring range), it sends a specific current error value of 3.6 mA (BALLUFF, 2026).

The Wenglor laser sensor is integrated to the CPU 1515F-2 PN via the IO-Link master communication module (CM 4xIO-Link). In addition to the measured distance, it can also transmit various status messages (warnings about optics contamination, undervoltage) and provides process data also from the built-in acceleration sensor (WENGLOR, 2026b). All this data is subsequently visualized on the test stand on the HMI TP1900 Comfort touch panel.

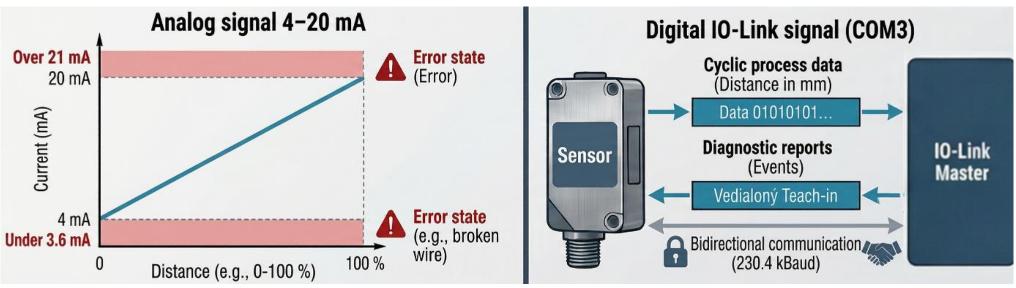

Fig. 4 Output transfer characteristics of the measuring elements
Obr. 4 Výstupná prevodová charakteristika meracieho člena

A fundamental difference in the outputs is the shape and character of the signal itself, whose theoretical foundations are based on signal processing (Fig. 5). The Balluff BTL6 sensor uses a continuous (analog) signal, which is defined continuously in time and amplitude (NAŠČÁK, KOLEDA, 2018). Its value smoothly and linearly increases from 4 mA to 20 mA depending on the position of the magnet. On the contrary, the Wenglor P2PY105 sensor works with a discrete signal, which is defined only at certain points in time (NAŠČÁK, KOLEDA, 2018). It transmits precise numerical values to the control system in digital form via the IO-Link bus, and its switching outputs assume only two discrete states, either closed or open.

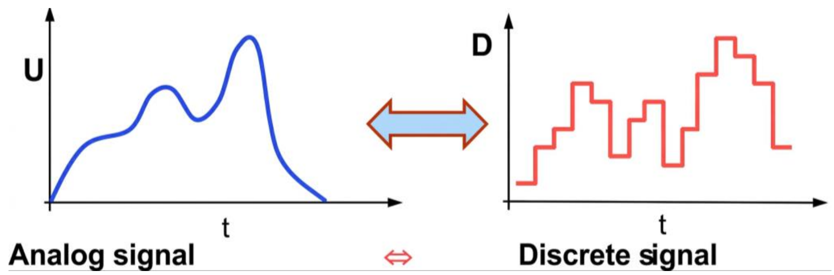

Fig. 5 Signal scheme of the given sensors: continuous (Balluff/left) and discrete (Wenglor/right). *U* – voltage, *t* – time, *D* – discrete value (NAŠČÁK, KOLEDA, 2018)
Obr. 5 Tvary signálov použitého senzora: spojitý (Balluf/vľavo) a diskrétny (Wenglor/vpravo). *U* – napätie, *t* – čas, *D* – diskrétna hodnota

DISCUSSION

Practical Applications and Integration: The selection of these sensors depends on the specific industrial requirements for range, precision, and diagnostics.

Industrial Use Cases:

- **Balluff BTL6 Application:** Due to its micrometer-level accuracy, this sensor is ideal for high-precision positioning tasks such as CNC tool placement or micro-assembly where sub-millimeter precision is paramount.
- **Wenglor P2PY105 Application:** The 10m range and 3mm reproducibility make this sensor suitable for anti-collision systems in mobile robotics or overhead cranes, where stopping distances are more critical than absolute positioning**.**

Predictive Maintenance and Diagnostics: The Wenglor sensor's IO-Link interface (SIEMENS, 2026c) provides a transformative advantage for Industry 4.0. Unlike the Balluff sensor's unidirectional analog signal, the Wenglor sensor transmits process data from a built-in acceleration sensor and monitors optics contamination (WENGLOR, 2026b). This acceleration data allows for the detection of mechanical vibrations in a robot arm, enabling the system to trigger maintenance before structural failure occurs.

CONCLUSION

Comparison on the test stand with a reference scale demonstrated fundamental differences in the technical parameters and data collection capabilities of the tested intelligent measuring elements. The Balluff magnetostrictive sensor provides an order of magnitude higher accuracy (≥ ±5 μm), while the Wenglor laser sensor excels in the measuring range and the amount of diagnostic data. The successful integration into the Siemens platform showed that the system can fully serve both technologies through appropriate modules - analog for continuous signal and IO-Link for discrete signal.

From the perspective of practical applications, magnetostrictive sensors are widely used in demanding industrial conditions, such as vertical hydraulic presses. As stated in the application note (GEFRAN, 2026), these sensors ensure highly precise position control (with a repeatability of 0.01 mm) and synchronized movement of the press columns during the pressing of metal workpieces. Thanks to their high shock resistance, this measurement is crucial for protecting the equipment from damage caused by unbalanced forces and for maintaining consistent production quality. On the other hand, laser displacement sensors are advantageously deployed for in-situ monitoring of precise processes. According to a study (WILLIAMS et al., 2019), the integration of laser sensors allows contactless monitoring of the deposited layer height and its thermal contraction in real-time during metal 3D printing (LPBF), enabling the system to detect process anomalies and prevent the occurrence of defects in the products.

Future Work: The knowledge, measured data, and integration methods analyzed in this study will serve as a direct basis for further research in the field of automation and advanced industrial robotics. The research will in the future focus on the application of intelligent measuring elements in solving complex tasks under real conditions. A particularly promising area is the integration of sensors for calibration purposes. As demonstrated by the authors (LIN et al., 2023), the use of external laser sensors for the automatic calibration of the Tool Center Point (TCP) in six-axis robots brings significant improvements. This contactless and time-efficient approach can automatically correct both positional and angular deviations of the tool, thereby substantially increasing the accuracy and repeatability of the manipulator's positioning at various movement speeds. These calibration and guidance procedures are essential for flexible and highly precise manufacturing.

In real industrial conditions, it is also essential to respond to the operational deviations of the technological equipment itself. The identified shortcomings of the press will therefore be resolved in detail in the future and compensated in all three spatial planes, i.e., in the X, Y, and Z axes (Fig. 6-left). The safe targeting of these spatial deviations and their direct connection with the manipulator's guidance system (Fig. 6-right) is crucial for the correct functioning of the workplace. I will use this to optimize the trajectory of an industrial robot removing sand cores from the press.

Fig. 6 Press imperfections in the X, Y and Z axes (left) and the manipulator removing sand cores from the press (right)
Obr. 6 Nedostatky lisu v osiach X, Y a Z (vľavo) a manipulátor odoberajúci pieskové jadrá z lisu (vpravo)

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GEOMETRIC MODIFICATION OF THE WORKING TOOL OF FORESTRY MILLING MACHINES OPERATING UNDER CONDITIONS OF HIGH TRIBOLOGICAL STRESS

GEOMETRICKÁ MODIFIKÁCIA PRACOVNÉHO NÁSTROJA PÔDNYCH FRÉZ PRACUJÚCICH V PODMIENKACH VYSOKÉHO TRIBOLOGICKÉHO NAMÁHANIA

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ABSTRACT: The article addresses the geometric modification of cutting tools for forest milling machines operating under conditions of high tribological stress. The aim of the research was to design new shapes for the cutting part of the tool, focusing on optimizing the material penetration process. Based on the analysis of existing design solutions and the identification of the most highly stressed areas, four geometric variants of the working surface were proposed: 2nd-, 3rd-, and 4th-degree polynomial profiles and a tangential ogival profile.
The proposed shapes were mathematically defined and subsequently analysed in terms of stress and strain distribution under operational loading. The results of the strength analysis confirmed that all variants meet the requirements for mechanical durability, with the most favourable results in terms of uniform stress distribution and minimal deformation achieved by the variant with a 4th-degree polynomial profile.
The findings suggest that using rounded geometric shapes, particularly higher-degree parabolic curves and ogival profiles, can lead to reduced stress concentration in the cutting wedge area, limited wear, and extended service life of the cutting tools. The proposed solutions represent a promising direction for further research.

