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High-speed wear tests on mower blade from various manufactures using the wear pot method

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Rotary mowers are often used for forage harvesting in agriculture, as this technology can achieve a high throughput. These knives are therefore exposed to high levels of wear and tear, and will also be often changed because of loss of material by bad cutting quality. That is why it is interesting to save costs during manufacturing in spite of a correspondingly long service life. This research records the current manufacturing quality of the mower blades and examines how they behave in comparison. Based on the obtained results, further decisions on the methods, procedures and ways of extending the life of the disc mower blades should be proposed. For the investigations, a test bench based on a wear pot was used. The wear that occurs on the blade is determined using several parameters and compared accordingly. The parameters of the test setup determined as a result of the test can be used for further studies of wear resistance.

Keywords
Disc mower blades, rotary mower, slurry pot, ellipse-fit method

The technological process of harvesting agricultural crops is one of the most important and energy-consuming stages of their cultivation. The reliability of harvesting machines directly affects compliance with agro technical deadlines, the quality and productivity of the crop. The working bodies of the mower, such as disc mower blades on mower decks, are one of the short-lived parts of their design, and moreover increasing the reliability of these parts is an urgent task. Despite the relatively low cost of disc mower blades, their excessive wear leads to a decrease in productivity and quality of crops and an increase in equipment downtime for repairs. In addition, blunt disc mower blades lead to a significant loss of efficiency and increased energy and resource consumption (Küper 2012). Abrasion is the most important damage mechanism in all sectors of the economy. It causes 76.3 % of the damage occurring in agriculture and forestry (Jahr et al. 2012b)

For this reason, for the development of new – the selection and operation – of existing harvesting machines, it is necessary not only to bring their working bodies (blades) into shape and configuration, but also to examine them with regard to their wear. Since it has been served as one of the parameters that ensures reliability and compliance with agro technological requirements during the harvesting process, such machines should be used.

However, obtaining disc mower blade wear results under field conditions is quite a tedious and time-consuming process, which is problematic for condicting multivariate studies. In addition, the field tests are not reproducible due to the constantly changing field conditions (also during the tests) such as outside temperature, humidity etc. Therefore, accelerated laboratory testing methods are

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often preferred (Fehrmann et al. 2005, Jahr et al. 2012b, Jahr et al. 2014, Katinas and Laskauskas 2017, Ojala et al. 2015). The aim of the research was to develop a reproducible test method to carry out comparative and reproducible high-speed wear tests in the laboratory on disc mower blades from different manufacturers and thus to examine and classify the current production quality and wear resistance. In addition, by recording and evaluating all the data, the measured values were examined for connections between the geometry, the surface hardness and the material/weight loss. Another goal was to study the dynamics and shape of the wear pattern of the cutting edges of disc mower blades under investigation in order to make further decisions about the methods, processes and possibilities of extending the service life of the disc mower blades in the subsequent research projects.

Materials and methods

The subject of the study were disc mower blades from seven different manufacturers. Blade manufacturer names have been renamed to “Maker A”, “Maker B”, “Maker C”, “Maker D”, “Maker E”, “Maker F” and “Maker G” to keep them anonymous (Figure 1).

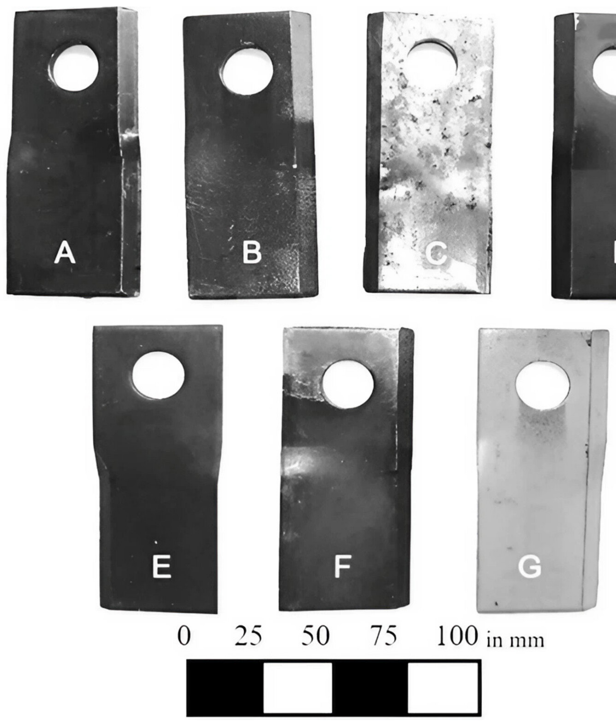


Figure 1: Disc mower blade from seven different makers

Disc mower blades from makers A, B, C, D, F and G were formed by rolling. The blades of maker E, on the other hand, were ground. The investigations were carried out using the existing wear test stand (Figure 2).

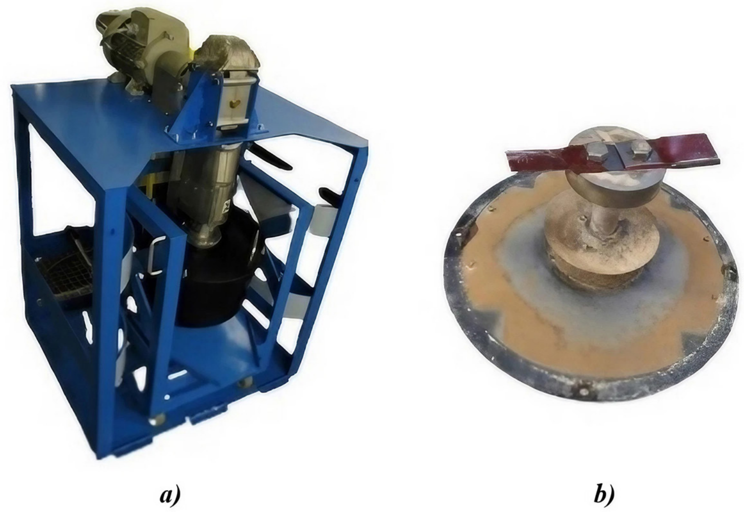


Figure 2: a) Photography, b) Wear pot cat with mounted blades

This test bench was developed by the FMDAuto Institute at HSD to compare the wear resistance and service life of various agricultural cutting tools under repeatable and comparable test conditions and at the same time to reproduce a realistic wear pattern (Jahr et al. 2012a).

The wear test rig consists of a swiveling container that is connected to a gearbox via a cardan shaft (Figure 2a). The gearbox is connected to a 3-phase AC motor with a power of 2.2 kW and a nominal speed of 1420 rpm. The disc mower blades are attached to the bracket of the slurry pot and fix with screws (Figure 2b). The speed of the disc mower blades was measured during all experiments on the cardan shaft and is approximately 1540 rpm at the rated speed of the engine. Two disc mower blades rotate in the slurry pot at the same time.