Key words: forestry milling machine, working tool, geometric modification, abrasive wear, stress analysis

ABSTRAKT: Príspevok sa zaoberá geometrickou modifikáciou pracovných nástrojov lesných fréz pracujúcich v podmienkach vysokého tribologického namáhania. Cieľom výskumu bolo navrhnúť nové tvary reznej časti nástroja s dôrazom na optimalizáciu procesu vnikania do materiálu. Na základe analýzy existujúcich konštrukčných riešení a identifikácie najviac namáhaných oblastí boli navrhnuté štyri geometrické varianty pracovnej plochy: profil polynómu 2., 3. a 4. stupňa a tangenciálny ogivál.
Navrhnuté tvary boli matematicky definované a následne analyzované z hľadiska rozloženia napätí a deformácií pri prevádzkovom zaťažení. Výsledky pevnostnej analýzy potvrdili, že všetky varianty spĺňajú požiadavky na mechanickú odolnosť, pričom najpriaznivejšie výsledky z hľadiska rovnomerného rozloženia napätia a minimálnych deformácií dosiahol variant s profilom polynómu 4. stupňa.
Zistenia naznačujú, že použitie oblých geometrických tvarov, najmä vyšších stupňov parabolických kriviek a ogiválnych profilov, môže viesť k zníženiu koncentrácie napätí v oblasti rezného klinu, k obmedzeniu opotrebenia a k predĺženiu technologickej životnosti pracovných nástrojov. Navrhnuté riešenia predstavujú perspektívny smer ďalšieho výskumu.

Kľúčové slová: lesná fréza, pracovný nástroj, geometrická modifikácia, abrazívne opotrebenie, pevnostná analýza

INTRODUCTION

Forestry milling machines play a crucial role in the removal of unwanted vegetation, biomass processing, soil preparation, and the construction and maintenance of forest roads. Their efficiency, service life, and operational reliability are directly dependent on the material composition, structural design, and geometry of the working tools (teeth), which are subjected to extreme dynamic loading and abrasive wear in heterogeneous forestry environments.

Current developments in the field of working tools are primarily focused on the selection of suitable construction materials, adaptation of tools to specific operating conditions, and optimization of cutting-wedge geometry, while also considering safety and environmental aspects. Manufacturers and research institutions try to achieve a balance between high wear resistance, sufficient mechanical strength, and economic efficiency in both production and operation.

Material selection and analysis play a key role in the research and development of working tools. These tools are exposed to intense abrasive wear, impact loading, and high contact pressures. For this reason, high-strength alloy steels are commonly used in their manufacture, often supplemented with hardfacing layers or carbide tips. Such material combinations provide the required balance of strength, hardness, and wear resistance, thereby extending tool service life even under severe operating conditions. Material-related aspects have been extensively investigated by several authors (Ťavodová et al. 2025; Bołoz, 2025; Vargová et al. 2023; Pirowski et al. 2022; Ťavodová and Hnilica, 2020; Falat et al. 2019; Ťavodová et al. 2019; Belenkiy et al. 2019; Ťavodová, 2018).

An important factor is also the influence of the working environment. Soil type, stone content, rock hardness, and vegetation characteristics significantly affect the wear rate and operational reliability of working tools. Consequently, different types of tools are designed for specific applications, with their geometry, material composition, and mounting systems optimized according to the particular working process. These aspects have been addressed by various authors (Vrublevskyi, 2025; Yazıcı, 2024; Marinov et al. 2023; Malvajerdi, 2023; Hnilica et al. 2017; Hnilica et al. 2015).

Another important aspect in tool development is the analysis of cutting-wedge geometry. Optimization of tooth shape or cutting wedges allows for a reduction in energy consumption, improvement in milling or crushing quality, and a decrease in dynamic loading of the machine. In practice, parameters such as cutting angle, cutting wedge geometry, tool arrangement on the rotor, and mutual spacing are analysed. These parameters are typically verified by manufacturers through experimental testing under real operating conditions, although such results are often not publicly available.

The development of working tools also considers safety and environmental aspects. Modern design approaches aim to minimize negative impacts on soil, reduce energy consumption, and improve operator safety. Environmental impacts of mulching processes on soil have been investigated by several authors (Iqbal et al. 2020; Ngouajio and McGiffen, 2004; Lamont, 2005; Oliveira and Merwin, 2001). Life-cycle cost (LCC) analysis of vegetation crushers has been addressed by Sujová et al. (2016; 2015).

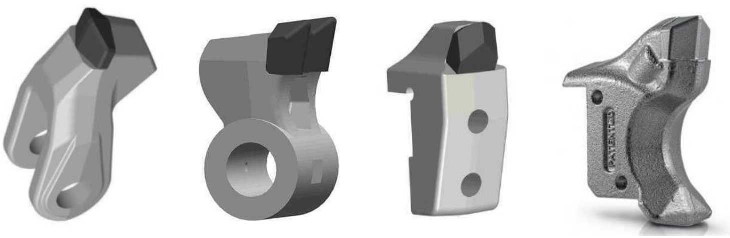
Therefore, a comprehensive analysis of working tools operating in heterogeneous environments represents an essential basis for the design and optimization of new construction solutions. The evaluation of existing tool types, their geometry, material composition, and operational characteristics enables the identification of key factors influencing their functionality and durability. These findings provide a foundation for the development of innovative working tools capable of operating efficiently under demanding conditions.

Forestry milling machines can be classified, according to their operational use, into several basic categories, including vegetation crushers, soil milling machines, and road milling machines.

Vegetation crushers are widely used in forestry, agriculture, and landscape maintenance for the removal of invasive vegetation, shrubs, and young trees. The working tools of these machines must be capable of efficiently processing various types of plant material while simultaneously resisting contact with soil and stones. The most commonly used types of working tools include:

- rotating blades (flails) (Fig. 1a),
- hammers (Fig. 1b),
- teeth (Fig. 1c).

a) b)



c)

d)

Fig. 1 Working tools of forestry milling machines; a – rotating blades (flails), b – hammers, c – teeth, d – road milling teeth (JYF Machinery, 2026)

Obr. 1 Pracovné nástroje lesných fréz; a – rotujúce nože (cepy), b – kladivká, c – zuby, d – frézovacie zuby

Rotating blades (flails) represent relatively lightweight cutting tools, primarily used for mulching grass, small shrubs, or soft vegetation. Their main advantages include low weight and reduced energy demand, allowing their use on lower-power machines. However, their disadvantages include lower impact resistance and limited capability for processing harder or thicker woody materials.

Hammers are more robust working tools, characterized by higher mass and greater impact energy compared to flails. This enables the processing of thicker woody materials. Their advantages include higher resistance to impacts with hard obstacles and the possibility of re-sharpening the cutting wedge.

Teeth represent the most durable type of working tools used for vegetation processing. Their design allows for efficient crushing of larger woody materials, roots, and other hard materials. These tools are typically manufactured from high-strength steels and are often equipped with carbide tips (tungsten carbide - WC), which significantly increase their resistance to wear.

Soil milling machines are used for mechanical soil treatment, seedbed preparation, and land reclamation. Their working tools are designed to disintegrate soil, mix organic material, and simultaneously crush residues of vegetation and root systems.

The primary working elements of these machines are teeth (Fig. 1c) mounted on rotating drums. Their geometry enables efficient penetration into the soil and effective disruption of its structure. The tool bodies are typically manufactured from forged alloy steels and subsequently subjected to heat treatment. The tips of the working tools are commonly reinforced with hard inserts, most often made of tungsten carbide (WC), which significantly increases resistance to abrasive wear under soil operating conditions.

Road milling machines used in forestry operations are intended for the removal of surface layers of forest roads during reconstruction and maintenance. The main working component of these machines is a milling drum equipped with cutting tools that, during rotation, progressively disintegrate and remove material from the road surface.

The road milling teeth (Fig. 1d) of road milling machines are designed to effectively break down hard construction materials. Their structure consists of a steel body and a carbide tip (tungsten carbide - WC), ensuring high wear resistance. An important feature of these tools is their ability to rotate within the holder, which enables uniform wear of the cutting part and extends tool service life.

The arrangement of tools on the drum is designed to ensure uniform loading of the machine and an optimal milling process. Both the drum and the working tools must withstand high dynamic forces generated during contact with the road surface.

A wide range of working tools for various types of milling equipment is currently available on the market. Manufacturers offer tools with different design solutions, which differ mainly in the geometry of the cutting part, the material used, and the mounting method.

Fig. 2 Shapes of fixed teeth for crushers and soil milling machines
Obr. 2 Tvary pevných zubov pre drviče nežiaducich nárastov a pôdne frézy

For vegetation crushers and soil milling machines, fixed teeth with carbide tips (WC) (Fig. 2) are most commonly used. These working tools are designed for operation in soil environments as well as for processing woody biomass. In forestry road milling machines, in addition to fixed teeth, rotary picks (Fig. 3) are also employed. These tools can achieve more uniform wear due to their ability to rotate within the holder, which contributes to an extended service life.

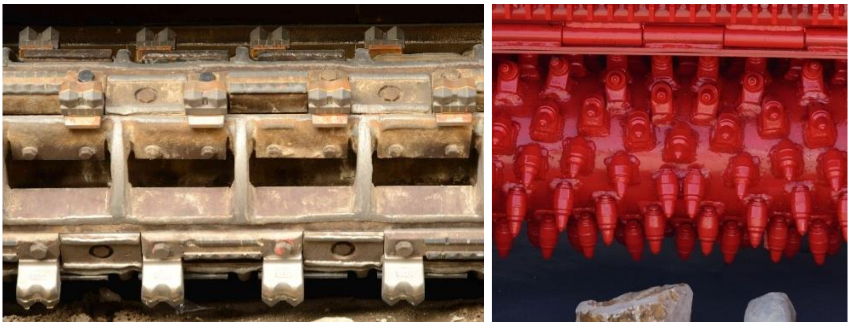


Fig. 3. Shapes of working tools for forestry road milling machines
Obr. 3 Tvary pracovných nástrojov pre lesné cestné frézy

A common feature of most modern working tools is the use of alloy steels for the tool body and hard materials for the cutting part. This combination of materials provides an optimal balance between strength, hardness, and resistance to abrasive wear. In terms of working surface geometry, tools with a conical working surface are most commonly used, particularly in vegetation crushers and soil milling machines.

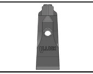
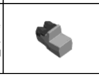
MATERIAL AND METHODS

The objective of the research was to design new geometric configurations of the cutting elements of forestry milling machine working tools, with an emphasis on optimizing the tool penetration process into the material and reducing the intensity of abrasive wear on the functional surfaces. The research methodology consisted of an analysis of the current design solutions of working tools, identification of the most highly loaded areas, the design of new geometrical shapes of the tool working surface, and their mathematical description.

In the first step of the research, an analysis of the design solutions of working tools used in forestry milling machines was carried out (Fig. 4). The analysis was primarily focused on the geometry of the working tools, the shape of the cutting part and the wear characteristics of the functional surfaces during operation. At present, working tools with a conical working surface (Fig. 5) are most commonly used, as they are structurally adapted for vegetation crushing and wood biomass processing.

	Recommended use for wood with less rocky grounds		Impact resistance in rocky terrain		Crushing, ground contact, excellent wear resistance, and high reliability		Bush clearing
	A tool that delivers excellent penetration with very low power consumption		Triple carbide tool designed for wear-resistant and sandy applications		Ideal for crushing fibrous vegetation		Bush clearing
	High impact resistance in rocky terrain		Single-sided blade with hardened surface designed for above-ground milling		Ideal for crushing fibrous vegetation		Best suited for use in situations where the head is frequently exposed to contact with rocks or soil
	Tool with excellent penetration at very low power consumption		Single-sided blade with hardened surface designed for above-ground milling		Ideal for achieving a finer and more aesthetic final result		Best suited for use in situations where the head is frequently exposed to contact with rocks or soil
	High impact resistance in rocky terrain, rotatable attachment		Single-sided blade with hardened surface designed for above-ground milling		Forestry tools Forest ground milling tools		Forest milling
	Tool with excellent penetration properties, rotatable attachment		Ideal for shredding in wear-intensive applications with heavy ground contact and rock content		Forestry tools Forest ground milling tools		Forest milling cutters and soil stabilizers, tooth with extra-large carbide tip for crushing stones
	Tool with maximum penetration capability, additional carbide inserts for abrasive conditions		Tool designed for the most demanding industrial applications, welded		Forestry tools Forest ground milling tools		Carbide tooth suitable for crushers
	Tool with maximum penetration capability, additional carbide inserts for abrasive conditions		General mulching and crushing		Forestry tools Forest ground milling tools		Tooth with extra-large carbide tip for crushing stones
	The finest and most consistent crushing results thanks to the double-tip blade geometry		Sandy or abrasive conditions, crushing		High abrasiveness, harvesting in		Crushers and soil stabilizers
	Tool with excellent penetration capability, additional carbide inserts for abrasive conditions		The best choice for applications in rocky terrain		High abrasiveness, harvesting in		Stone crushers and soil stabilizers
	Crusher of undesirable advance growth and soil stabilizers		Crusher of undesirable advance growth		Milling or crushing stones, mulching and deep milling of surfaces, stump removal		Crushing of undesirable advance growth, suitable for mulching below ground level
	Crusher of undesirable advance growth		Crusher of undesirable advance growth		Stone and vegetation crusher		Crushing of undesirable advance growth, rotates to three positions
	Crusher of undesirable advance growth		Crusher of undesirable advance growth		Stone and vegetation crusher		Crusher of undesirable advance growth
	Crusher of undesirable advance growth		Crusher of undesirable advance growth		Crushing vegetation, medium-duty soil cultivation and stump removal		Crusher of undesirable advance growth
	Crusher of undesirable advance growth		Crusher of undesirable advance growth		Crushing vegetation for harder materials, milling stones, concrete and asphalt		Crusher of undesirable advance growth
	Crusher of undesirable advance growth, double-sided tooth		Crusher of undesirable advance growth		Forest milling		Crusher of undesirable advance growth
	Crusher of undesirable advance growth		Crusher of undesirable advance growth		Crusher of undesirable advance growth		Tooth with one large carbide tip for crushing stones and additional carbide protection
	Crusher of undesirable advance growth		Crusher of undesirable advance growth		Crusher of undesirable advance growth		Crusher of undesirable advance growth
	Crusher of undesirable advance growth		Crusher of undesirable advance growth		Crusher of undesirable advance growth		Crusher of undesirable advance growth
	Crusher of undesirable advance growth		Stone crushing or chipping, mulching and deep surface milling, stump removal		Crusher of undesirable advance growth		Crusher of undesirable advance growth

Fig.4 Design of working tools (JYF Machinery, 2026; KingKong Tools, 2026; Prinoth, 2026; Fecon, 2026; LM Technic, 2026; Quadco, 2026; FAE, 2026; Plaisance, 2026; Bugnot, 2026; PTH, 2026; Bandit, 2026; Baumalight, 2026; Seppi m_, 2026)
Obr.4 Konštrukčné riešenia pracovných nástrojov

	Cutting teeth for concrete milling cutters, suitable for road milling machines		Paved roads		Mining milling		Radial teeth suitable for drilling tools and accessories
	Cutting teeth for concrete milling cutters, suitable for road milling machines		Paved roads		Conical teeth for earth augers, buckets, pilot holes, and rippers		Welded carbide teeth suitable for ground augers
	Cutting teeth for concrete milling cutters, suitable for road milling machines		Peat soil, paved roads		Underground and surface mining		Exposed stumps, buried stumps
	Cutting teeth for concrete milling cutters, suitable for road milling machines		Stone crushers and forestry cutters		Underground and surface mining		Stump grinder
	Cutting teeth for remixers, suitable for asphalt recycling machines		Stone crushers and forestry cutters		Mining milling		Teeth for road milling, suitable for concrete milling machines
	Stone crushers and forestry cutters		Mining milling		Cutter teeth for road milling, designed for milling drums		Rock crushing tool
	Underground and surface mining		Rock crushing tool		Rock crushing tool		Mining milling
	Peat soil, low stone content		Rock crushing tool		Peat soil, low stone content, paved roads, stone ground		Specially designed for continuous use on hard rock such as basalt, gneiss, and granite

continuation of Fig. 4 Design of working tools
pokračovanie Obr.4 Konštrukčné riešenia pracovných nástrojov

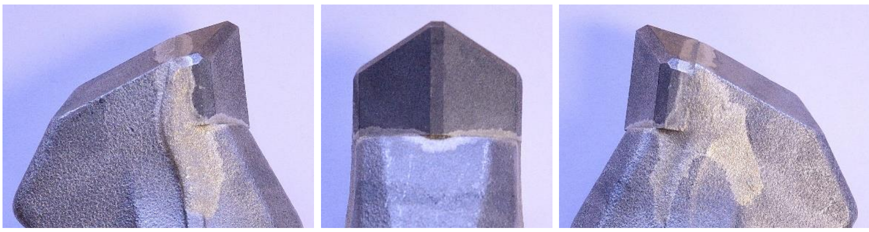


Fig. 5 Working surface of conical teeth
Obr. 5 Pracovná plocha zubov s kónickým tvarom

As stated in the Introduction, the operating conditions of forestry milling machines are characterized by a heterogeneous working environment in which the working tool comes into contact not only with woody biomass, but also with soil, minerals, and rocks. Because of these conditions, intensive abrasive wear occurs, particularly on the frontal functional surface of the tool (Fig. 6). Based on the wear analysis, areas with the highest mechanical loading were identified, where elevated surface stresses and plastic deformation of the micro-surface layers of the tool material occur (Fig. 7). Once the material strength limit is exceeded, surface layer delamination takes place, leading to gradual material loss of the working tool (Ťavodová, 2018).

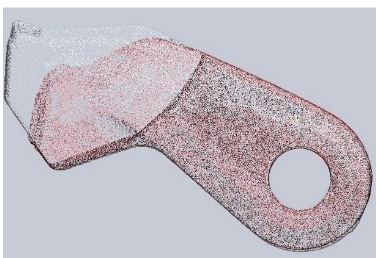


Fig. 6 Tool wear (Ťavodová, 2018)
Obr. 6 Úbytok materiálu na nástroji

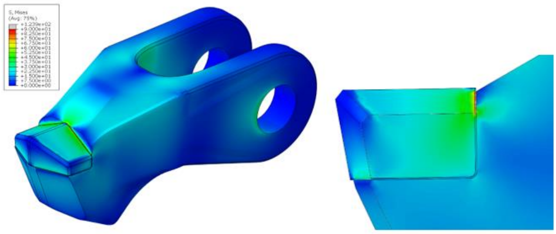


Fig. 7 Stress analysis of a working tool (Ťavodová 2018)
Obr. 7 Napäťová analýza pracovného nástroja

Based on the performed analysis, a basic structural model of the forestry milling tool was defined (Fig. 8), which served as the reference model for the design of new geometrical solutions. The working tool consists of the tool body (1) and a hard cutting tip (2). The functional part of the tool is the frontal surface (3), representing the working contact surface interacting directly with the processed material. The rear part of the tool body is formed by the back surface (4).