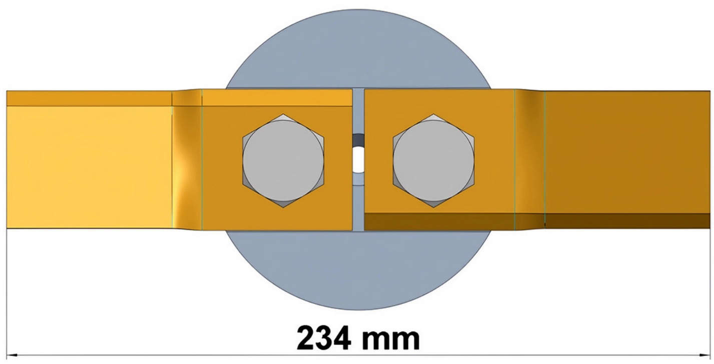
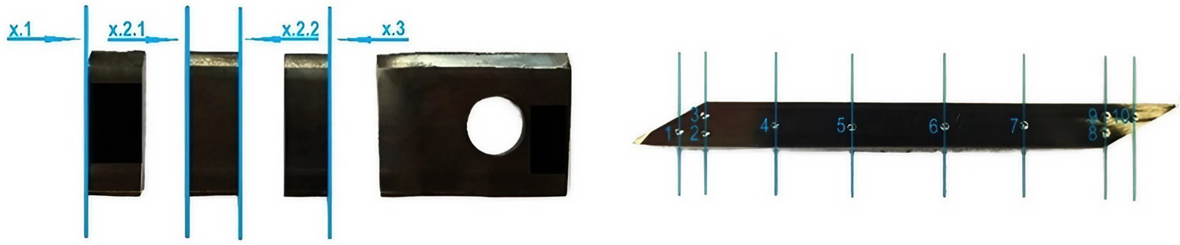


Figure 3: Schematic representation of the distance between the tips of all examined blades on the holder in diameter

The distance between the tips of all examined blades on the holder is approximately 234 mm in diameter (Figure 3). The linear velocity of the blades is about 19 m/s. The slurry pot is filled with a gravel-water mixture. This mixture serves as an abrasive medium for the wear tests. The slurry consists of homogeneous gravel with a specific concentration and grain size distribution as presented below.

In order to be able to evaluate the manufacturing quality of the mowing blades, the material compositions are also determined using X-ray fluorescence analysis (XRF) and the hardness of the mowing blades. The X-ray fluorescence analysis was carried out using the X-MET8000 expert measuring device from Oxford Instruments. Three measurements were taken at different points on each disc mower blade. A prerequisite for the analysis is that the paintwork on the disc mower blades must be removed at the measuring points, which was already carried out at the beginning of the measurements.



a) *b)*

Figure 4: Exemplary representation of the measurement plan for determining the hardness of the disc mower blades: a) four sections of the disc mower blades, b) ten measuring points on the cross section of each section of the disc mower blades

The hardness of the blade material was determined according to Rockwell C (DIN EN ISO 6508-1). The universal machine “DIA TESTOR 2” from the manufacturer Wolpert was used for this purpose. In order to determine the hardness of the disc mower blades for each manufacturer, they were divided into four sections with a cutting saw (Figure 4a). Ten measuring points were defined for each section. Three measuring points at the tips for both sides and four measuring points distributed over the blade (Figure 4b).

In the present work, no microstructure was examined and thus no tribolayer formation was observed. A total of two randomly selected blades from each manufacturer were tested for surface hardness. These measuring points were chosen to find out whether the disc mower blades were hardened through or only hardened on the cutting edges or on the edge. Two disc mower blades per manufacturer were examined here.

The precision balance KERN 440-55N (Kern & Sohn GmbH) with an accuracy/linearity of ± 0.6 g is used to determine the weight of the disc mower blades before and after the wear tests. An optical 3D measuring device "GFM MikroCAD Lite" (GFMesstechnik) with a lateral resolution of 17.3 µm and a vertical resolution of 1 µm is used to determine the cutting edge geometry of the disc mower blade. This measuring device works according to the fringe projection method. The measurement object is illuminated with a stripe pattern generated by a DLP (Digital Light Processing) projector. A high-resolution camera is directed at the measurement object from a different angle records to project light pattern. The height information is contained in the perspective stripe deformation (Jahr et al. 2014). 2D cutting edge profiles are then extracted from the 3D data (Figure 5).

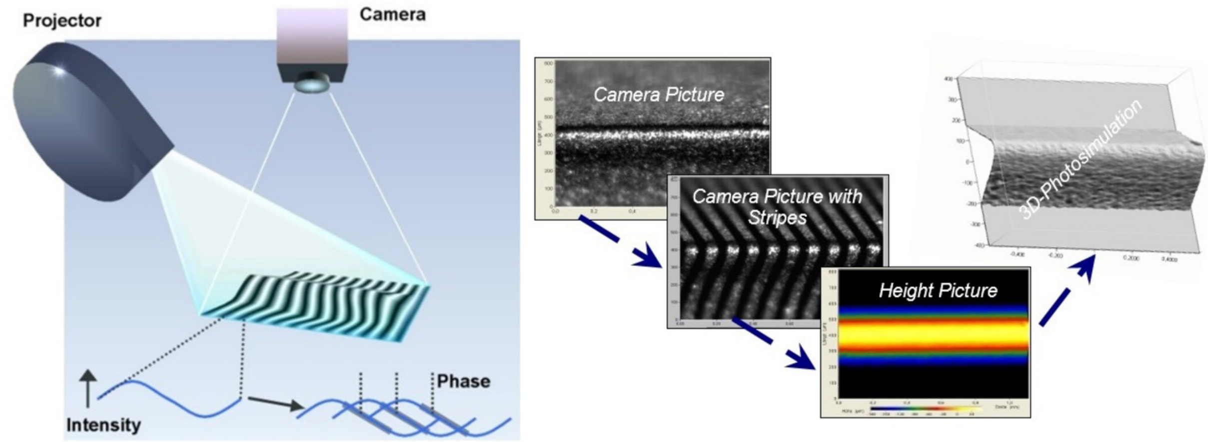


Figure 5: Stripe projection method, principle of the phase-measuring fringe projection, e. g. cutting edge, according to Tikal (2009)

To measure the cutting profile, the blades were divided into four sections. 25 measuring strips of 12 mm were laid out for each section, with the exception of the last section (Figure 6). 13 measuring strips were laid out there, since the cutting edge has been end at this point – which results in 88 measuring lines.