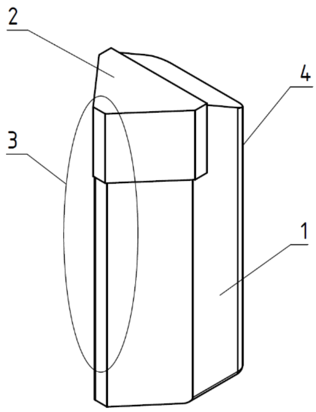


Fig. 8 Basic structural model of the forestry milling tool; 1 – the tool body, 2 – the cutting wedge (tip), 3 – the frontal surface, 4 – the frontal surface
Obr. 8 Základný konštrukčný model pracovného nástroja lesnej frézy; 1 – telo nástroja. 2 – rezný klin (špička), 3 – čelná plocha, 4 – chrbtová plocha

During the design of new tool variants, the fundamental structural concept was preserved, while modifications were primarily implemented in the geometry of the frontal working surface, which critically influences the interaction between the tool and the processed material.

Based on the wear analysis and comparison with working tools used in related applications, such as road and mining milling machines (Fig. 4), new unconventional shapes of the working surface were proposed. The design was based on the assumption that smoothly curved surfaces may contribute to a more uniform distribution of loading forces in the tool–material contact zone, thereby reducing stress concentration and the intensity of abrasive wear. Four basic geometrical variants of the working surface were proposed:

- second-degree polynomial profile (P2),
- third-degree polynomial profile (P3),

- fourth-degree polynomial profile (P4),
- tangential ogive profile (OG).

These shapes represent different geometrical evolutions of the cutting wedge in the cross-section of the tool working surface.

The second-degree polynomial profile P2 (Fig. 9a) is defined by a quadratic function:

$$f(x) = ax^2 + b, \qquad a \neq 0 \tag{1}$$

where a is the curvature coefficient of the parabola, b represents the vertical shift, and x is the horizontal coordinate of the tool profile.

The third-degree polynomial profile P3 (Fig. 9b) corresponds to a semicubical (Neil's) parabola defined by:

$$y^2 = ax^3, \qquad a \neq 0 \tag{2}$$

where a determines the curvature and x, y are the coordinates of the cutting wedge profile. This geometry ensures a gradual increase in curvature away from the tool tip.

The fourth-degree polynomial profile P4 (Fig. 9c) is described by a quartic function $f(x) = ax^4 + bx^3 + cx^2 + dx + e, a \neq 0$. In this study, a simplified biquadratic form was used:

$$y(x) = ax^4 + bx^2 + c, \qquad a \neq 0 \tag{3}$$

where a, b, c define the shape and curvature of the profile, x is the horizontal coordinate of a point on the tool profile. This geometry enables a very smooth transition of curvature along the working surface.

The tangential ogive profile OG (Fig. 9d) is formed by a circular arc smoothly connected to the axis of symmetry. It is defined by the radius r and the ratio of height h to base length l, which is equal to 1:1. The shape of a tangential ogive is described by the equation:

$$(r_1(2h - 2r) + l(r - l/4) = h^2 \tag{4}$$

where r is the radius of curvature, h is the ogive height, and l is the base width.

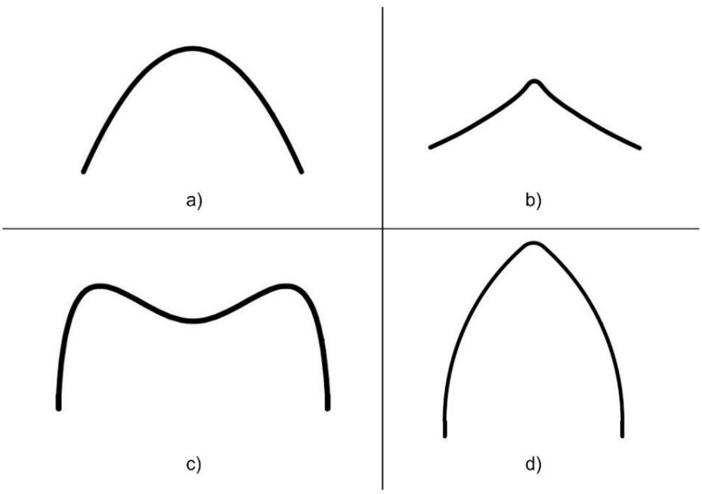


Fig. 9 Geometric variations in the profile of the tooth working surface; a – second-degree polynomial profile (P2), b – third-degree polynomial profile (P3), c – fourth-degree polynomial profile (P4), d – tangential ogive profile (OG) (Hnilica et al. 2026)
Obr. 9 Geometrické varianty profilu pracovnej plochy zubov; a – polynóm 2. stupňa P2, b – polynóm 3. stupňa P3, c – polynóm 4. stupňa P4, d – tangenciálny ogivál OG

The proposed shape variants were evaluated in terms of their potential influence on the tool penetration process and the distribution of mechanical loading in the tool–material contact zone. The evaluation was based on a geometrical analysis of the cutting wedge profile and on the assumption that a smoothly curved working surface enables more gradual load transfer and reduces stress concentration in the area of the cutting wedge (tool tip).

The proposed unconventional working surface geometries represent an alternative design approach for forestry milling machine working tools, which may contribute to the optimization of the vegetation crushing process, reduction of abrasive wear, and extension of tool service life.

RESULTS

Based on the analysis of existing working tools used in forestry milling machines and vegetation crushers, a geometric modification of the cutting part of the working tool was carried out. The objective of the design was to optimize the shape of the cutting wedge in order to reduce wear intensity, improve stress distribution in the tool tip area, and at the same time maintain sufficient strength.

The design of new geometric variants was based on research into working tools used in similar applications, particularly in the field of mining cutters and road milling tools (Gajewski et al. 2013; Songyong et al. 2017; Krauze et al. 2015; Kotwica, 2018; Boloz and Bialy, 2025; Bołoz, 2019; Bołoz, 2025), as well as ballistic projectiles (Fedorov et al. 2026; Fedorov et al. 2021; Xu et al. 2023; Ben-Dor et al. 2013; Ben-Dor et al. 2003; Feldgun and Yankelevsky, 2020; Yankelevsky et al. 2022).

Working tools often employ conical or sharp geometries of the cutting part, which allow good material penetration, however, from a tribological point of view, they exhibit an increased rate of wear, particularly in the tip. For this reason, rounded geometrical shapes were preferred in the design, as they enable a more uniform stress distribution and reduce stress concentration in critical areas of the tool.

One of the proposed solutions was a cutting wedge (tip) based on the shape of a tangential ogive (Fig. 10a). This geometric shape is characterized by a smooth transition of curvature and favourable penetration properties. The original sharp tip was structurally modified by rounding in order to eliminate local stress concentration and increase the tool's resistance to damage when in contact with hard inclusions in soil or rock.

Another variant of the cutting wedge was designed based on a second-degree polynomial geometry (Fig. 10d). The parabolic curve allows for a smooth change in curvature and creates suitable conditions for a more stable cutting process. In some variants, the geometry was supplemented with slight chamfering or modification of the transition between the cutting part and the tool body, thereby improving mounting conditions.

The third analysed variant was based on a third-degree polynomial geometry (Fig. 10g). The curve parameters were determined analytically based on the required dimensions of the cutting wedge (tip). Characteristic points necessary for creating the geometric model were subsequently derived from the graphical representation of the function. As in the previous solutions, the tool tip was rounded to eliminate sharp transitions and reduce the risk of local damage during operation.

The last analysed variant of the cutting wedge (tip) was based on a fourth-degree polynomial geometry (Fig. 10j). This type of curve enables an even smoother curvature progression compared to second and third-degree polynomials, which may lead to a more favourable stress distribution in the cutting part of the tool. The function parameters were defined based on the required dimensional characteristics of the cutting tip, and a geometric model was subsequently created from the function profile.

The proposed geometric variants thus represent another possible modification of the working tool, which may contribute to improved operational performance and extended service life of working tools in forestry milling applications under demanding conditions.

A strength analysis was performed on four proposed variants (Fig. 10) of the working tools using the Autodesk Inventor Professional – Stress Analysis. The base material of the tool body was considered to be chromium–manganese–silicon steel with a tensile strength of approximately 1,450 MPa, determined based on hardness measurements and subsequent conversion to tensile strength. The displacement in the support direction was constrained on the supporting surface (the frontal surface) of the tool. The applied load of 17,800 N was calculated from the torque (operating conditions on the adapter rotor) and acted on the tool in the direction of the cutting wedge (tip) of the working tool (the frontal surface). The loading frequency was set for a rotational speed of 1,000 min^{-1} (Ťavodová, 2018). The cutting wedge was assumed to be made of tungsten carbide with a tensile strength of approximately 350 MPa and a compressive strength of 4,780 MPa (MakeItFrom, 2025).