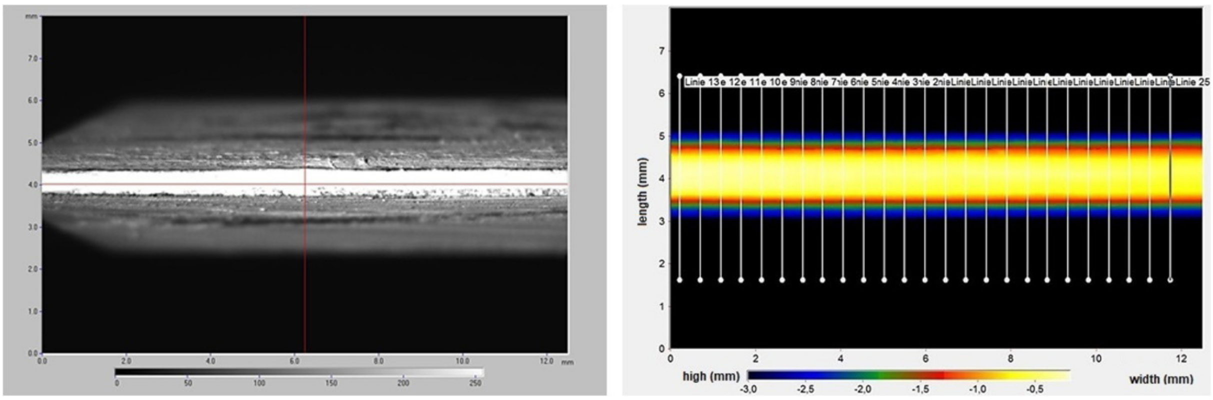


Figure 6: Camera image 12 mm (left) and height picture of the cutting edge 12 mm (right)

The measurement of the cutting profile was carried out on all disc mower blades. In addition, to reduce the falsification of the measurement data due to reflections, the surface of the cutting edge of the disc mower blades was dulled with a chalk spray without influencing the cutting edge geometry. First, one side of each disc mower blade was measured and then subjected to the wear test. The worn side was then measured, too. This process was then repeated on the back of the disc mower blade.

Analyzing methods

There is currently no standardized analysis method for characterizing wear and for determining wear resistance, edge retention and energy efficiency of agricultural cutting tools. Methods from machine tool construction are used that are neither standardized, technically mature, nor entirely suitable for agricultural applications. Determining the weight loss (Kurzynski 1999) and reducing the blade width (Fehrmann et al. 2005) are relatively simple methods of wear analysis. The weighting of the blades and the determination of the blade width before and after the wear test give a quantitative indication of wear. They neither take into account the edge holding property nor the energy efficiency (Jahr et al. 2015). These description models for cutting edge shapes include, for example, geometric approximations (circle-fit and ellipse-fit-method), *k*-factor model, Bosch norm, etc. (Jahr et al. 2015, Tikal 2009, Uhlmann et al. 2011, VDI/VDE 2654 Blatt 2).

As part of this research work, the weight loss/material loss method was selected as the method for wear analysis of the disc mower blades. The replacement radius was selected to characterize the cutting geometry of the disc mower blades before and after the wear test, as this has been well proven through the numerous wear tests at the FMDauto-Institute, and it seems to be particularly suitable for the description/illustration of the cutting edge. To do this, the cutting edge is approximated with an ellipse (ellipse fit method) (Figure 7a and b).

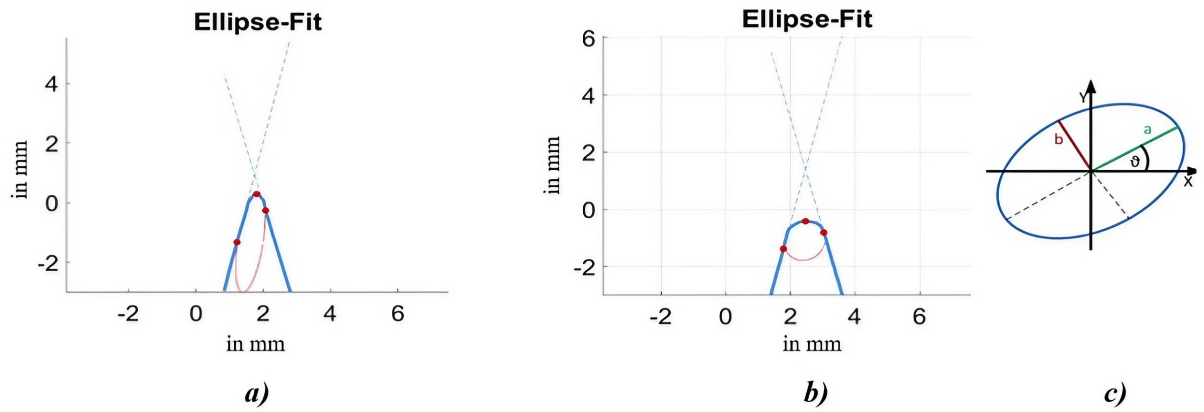


Figure 7: Measurement with the ellipse fit method: a) new knife, b) worn knife and c) parameters of an ellipse

The radii of the semi-axes a and b and the angle ϑ (Figure 7c) can define the ellipse. The equivalent radius is a degree of wear rate and edge retention and is calculated according to equation 1 (Jahr et al. 2015, Sim 2017):

Substitution radius $r = a \times cos^2 \vartheta + b \times sin^2 \vartheta$ (Eq. 1)

The ellipse fit method has been implemented in the Matlab software. Using the programmed Matlab routine, the semi-axes a and b, the angle ϑ, substitution radius and wedge angle can be determined automatically from the measurement data. First of all, preliminary tests are carried out on the knives in order to define the initial state. The weight and cutting edge geometry of the new disc mower blades are determined, and moreover existing manufacturing blade defects are checked and separated. The disc mower blades are then subjected to the wear test bench. The final condition of the blades after the wear tests is then analysed.

Abrasive slurry

Determination of an optimal test duration

In order to clarify the most suitable suspension for the wear tests, an optimal test duration was first researched. The duration of the test should be minimal, but the slurry should still have a high degree of comminution. The wear of the disc mower blades was not examined at this time, only the slurry. In determining the optimum test duration, it was assumed that there would be no wear without gravel. It was believed that as the gravel is crushed, the abrasive effect of the mixture decreases and thereby the efficiency of the abrasive slurry diminishes. Therefore, a mixture of two litres of gravel and six litres of water was used in all tests, and a total of six runs were carried out with different times: 5 min, 10 min, 15 min, 30 min, 60 min and 90 min. The gravel content was weighed both before and after each run. The grain size of the gravel used was specified by the quartz sand manufacturer "Euroquarz" with a range of 2–4 mm. In order to check the initial condition of the gravel, five measuring cups, each with two litres of gravel, were examined using a sieve analysis. The comminution process in the slurry pot of the wear test bench could be examined with the aid of the sieve analysis. A screen tower made up of three individual screens was used, which are standardized according to DIN ISO 3310-1. The nominal mesh size of the individual screens is 2 ± 0.07 mm, 1 ± 0.03 mm and 0.5 ± 0.02 mm (DIN ISO 3310-1:2017-11). Based on the respective mass of the dried suspension after the sieve analysis, the mass fractions of the individual particle classes were calculated using equation 2.

$$Q_i = \frac{m_i}{m_0} \times 100\,\% \qquad \text{(Eq. 2)}$$

Here, m_i is the respective mass of the dried slurry corresponding to a specific grain size or sieving stage, and m_0 is the weight indicating the initial weight of the gravel. A total of four mass fractions Q_i of four grain classes could be defined. Figure 8 shows the approximation functions of the percentage change in the mass fractions Q_1 and Q_4 over the test period.

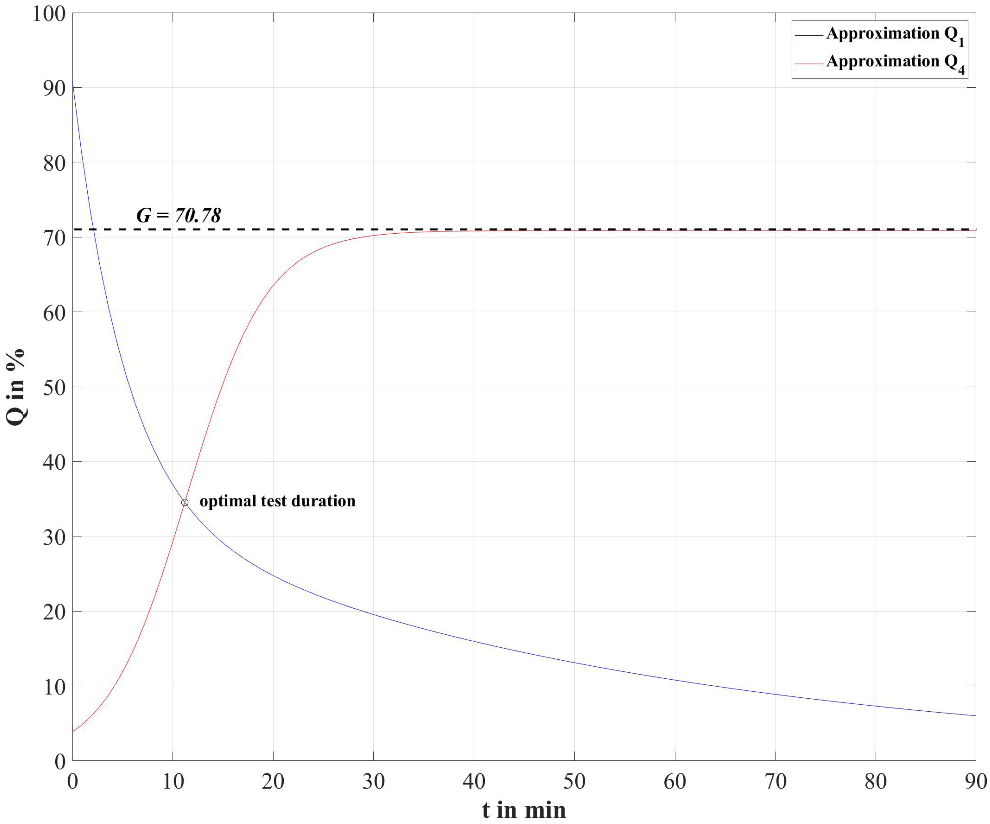


Figure 8: Approximation functions of the percentage change in mass fraction Q_1 and Q_4

The change in mass fraction Q_4 was approximated by a user-defined function. A logistic or S-shaped function was used (equation 3):

$$Q_1(t) = G \times \frac{1}{1 + e^{-k \times G \times t}\left(\frac{G}{f(0)} - 1\right)} = 70.87 \times \frac{1}{1 + 17.39 \times e^{-0.2507 \times t}} \quad \text{(Eq. 3)}$$

As it can be seen in Figure 8, the logistic function increases exponentially at the beginning. After a certain time, the growth steadily decreases until the saturation limit G is reached. As the test duration increases, the mass fraction Q_4 for the particle size class smaller than 0.5 mm increases exponentially. After just 15 minutes, there are already more than 50 % particles smaller than 0.5 mm in the slurry pot. The change in the mass fraction Q_1 over the duration of the test was approximated by an exponential function (Figure 8):

$$Q_4(t) = a \times e^{b \times t} + c \times e^{d \times t} = 56.14 \times e^{-0.19 \times t} + 34.73 \times e^{-0.02 \times t} \quad \text{(Eq. 4)}$$

An exponential decrease with increasing test duration can be observed for the mass fraction . After just 15 minutes, there is only just under 30 % gravel with a grain size of 2–4 mm in the slurry pot. The two functions $Q_1(t)$ and $Q_4(t)$ have a common point of intersection (Figure 8). This represents the optimal test duration. In addition, the turning point of the approximation function $Q_4(t)$ is also located at this point. This means that the increase in fine particles steadily decreases from this point. To determine the point of intersection, the two approximation functions $Q_1(t)$ and $Q_4(t)$ were equated and resolved to zero. The intersection point is at a test duration of approximately 11.17 minutes. During this test time, the proportion of fine particles and coarse particles is balanced. A mass fraction of 35 % can be determined for both grain classes. The optimal test duration was rounded down to a value of 12 minutes for the further wear experiments.

Determining the optimum ratio of abrasive slurry

The optimum ratio of the slurry was ensured for the disc mower blades under investigation by means of DoE (mixture test design), in which various test parameters, namely the sand, gravel and water proportions, were determined for the previously determined constant test duration of 12 minutes and constant speed of the disc mower blades were varied from approximately 1540 rpm. The use of a mixture of water, sand and gravel in wear tests provides a more realistic representation of the abrasive environments in which the disc mower blades are actually used. This mixture enables a practical assessment of the wear resistance and abrasion resistance of disc mower blades (Bhakat et al. 2004). The sand and gravel also come from the quartz sand manufacturer “Euroquarz”. The grain size of the sand was 0.125–0.355 mm. The volume of all the components of the slurry was eight liters. A two-level simplex lattice plan was selected as the experimental plan. A total of 14 wear experiments with five repetitions were carried out in the central test point for the repeatability tests. This was followed by the calculation of the regression functions for the target values and the determination of an optimal mix of wear. The resulting mixture of the slurry causes high wear of the disc mower blades in a shorter time.

Percentage material/weight loss and percentage change in sharpness (increase/decrease in substitution radius) of the disc mower blades were selected as the target values for the poly optimization. The aim of the optimization was to maximize the respective target value, since the slurry sought should ensure maximum wear. Using Analysis of Variance (ANOVA), it was found that the wear on the disc mower blades is highest with a mixture of gravel and water and as a result is significant with regard to the target values. The results of the preliminary wear study also showed that the main and interactions (mixture components) (B) sand, (C) water and AB (gravel and sand) are not statistically significant and therefore have hardly any influence on the wear in relation to the target values of the preliminary wear study (Figure 9). The non-significant main and interactions were nevertheless taken into account in the regression analysis.