In the first design, the maximum stress was concentrated in the upper part of the cutting wedge (tip), reaching a value of 1,270 MPa (Fig. 10b). The greatest deformation was also recorded in this area, with a value of 0.06 mm (Fig. 10c). These results indicate that the tool design is satisfactory in terms of mechanical resistance, as the stress does not exceed the strength limits of the materials used. The deformation is negligible and does not affect the functionality of the tool.

The analysis of the second variant showed a change in the load transfer mechanism. The stress was no longer concentrated exclusively at the tip of the cutting wedge but was partially transferred towards the rear part of the tool, with a maximum value of 141 MPa (Fig. 10e). This contributed to a more uniform stress distribution within the structure. Maximum deformations remained at a very low level of 0.012 mm and did not affect tool functionality (Fig. 10f).

In the case of the third design, the highest stress was recorded in the front part of the cutting wedge (tip), particularly in the area of the front radius and the edges of the cutting wedge (Fig. 10h), with a maximum value of 295 MPa. The maximum displacement (Fig. 10j) was observed in the cutting wedge (tip) area and reached a value of 0.034 mm. Despite local stress concentration, deformation values remained low, confirming sufficient strength and structural stability.

The fourth design exhibited the lowest stress values among all analysed variants. The maximum stress was concentrated in the rear part of the tool (Fig. 10k), reaching 101 MPa. The greatest displacement (Fig. 10l) was recorded in the cutting wedge (tip) area, with a value of 0.0096 mm. These results confirm very good mechanical resistance of the design and its suitability for practical application.

Based on the performed strength analysis, it can be concluded that all four proposed variants of the working tools meet the requirements for mechanical strength under the considered operational loading. The maximum values of stress and deformation do not exceed the critical limits of the materials used. Differences between the individual variants were mainly observed in the character of load transfer and the localization of maximum stresses, with the lowest deformation values recorded for the fourth variant of the working tool.

A comparison of the proposed geometrical variants indicates that all analysed shapes represent potentially suitable alternatives to conventional conical cutting tools. The ogival shape provides a smooth curvature transition and good penetration properties, which may be advantageous, particularly when penetrating harder materials. The second-degree parabola creates a simple and structurally easy-to-define geometry with a smooth change in curvature, which may contribute to a more stable crushing process.

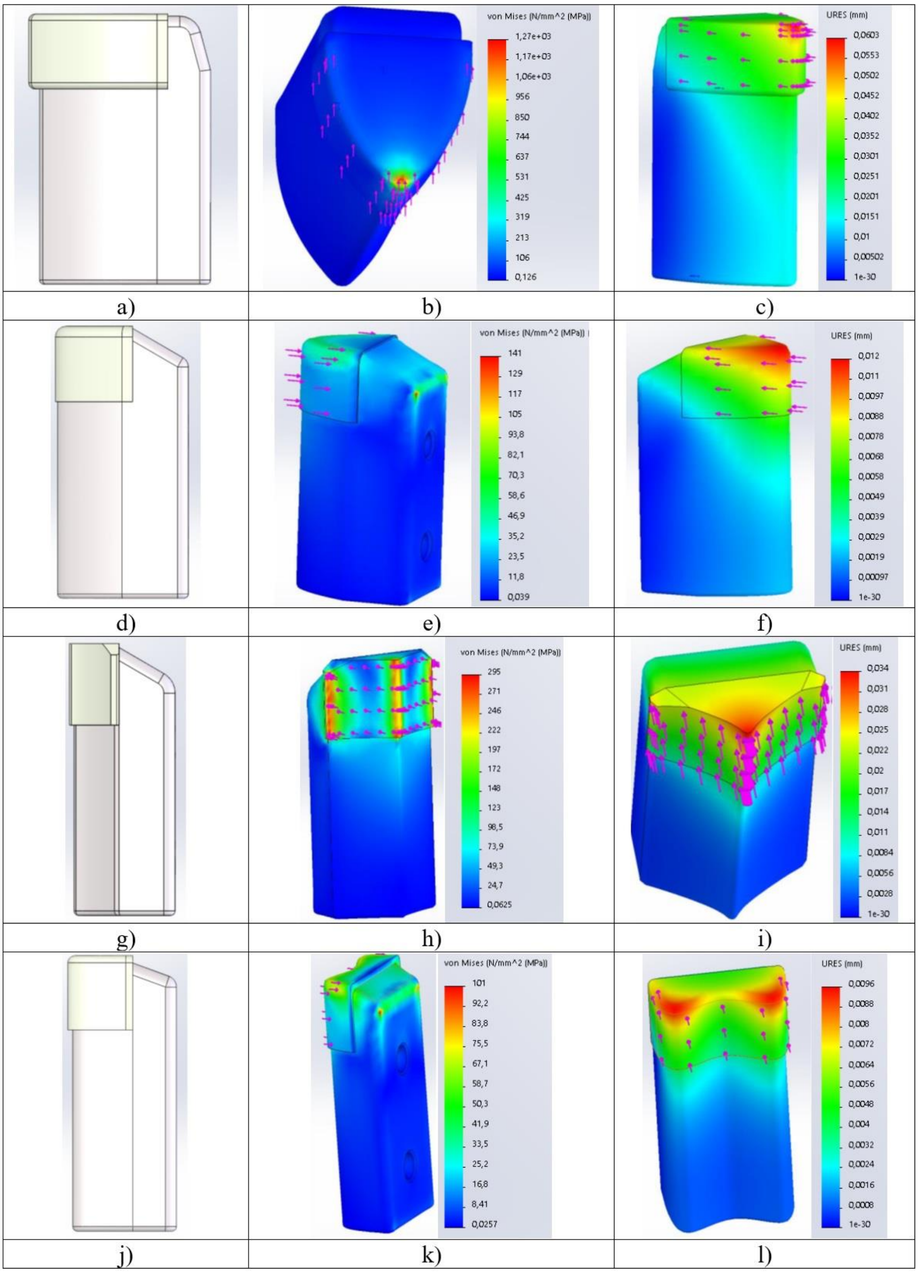


Fig. 10 Geometric designs of the working tool; a – working tool (OG), b – stress analysis (OG), c – displacement analysis (OG), d – working tool (P2), e – stress analysis (P2), f – displacement analysis (P2), g – working tool (P3), h – stress analysis (P3), i – displacement analysis (P3), j – working tool (P4), k – stress analysis (P4), l – displacement analysis (P4)
Obr. 10 Geometrické riešenia pracovného nástroja; a – pracovný nástroj (OG), b – analýza napätia (OG), c – analýza deformácie (OG), d – pracovný nástroj (P2), e – analýza napätia (P2), f – analýza deformácie (P2), g – pracovný nástroj (P3), h – analýza napätia (P3), i – analýza deformácie (P3), j – pracovný nástroj (P4), k – analýza napätia (P4), l – analýza deformácie (P4)

Geometries based on third and fourth-degree parabolas provide an even smoother curvature progression in the area of the tool tip, thereby reducing the probability of local stress concentrations. It is assumed that these shapes may also positively influence the wear behaviour of the cutting part of the working tool, as the contact load is distributed over a larger area of the cutting wedge.

From the perspective of working tool design, it is also necessary to consider the technological complexity of manufacturing the individual geometrical variants. While lower-degree parabolic shapes are relatively simple to model and manufacture, more complex higher-degree curves may impose increased demands on manufacturing accuracy. The proposed geometrical modifications therefore represent a compromise between structural simplicity, mechanical resistance, and the potential extension of the tool's service life.

Based on the performed geometrical analysis, it can be stated that all proposed variants represent feasible design solutions for the working tool. However, the use of higher-degree parabolic curves provides more favourable conditions in terms of shape smoothness and stress distribution, which may have a positive effect on the service life of forestry milling machine tools. Nevertheless, further experimental validation and numerical stress analysis simulating subsurface layer deformation are required to more accurately describe the loading state of the working tool and to definitively confirm the suitability of the individual variants.

CONCLUSION

The presented study was focused on the geometric modification of a working tool used in forestry milling machines (vegetation crushers and soil milling machines). The main objective was to analyse and design alternative shapes of the cutting wedge that could improve the operational performance of the working tool and potentially contribute to extending its service life.

Based on the performed analysis, several geometrical variants of the cutting part of the tool were proposed, including an ogival shape and profiles defined by second, third, and fourth-degree parabolic curves. The proposed shapes were selected with the aim of achieving a smoother curvature progression in the cutting area and reducing stress concentration in the tool tip area. The individual designs were subsequently implemented into structural models of the working tool, considering the mounting and operational requirements of the milling equipment.

The obtained results indicate that the use of rounded geometrical profiles, particularly those defined by higher-degree parabolic curves and a tangential ogive, may contribute to a more favourable stress distribution and a reduction. The proposed geometric modifications thus represent a potential contribution to increasing the service life of working tools.