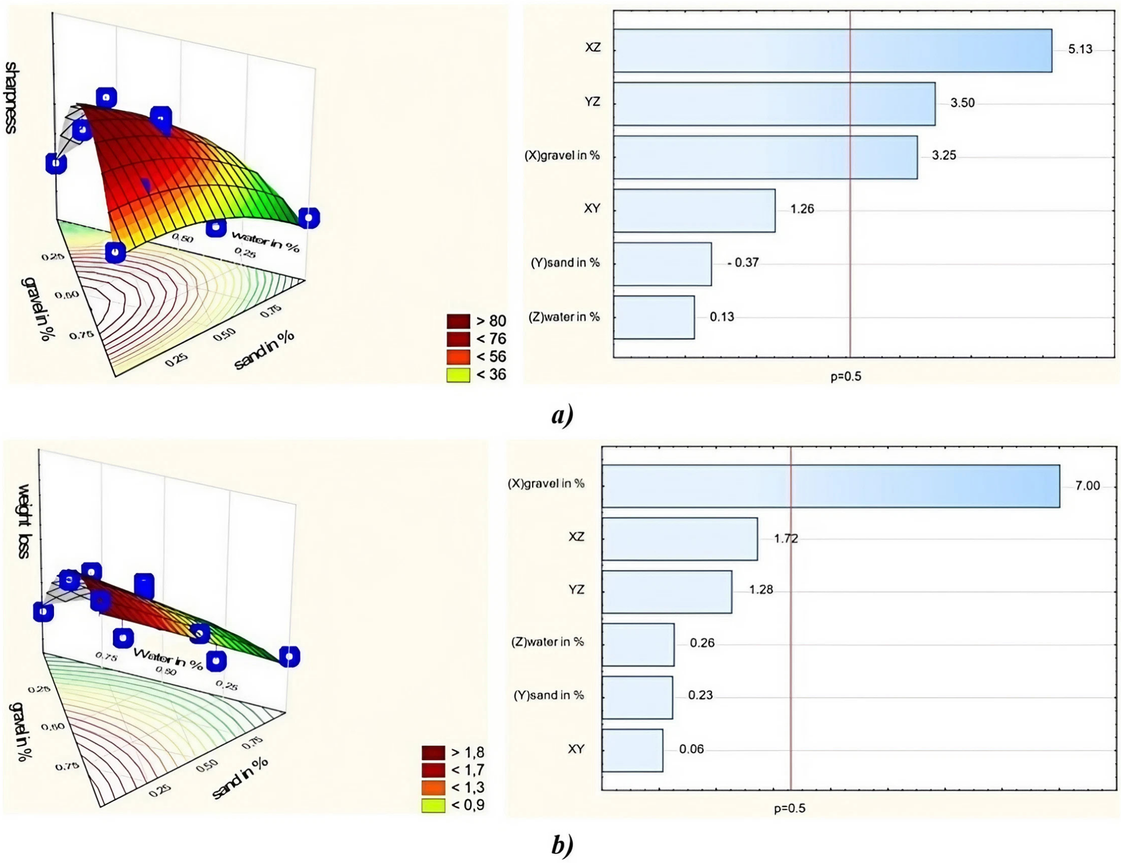


Figure 9: a) Contour plot of the multiple regression model and pareto chart of the substitution radius, b) Contour plot of the multiple regression model and pareto chart of weight loss

The following objective functions were obtained for the percentage material/weight loss and the percentage change in sharpness of the disc mower blades:

$$\text{Sharpness} = 6.8719 \times A - 4.1651 \times B + 1.4451 \times C + 62.8776 \times AB + 256.4060 \times AC + 174.8000 \times BC \quad \text{(Eq. 5)}$$

$$\text{Weight loss} = 1.9367 \times A + 0.0639 \times B + 0.0730 \times C + 0.0753 \times AB + 2.0934 \times AC + 1.5480 \times BC \quad \text{(Eq. 6)}$$

The contour plots of these objective functions are shown in Figure 9.

The multi-objective optimization of the slurry mixture was performed using the Paretosearch algorithm in Matlab software. In theory, the algorithm converges to the points near the true Pareto front, which represents the set of all Pareto optima (Figure 10).

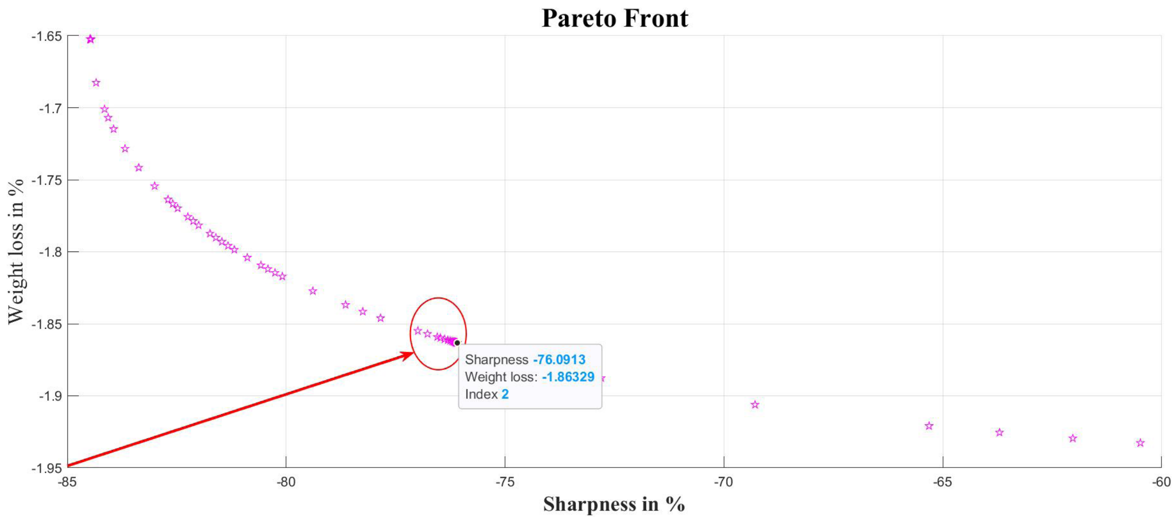


Figure 10: Pareto front. Optimal wear mixture

A mixing ratio of 75 % gravel and 25 % water was calculated as the optimal slurry mixture, which corresponds to two liters of water and six liters of gravel. The determined ratio of the slurry thus provides constant abrasiveness. Consequently, the effects of changing abrasive particle size during testing were minimized. Table 1 summarizes the test parameters used in the wear experiments on the disc mower blades. Six disc mower blades from each manufacturer were worn on both sides and then examined.

Table 1: Experimental parameters

Experimental parameters	**Values**
Rotational speed in rpm	1540
Mixing ratio in liter	8 (70 % gravel and 30 % water)
Test duration in min	12

Abrasive wear test

Table 2 below shows the measurement results of the material analysis of the disc mower blades. Since the material composition of the disc mower blades being examined is not known, the measurement results obtained can neither be confirmed nor denied.

Table 2: Materials of the mower blades of the seven different manufacturers according to X-ray fluorescence analysis

Characteristic value	Maker A	Maker B	Maker C	Maker D	Maker E	Maker F	Maker G
Material	60Mn SiCr4	60Mn SiCr4	ST44.4	61MN SiCr7	ST44.4	60Mn SiCr4	60Mn SiCr4

After the hardness test, the measurement data were first presented with box plots to identify outliers. The distribution analysis was then carried out on all measured values per manufacturer. It showed that the data are normally distributed (p = 0.95). From the measurement data, it can be deduced that all disc mower blades examined are hardened (Table 3).

Table 3: Results of the Rockwell C hardness test

Characteristic value	Maker A	Maker B	Maker C	Maker D	Maker E	Maker F	Maker G
Rockwell C hardness	48.95 ± 1.01%	48.82 ± 1.28%	48.08 ± 0.57	47.48 ± 1.07%	46.38 ± 0.96%	50.94 ± 1.12%	48.94 ± 0.95%

The disc mower blades from manufacturer E have the lowest hardness with approximately 46.38 HRC. The hardness value of the disc mower blades from manufacturers A, G, B, C and D is very identical and is approximately 48.00–49.00 HRC. The blades from manufacturer F are the hardest at around 50.94 HRC. Figure 11 shows the results of the hardness test for each manufacturer as arithmetic mean values with the scatter in the 95% confidence interval.

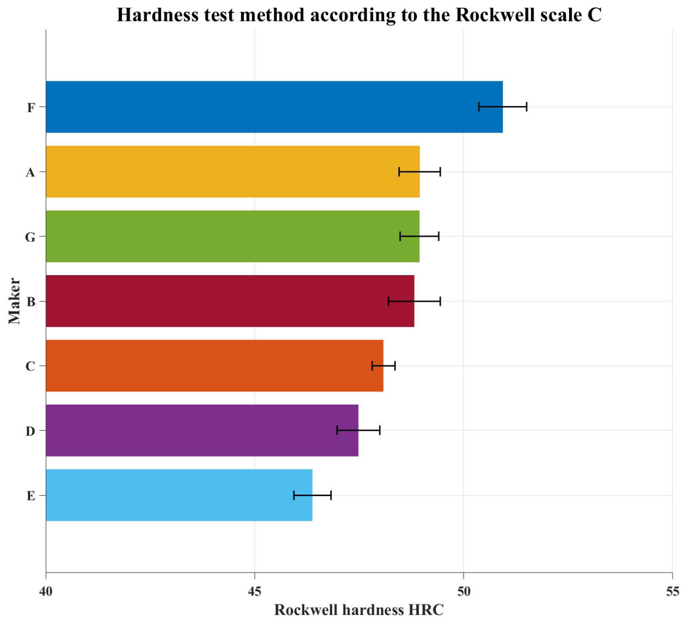


Figure 11: Results of the Rockwell C hardness test

The arithmetic mean and the confidence interval were calculated for each manufacturer from the measurement data of the weight/material loss of the disc mower blades. The blades were weighed after each wear cycle (n = 12 measurement values). The measurement data obtained are subject to the normal distribution (p = 0.95). Table 4 below shows the measurement results of the weight loss of the disc mower blades from the seven different manufacturers.

Table 4: Measurement results of the disc mower blades weight loss from the seven different manufacturers

Characteristic value	Maker A	Maker B	Maker C	Maker D	Maker E	Maker F	Maker G
Mean values of weight loss with confidence interval in g	2.00 ± 21.32%	2.31 ± 18.53%	2.12 ± 21.48	2.28 ± 15.99%	2.76 ± 10.39%	1.98 ± 9.24%	2.30 ± 13.00%

Figure 12 below shows the weight loss of the disc mower blades from the seven different manufacturers in absolute numbers (in grams).

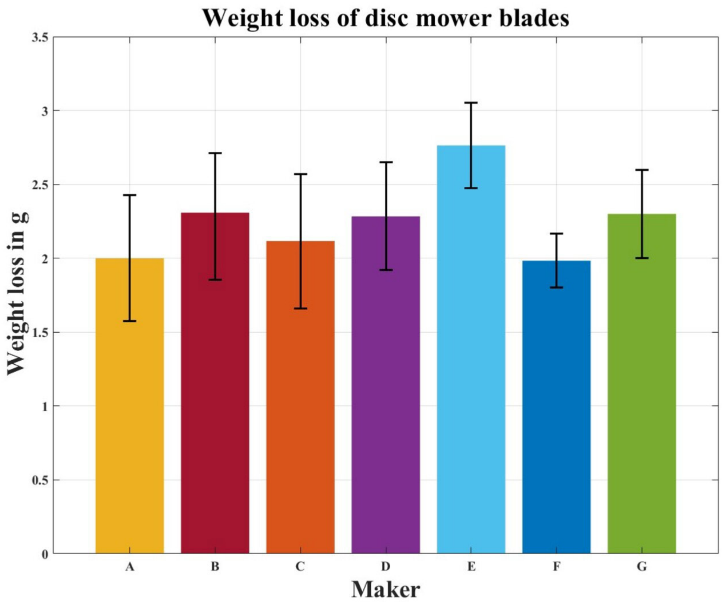


Figure 12: Loss of material / weight loss of the mower blades per manufacturer per wear test

From Table 4 and Figure 12 it can be concluded that the disc mower blades of manufacturer F with 1.98 g ± 9.42 % and manufacturer A with 2.00 g ± 21.32 % have the lowest weight loss and thus a higher wear resistance than the disc mower blades of the other manufacturers based on the weight loss method. Disc mower blades from manufacturer E have the lowest wear resistance. This mower blades came off with an average weight loss of 2.76 g ± 10.39 %. According to Figure 12, other manufacturers' blades showed mediocre material loss and thus have mediocre wear resistance in contrast to other disc mower blades.

When analyzing the measurement data of the cutting edge geometries, firstly the median value of the change in the substitution radius of each measurement section was determined using a box plot, and the outliers were removed. Secondly, the median values of the sections were averaged first from the front and then from the back per blade, so that there are two values for each disc mower blade, one after the first test run and one after the second test run (after the disc mower blade had rotated). It was now possible to examine the values under the criterion of abrasion or according to the positions as described below. Then the arithmetic mean of the change in substitution radius was calculated for each individual disc mower blade and then for each blade manufacturer. Figure 13 shows the schematic structure of the evaluation of the change in the equivalent radius.

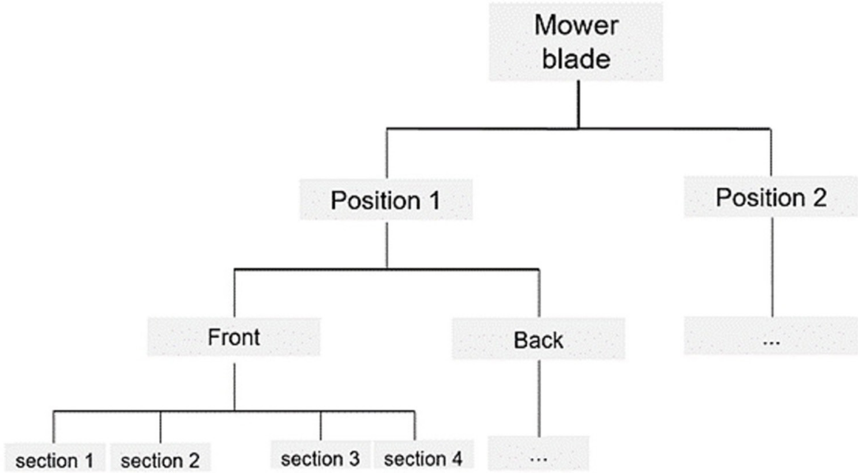


Figure 13: Schematic representation of the course of the evaluation of the change in the substitution radius

Figure 14 shows the percentage changes in the sharpness of disc mower blades from all manufacturers as trend lines of the median values for each section.