For the next research, it is recommended to focus on numerical analysis of the stress state and experimental validation of the proposed geometrical variants under real operating conditions.

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RESEARCH ON THE POSSIBILITIES OF PREDICTIVE MODELING BASED ON CUTTING FORCES AND ELECTRICAL POWER CONSUMPTION IN MILLING MDF BOARDS

VÝSKUM MOŽNOSTÍ PREDIKTÍVNEHO MODELOVANIA NA ZÁKLADE REZNÝCH SÍL A ELEKTRICKÉHO PRÍKONU PRI FRÉZOVANÍ MDF DOSIEK

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ABSTRACT: This article deals with the analysis of cutting forces and electricity consumption during CNC milling of MDF boards to identify the influence of the main technological parameters and to create reliable prediction models. Experimental measurements were carried out on a 5-axis CNC machining center, while various combinations of spindle speed (14 000, 16 000, 18 000 RPM), feed speed (6, 8, 10 m.min^{-1}), and milling type (conventional and climb) were monitored. Cutting force was measured using a piezoelectric dynamometer and energy consumption using a power quality analyser. The results of the analysis of variance showed that spindle speed and feed rate have a statistically significant effect on both cutting force and energy consumption, with the milling type mainly affecting the cutting force. With increasing speed, the cutting force decreases, while higher feed leads to its increase. Energy consumption increases with increasing speed and feed. Based on the experimental data, machine learning models (C&RT, Boosted Trees, neural networks) were created and compared. The best results were achieved by the C&RT model, which showed high prediction accuracy and good interpretability. The identified models enable effective prediction of the cutting process and represent a tool for optimizing machining in terms of energy efficiency and production quality.

Keywords: CNC milling, MDF board, electric power, cutting force, predictive model

ABSTRAKT: Článok sa zaoberá analýzou rezných síl a spotreby elektrickej energie pri CNC frézovaní MDF dosiek s cieľom identifikovať vplyv hlavných technologických parametrov a vytvoriť spoľahlivé predikčné modely. Experimentálne merania boli realizované na 5-osom CNC obrábacom centre, pričom boli sledované rôzne kombinácie otáčok vretena (14 000, 16 000, 18 000 min^{-1}), posuvovej rýchlosti a typu frézovania (súbežné a protibežné). Rezná sila bola meraná pomocou piezoelektrického dynamometra a spotreba energie pomocou analyzátora kvality elektrickej energie. Výsledky analýzy rozptylu preukázali, že otáčky vretena a posuvová rýchlosť majú štatisticky významný vplyv na reznú silu aj spotrebu energie, pričom typ frézovania ovplyvňuje najmä reznú silu. So zvyšujúcimi sa otáčkami dochádza k poklesu reznej sily, zatiaľ čo vyšší posuv vedie k jej nárastu. Spotreba energie rastie so zvyšujúcimi sa otáčkami aj posuvom. Na základe experimentálnych dát boli vytvorené a porovnané modely strojového učenia (C&RT, Boosted Trees, neurónové siete). Najlepšie výsledky dosiahol model C&RT, ktorý vykázal vysokú presnosť predikcie a dobrú interpretovateľnosť. Identifikované modely umožňujú efektívnu predikciu rezného procesu a predstavujú nástroj pre optimalizáciu obrábania z hľadiska energetickej efektívnosti a kvality výroby.

Kľúčové slová: CNC frézovanie, MDF doska, elektrický príkon, rezná sila, prediktívny model

INTRODUCTION

In contemporary manufacturing, cutting parameters are crucial in milling operations, as they significantly influence both the cutting tool and the workpiece. For this reason, careful consideration of cutting forces and their effects is essential. These forces directly impact tool wear, surface integrity, dimensional precision, machine stability, and overall energy consumption (Petre, Găvruş 2023, Chatterjee et al. 2020, Hernández-González et al. 2021). Proper evaluation of cutting forces during milling enables improved optimization of machining parameters within the production process (Wyeth et al. 2009, Anh, Tung 2025, Felhő et al. 2026).

Although milling remains one of the most widely applied manufacturing methods, a comprehensive understanding of cutting forces and power consumption under real milling conditions is still not fully exploited. Since power consumption is closely linked to energy efficiency and operational costs in industry, obtaining reliable data is essential for process improvement. Previous experimental studies reveal substantial variability in measured cutting forces and energy usage, particularly regarding the effects of cutting speed, feed rate, depth of cut, and material type (Korkmaz et al. 2022). The influence of cutting speed on cutting forces is described inconsistently in the literature, ranging from negligible to increasing effects (Pahlitzsch, G.; Dziobek 1959, Porankiewicz et al. 2007). In contrast, higher feed per tooth increases chip thickness, leading to greater cutting forces and elevated power consumption (Hlásková et al. 2015, Orlowski, Ochrymiuk 2017). Differences in machine tools, sensing systems, and machining conditions complicate direct comparison of results and limit the generalization of findings. Therefore, systematic measurement of cutting forces and power consumption during milling is necessary not only to deepen process understanding but also to validate predictive models and support energy-efficient optimization without compromising machining quality.

Energy consumption typically increases with higher spindle speeds and decreases with higher feed rates, whereas surface quality often exhibits the opposite behavior (Bal, Dumanoğlu, 2019). Furthermore, milling strategies affect productivity, surface roughness, and vibration levels, all of which are critical factors in determining an optimal tool path (Silva et al. 2024).

This study focuses on utilizing electrical power and cutting force data obtained during the milling of medium-density fiberboard to develop predictive models based on machine learning techniques. The article is based on the authors' experiment (Čuchor et al. 2026) and expands on its results. Initially, the measured data are statistically processed and analyzed to determine the significance of individual technical and technological milling parameters. Subsequently, machine learning models are developed, parameterized, and rigorously evaluated to assess their suitability for the specific dataset. Model performance is assessed using the correlation coefficient between measured and predicted values, as well as the root mean square error.

MATERIAL AND METHODS

Samples of medium-density fibreboard (MDF) boards were used as experimental material with dimensions of 350 × 160 × 18 mm. Medium-Density Fiberboard is an engineered wood product produced by hot-pressing wood fibers bound with synthetic resins, most commonly urea–formaldehyde (UF), under controlled heat and pressure (Hong et al. 2017). The manufacturer of sample material MDF E1 (EN ISO 12460-5) company KRONOSPAN (Zvolen, Slovakia) guarantees the technical specification according to technical sheet of manufactured product (material density: 750 kg·m3 ±7 %, tolerance of thickness: ±0,2mm).

The tool used in the experiment was spiral monolithic positive 3-spiral end mill SCH3UFN284R 20 × 90 × 20 (Freud, S.p.A, Italy).

Measurements were carried out on the Z5-31 SCM TECH 5-axis CNC machining centre (SCM Group, Rimini, Italy). This machine is particularly suitable to produce furniture panels and is designed to perform high-precision operations such as complex 3D shaping, contouring, and drilling. The machine is equipped with an 11 kW "Prisma 5" vertical electro-spindle capable of reaching speeds of up to 24 000 rpm, which enables efficient execution of demanding routing and milling processes. The spindle is belt-driven and water-cooled, providing stable thermal regulation during operation. In addition, the CNC machine uses the HSK 63 spindle interface, ensuring high rigidity and enabling rapid tool change.

CNC machines capability is supported by a broad movement envelope, typically around 3 110 mm (X), 1 300 – 1 550 mm (Y), and 160 mm (Z), with continuous rotation along axes B (±320°) and C (±640°). This enables complex multi-sided machining without repositioning the workpiece. Safety and ergonomics are embedded into the machine design through features like bumper-style collision protection, automatic lubrication, and dust extraction interfaces. The control system is PC-based (SCM 2015).

The cutting parameters were selected according to the practical operation based on several factors of the CNC milling machine and the recommended cutting conditions for the applied cutting tool. Spindle speeds of 14 000, 16 000, and 18 000 rpm and feed speeds of 6, 8, and 10 m.min^{-1} were chosen to cover a range of machining conditions commonly used in high-speed milling. This range enabled the investigation of the influence of cutting speed and feed speed on the milling process while maintaining process stability and preventing excessive tool wear. Furthermore, both up milling (conventional milling) and down milling (climb milling) were employed to assess changes in power consumption and measurements of cutting forces. The experimental milled assembly is shown in Figure 1.