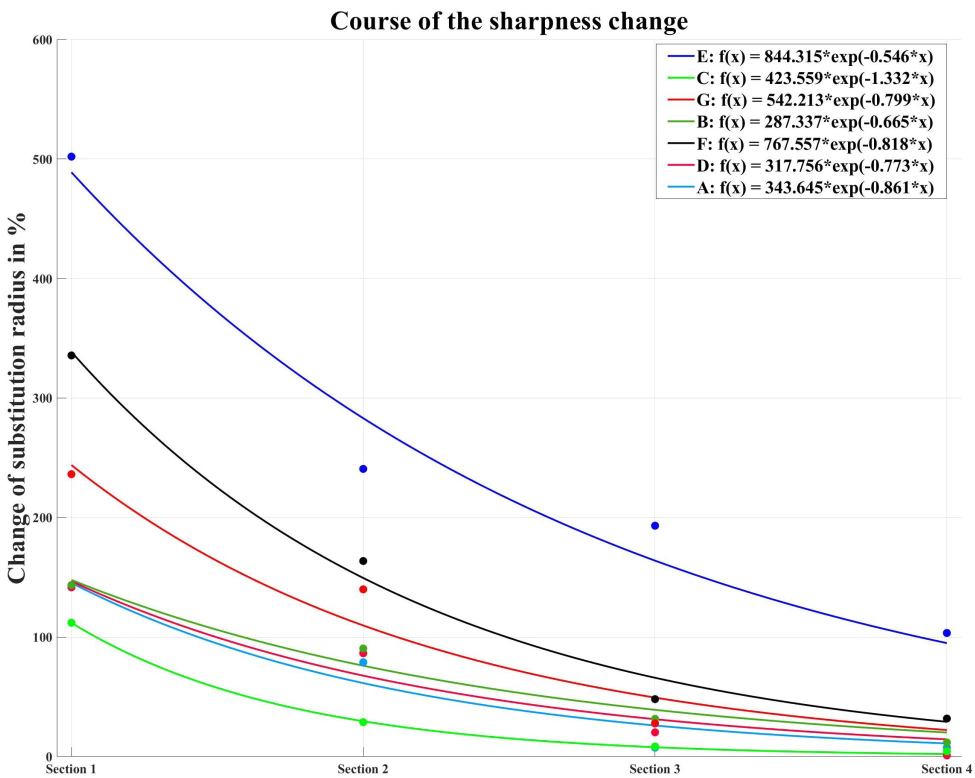


Figure 14: The course of the change in sharpness of the disc mower blades

These present the dynamics and shape of the wear pattern along the cutting edge. Compared to the trend lines of the cutting edge of the new blades, which show a linear progression, the trend lines of the worn blades now fall exponentially. Sections 1 and 2 have the greatest increase in replacement radius of any blade and, as a result, the greatest wear. Notably, blades from manufacturers E, F, and D have seen by far the largest increase in replacement radius. Blades from manufacturer C showed the smallest change in substitution radius.

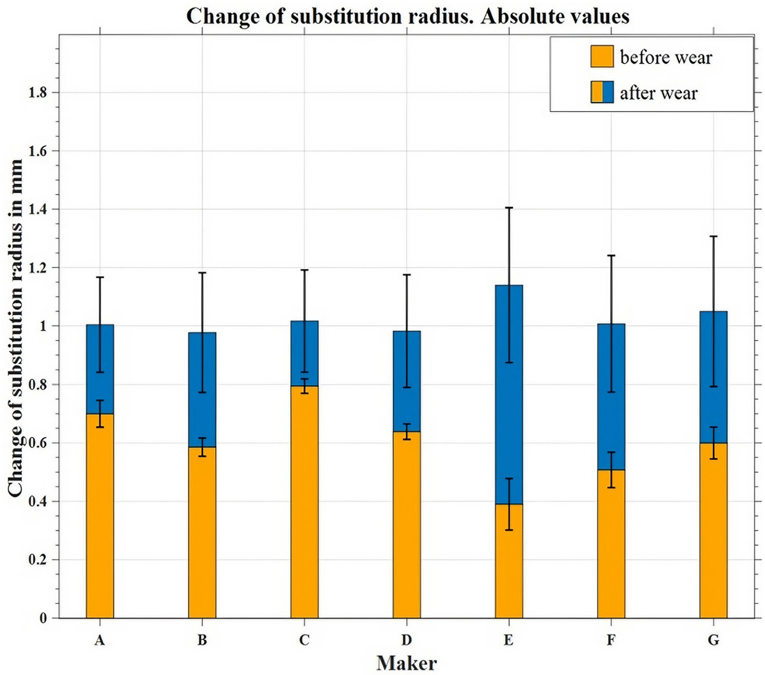
In Table 5 and Figure 15 the absolute and relative increase in substitution radius of the cutting edges of disc mower blades from all manufacturers is plotted as average values of all sections before and after wear with the confidence interval. The number of values was 16 (Figure 13). The measurement data obtained are subject to the normal distribution (p = 0.95).

Table 5: Mean values of substitution radius with the confidence interval of the cutting edge of the new and worn blades from the seven different manufacturers

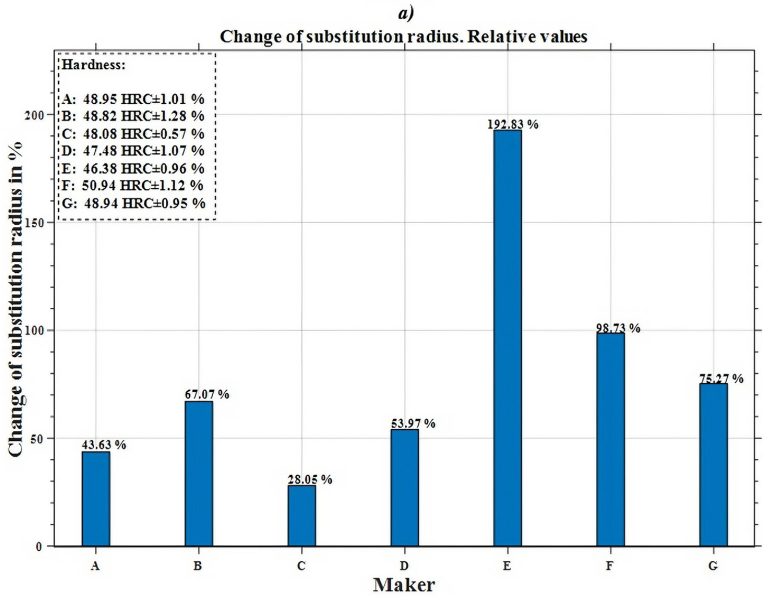
Characteristic value	Maker A	Maker B	Maker C	Maker D	Maker E	Maker F	Maker G
Mean values of substitution radius with the confidence interval, before wear in mm	0.70 ± 6.56%	0.59 ± 5.40%	0.79 ± 3.11	0.64 ± 4.19%	0.39 ± 22.68%	0.51 ± 11.95%	0.60 ± 9.09%
Mean values of substitution radius with the confidence interval, after wear in mm	1.00 ± 16.21%	0.98 ± 20.97%	1.02 ± 17.23	0.98 ± 19.65%	1.14 ± 23.28%	1.01 ± 23.22%	1.05 ± 24.49%

According to Table 5 and Figure 15, it can be seen that the new disc mower blades from manufacturer E have the smallest substitution radius at 0.39 mm ± 22.68% and are correspondingly sharp. The new disc mower blades from manufacturer C, on the other hand, are blunt with a substitution radius of 0.79 mm ± 3.11%. Table 5 and Figure 15 demonstrate that the blades manufactured by E have the lowest wear resistance. These blades have a substitution radius of 1.14 mm ± 23.28% after the wear test, which is the largest among all the mower blades tested. Furthermore, the blades from this manufacturer showed a relative increase in the substitution radius of approximately 193%, which is the highest among all the blades tested, followed by the blades from manufacturer F with an increase of around 99%. It can be inferred that the blades produced by these two manufacturers lose their sharpness more quickly than those produced by other manufacturers.