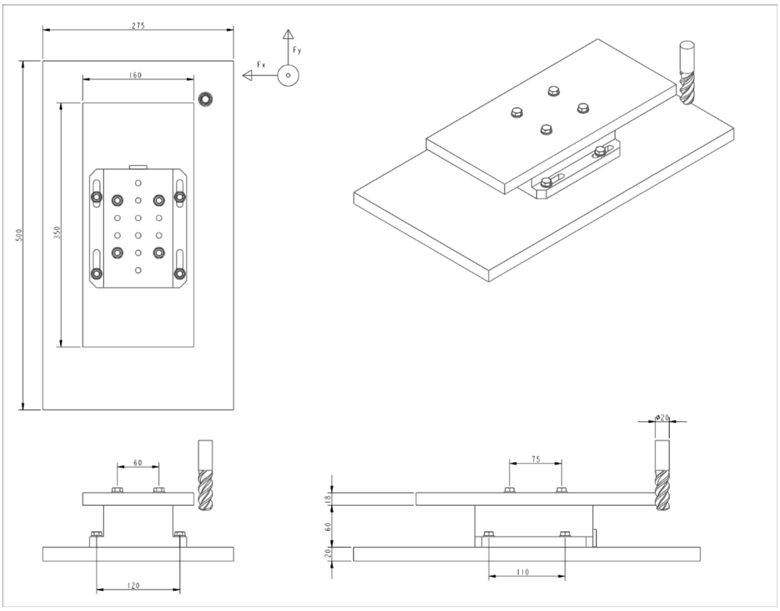

Fig. 1 Simplified drawing of experiment
Obr. 1 Zjednodušená schéma experimentu

The power consumption of the milling process was measured using a three-phase power quality analyser MI 2893 Power Master XT (Metrel d.o.o., Slovenia). The analyser was connected to the electrical power supply of the CNC machining centre using current probes and voltage clamps. The voltage clamps were attached to the phase conductors, as well as to the neutral and protective conductors through the installed 32 A 5P socket. The current probes were positioned according to the direction of current flow; if connected in the opposite direction, the measured values at the terminals would appear as negative.

After completing the measuring circuit, a test signal measurement on the individual phases was performed to verify correct operation. The data acquisition and analysis were carried out using the Metrel PowerView v3.0 software.

Cutting force measurements were carried out using a three-component piezoelectric dynamometer Kistler 9257B (Kistler Group, Winterthur, Switzerland). This dynamometer is designed to measure orthogonal force components F_x, F_y, and F_z during machining operations such as milling, turning, and grinding. In this study, it was specifically used for the milling process.

The Kistler 9257B integrates four three-component quartz force sensors, which are preloaded between a base plate and a 100 × 170 mm top plate. This configuration enables the measurement of forces and moments with high stiffness and a high natural frequency (Kistler 2019). The dynamometer was mounted on a wooden particleboard, which was fixed to the CNC machining centre using pneumatic grippers. This setup ensured that the dynamometer remained stable during the milling process. The experimental sample was attached to the dynamometer using hexagonal bolts, which secured the material firmly in place.

A minimum safe distance of 50 mm was established and clearly marked around the dynamometer. This zone was continuously monitored during machining. The tool path was carefully observed, and if the cutting tool approached or entered the marked area, the milling process would be immediately stopped to prevent damage to the dynamometer.

Program used for cutting forces measurement was DynoWare v3.2.5.0. Sampling rate of signal during measurement was 5000 Hz. The entire milling cycle with one sample was recorded in one measurement, which includes 3 conventional and 3 climb millings. Overall force was computed by term:

$$F_c = \sqrt{F_x^2 + F_y^2 + F_z^2}, \tag{1}$$

where F_x, F_y and F_z [N] are measured forces in x, y and z axis according to coordinate system of dynamometer.

The values of total force F_c and power input P were subjected to analysis of variance and to assess their suitability for creating prediction models.

RESULTS AND DISCUSSION

The measured values of the force components in the x, y and z axes were converted into the total force with respect to their distribution in a rectangular coordinate system according to the equation (1). Subsequently, this was analyzed using the analysis of variance and the influence of independent technological parameters on it was investigated. Descriptive statistics for F_c are shown in Tab. 1, the ANOVA itself in Fig. 2. The total cutting force F_c was slightly higher during climb milling (average conventional: 28.93; climb: 29.27 N), whereby similar findings have been reported by Hanincová et al. (2024) and Kopecký et al. (2019)

Table 1. Descriptive statistics of the total force
Tabuľka 1 Popisná štatistika pre celkovú silu

Effect		Number	Mean [N]	Std. Dev. [N]	Std. Err. [N]	-95% [N]	95% [N]
Total		180	29,101	1,952	0,146	28,814	29,388
n [rpm]	14000	60	30,409	1,432	0,185	30,039	30.779
	16000	60	29,785	1,246	0,161	29,464	30.107
	18000	60	27,109	1,307	0,169	26,771	27.446
f [m. min	6	60	27,842	1,669	0,215	27,411	28.273
	8	60	29,124	1,040	0,134	28,855	29.393

	10	60	30,337	2,128	0,275	29,787	30.887
Climb		90	29,271	2,008	0,212	28,850	29,691
Conventional		90	28,931	1,891	0,199	28,535	29,327

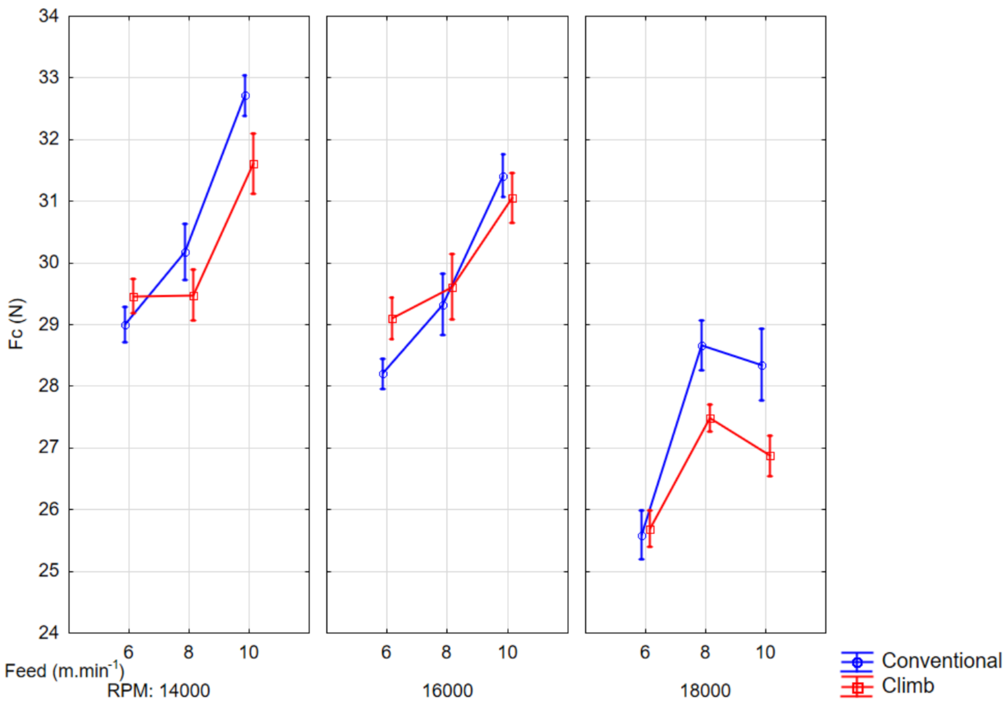

Fig. 2 Analysis of variance dependence of the total force on milling technological parameters
Obr. 2 Analýza rozptylu závislosti celkovej sily na technologických parametroch frézovania

From the analysis of the variance of the independent technological parameters influence on the total force, it is visible that with increasing spindle speed this force decreased. This may be due to faster rotation of the tool and decreasing thickness of the removed material, which therefore decreases the force required to cut it. With increasing feed speed, this effect is the opposite.

In Table 2 results indicate that spindle speed (F-test parameter $F = 614.56$, probability of similarity $p < 0.001$), feed rate ($F = 311.32$, $p < 0.001$), and milling type ($F = 17.31$, $p < 0.001$) all significantly influence parameter Fc. Among these factors, spindle speed exhibits the strongest effect, followed by feed rate, while milling type contributes to a lesser extent.

Table 2 F-test for total force F_c
Tabuľka 2 F-test pre celkovú silu F_c

Effect	SS	MS	F	p
n [rpm]	368,85	184,43	614,56	<0,001
f [m.min^{-1}]	186,85	93,43	311,32	<0,001
Milling Type	5,19	5,19	17,31	<0,001

A similar analysis was also performed on the values for the consumed electrical power. The power required for milling was calculated as the difference between the power input during idle operation and the power input during material removal. Descriptive statistics are shown in Table 3, and the graphical course of the ANOVA is shown in Fig. 3.

Table 3 Descriptive statistics for consumed electrical power
Tabuľka 3 Popisná štatistika pre spotrebovaný príkon

Effect		Number	Mean [kW]	Std. Dev. [kW]	Std. Err. [kW]	−95% [kW]	95% [kW]
Total		180	0,145	0,041	0,003	0,139	0,151
n [rpm]	14 000	60	0,125	0,023	0,003	0,119	0,132
	16 000	60	0,127	0,030	0,004	0,119	0,134
	18 000	60	0,182	0,038	0,005	0,172	0,192
f [m.min-1]	6	60	0,122	0,023	0,003	0,116	0,128
	8	60	0,144	0,046	0,006	0,132	0,156
	10	60	0,168	0,037	0,005	0,158	0,177
Climb		90	0,145	0,039	0,004	0,137	0,153
Conventional		90	0,145	0,043	0,005	0,136	0,154

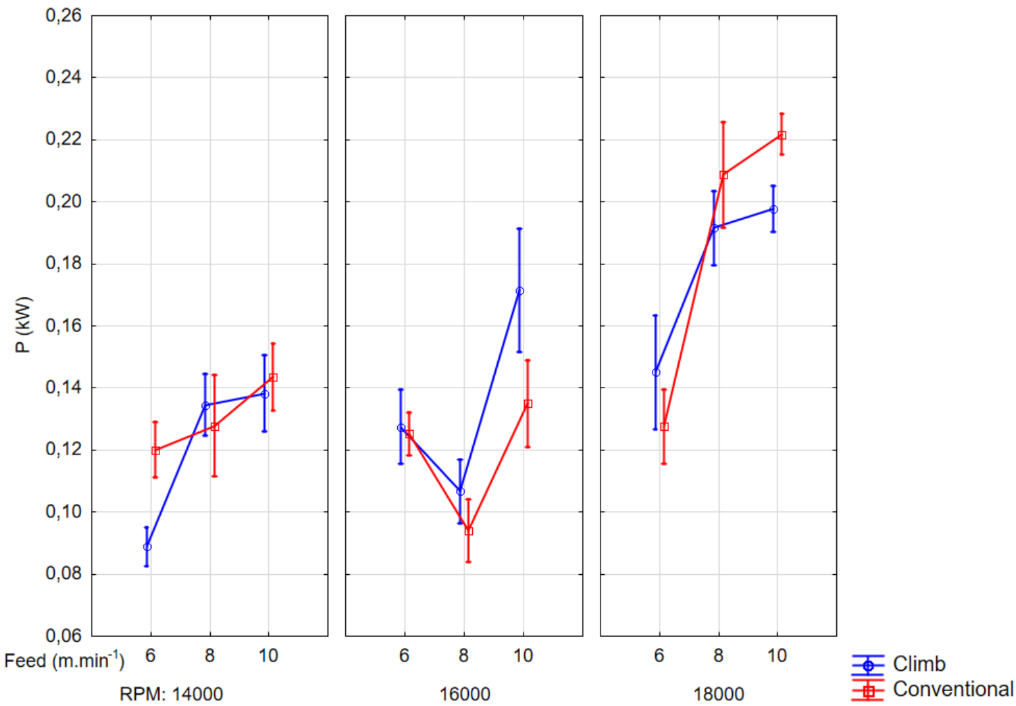

Fig. 3 Analysis of variance dependence of input power on milling technological parameters
Obr. 3 Analýza rozptylu závislosti príkonu na technologických parametroch frézovania

Figure 3 shows the dependence of the consumed power required for material removal by the technological parameters of milling. With increasing speed of rotation of tool, the consumed electrical power increases mainly due to higher currents flowing through the electric winding of the electric spindle. A similar effect can be observed for the feed speed.

The F-test for power consumption in Table 4 indicates that spindle speed ($F = 210.13$, $p < 0.001$) and feed rate ($F = 104.58$, $p < 0.001$) significantly influence the response. In contrast, milling type does not exhibit a statistically significant effect (F = 0.01, p = 0.931). This suggests that parameter *P* is determined mainly by cutting conditions rather than by the type of milling process.

Table 4 F-test for input power *P*

Tabuľka 4 F-test pre príkon *P*

Effect	SS	MS	F	p
n [rpm]	0,13	0,06	210,13	<0,001
f [m.min^{-1}]	0,06	0,03	104,58	<0,001
Milling Type	0,00	0,00	0,01	0,93

After analysis of variance for total force and power, the measured values were used to create prediction models in the Statistica 12 (StatSoft, Inc.). 20 % of the input data was allocated for model testing. 3 basic models were compared: 1. Classification and regression tree (C&RT), 2. Boosted trees and 3. Neural network. The resulting correlation matrix for training and testing data is in Table 5.

Table 5 Correlation matrix of coefficients R^2 of model building

Tabuľka 5 Korelačná matica koeficientov R^2 zostavenia modelov

Model	F_c		P	
	Training	Testing	Training	Testing
1.C&RT	0,966	0,963	0,923	0,918
2. Boosted trees	0,963	0,961	0,917	0,885
3. Neural network	0,914	0,925	0,921	0,898

The correlation matrix shows that the most suitable model for predicting the resulting force and the consumed power is the C&RT model. A model of this type is relatively easy to interpret and algorithmize for predicting the input values of rotation speed, feed speed and milling type. The most significant predictor for predicting the force were revolutions; for predicting the power, it was feed speed.

According to Generalized regression model the prediction equation for total force is:

$$F_c = 37{,}31 - 0.00082a + 0{,}624b + 0{,}17c, \tag{2}$$

where *a* are RPM, *b* is feed speed (m.min^{-1}), *c* is +1 (conventional milling) or -1 (climb milling)

For computing of power consumption is prediction equation as follows:

$$P = -0{,}173 + 1{,}414.\,10^{-5}a + 0{,}0114b + 0{,}11.\,10^{-3}c, \tag{3}$$

where *a* are RPM, *b* is feed speed (m.min^{-1}), *c* is +1 (conventional milling) or -1 (climb milling)

Figure 5 shows the predicted total force values for the input measured values based on the C&RT model. The thick blue line represents their linear fit; the dashed lines are the regression bands bounding the interval ±0,95%. Almost all the predicted values lie in this interval. Similarly, Figure 6 shows the predicted power values for the input power measured values also from the same C&RT model. Here too, almost all the values lie in the interval ±0,95%.

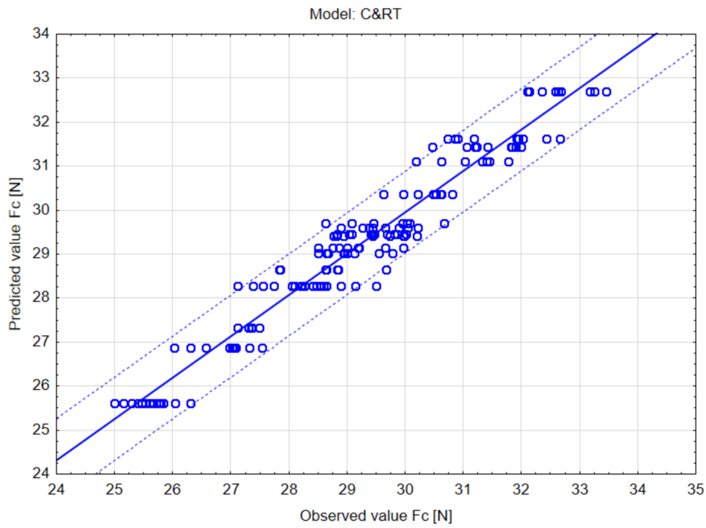

Fig. 5 C&RT model predictions for total force F_c
Obr. 5 Predikcie modelu C&RT pre celkovú silu F_c

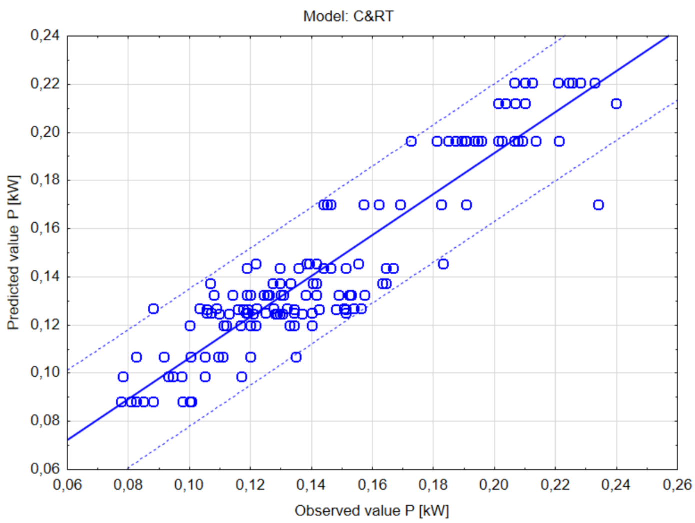

Fig. 5 C&RT model predictions for input power P
Obr. 5 Predikcie modelu C&RT pre príkon P

It is evident from Figures 5 and 6 that although the models achieve sufficient accuracy, they assign the same values of predicted values to a rather large range of input data. This could be improved by finer subdivision of the model tree, or by expanding the input values.

CONCLUSIONS

This work investigated the influence of selected technological parameters on cutting force and electrical power consumption during CNC milling of MDF boards. Experimental measurements confirmed that spindle speed and feed rate are the dominant factors affecting the monitored process variables.

An increase in spindle speed resulted in a reduction of cutting force, while higher feed rates caused both cutting force and power consumption to increase. The effect of milling strategy was less significant, particularly in the case of electrical power consumption, where no statistically important influence was observed.

Several predictive models based on machine learning techniques were evaluated using the measured experimental data. Among the tested approaches, the C&RT model provided the most reliable results and achieved the highest prediction accuracy for both monitored outputs. In addition to good predictive performance, the model also offers relatively simple interpretation, which may be advantageous for practical implementation in manufacturing environments.

The obtained results indicate that predictive modelling can be a useful tool for better understanding and optimization of milling processes. Future work will focus on extending the dataset, incorporating additional process variables, and improving model robustness for broader industrial applicability.

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