Blades from manufacturers A and C showed the smallest relative increase in substitution radius, while those from A, B, and D had the smallest substitution radius after wear. Disc mower blades from other manufacturers have a medium relative increase in substitution radius and, as a result, medium wear resistance in contrast to other discs clipped mower blades. The increased scatter of measurement data for the substitution radius of new disc mower blades from some manufacturers is a result of varying manufacturing quality. In the case of worn disc mower blades, the increased spread is determined by the different wear of each blade section.



a)



b)

Figure 15: a) Absolute change of substation radius, b) Relative change of substation radius

The tips of the disc mower blades, in particular, were worn down to such an extent that it was not always possible to measure them sufficiently well (Figure 16). Therefore, the number of measurement data in the first section varies from disc mower blade to disc mower blade.

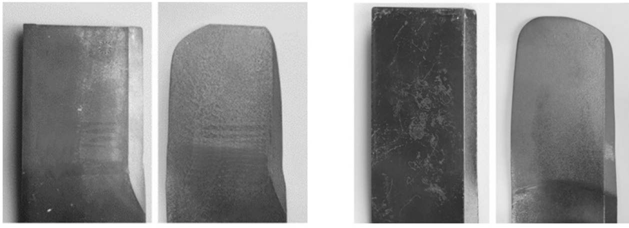


Figure 16: Exemplary representation of the mower blades from manufacturer E (left) and manufacturer C (right) before and after wear

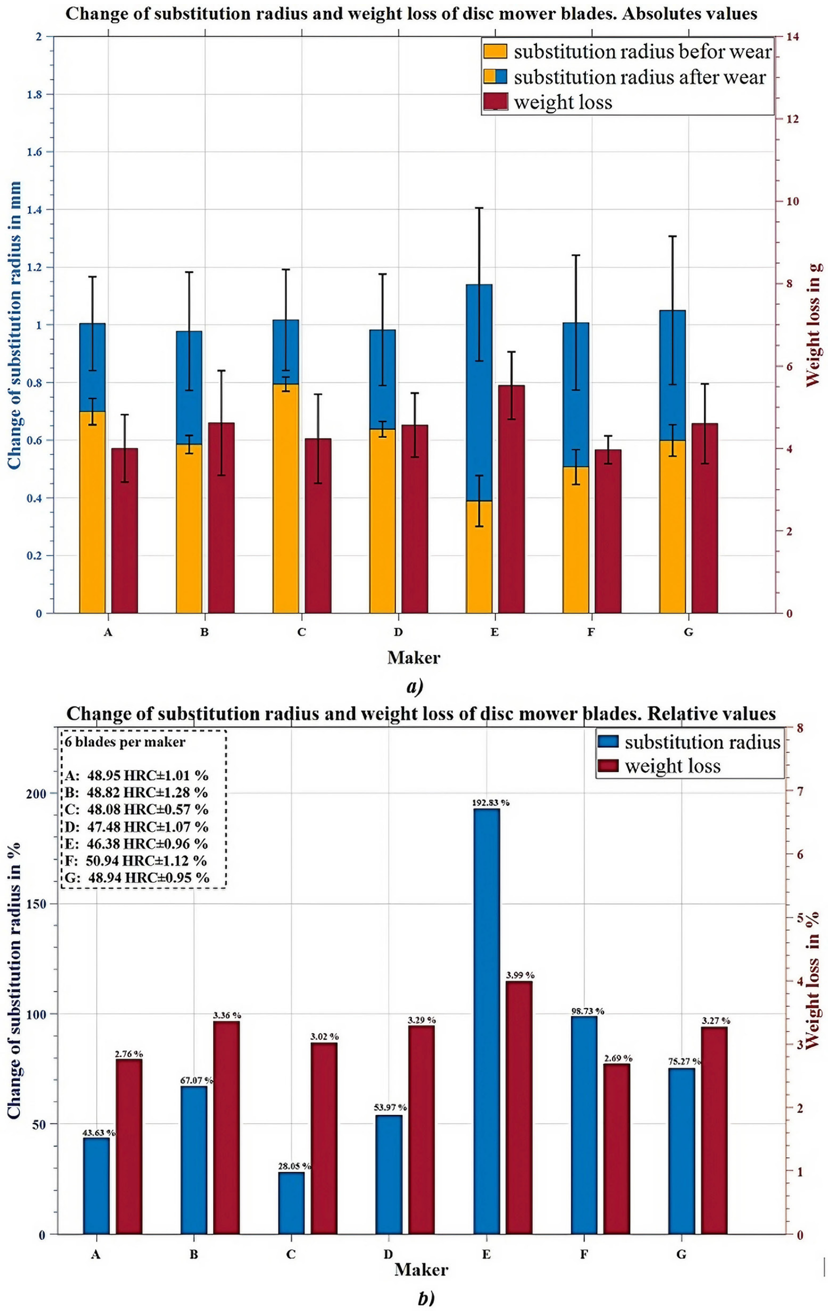


Figure 17: a) Absolute change of substitution radius (left) and absolute weight loss per Maker (right) before and after wear, b) Relative change of substitution radius (left) and relative weight loss per Maker (right) before and after wear

Based on the results of the wear experiments, two diagrams were prepared for a better overview (Figure 17) presenting the absolute and relative changes in sharpness and weight loss of the disc mower blades of all manufacturers as mean values with the confidence interval before and after wear. In this case, the mean values and confidence intervals of the weight/material loss per disc mower blade (n = 6 measurement values) were calculated.

For a better overview, all measurement results of the wear tests are summarized in Table 6. Comparing the measurement data from Table 6, it can be summarized that the disc mower blades from manufacturer A have the highest wear resistance when evaluated accordingly to the two wear methods. These manufacturers' blades rank second in substitution radius change and second in weight/material loss. In addition, they have the second smallest substitution radius on average according to the wear experiments and therefore remain sharp and capable of cutting. From this, it follows that when mowing with the blades of manufacturer A, a medium constant area performance, a medium fuel consumption per hectare and a clean cut can be expected in the long term.

Table 6: Summary of test results per blade from all Makers

Maker	Substitution radius, before wear in mm	Substitution radius, after wear in mm	Change of substitution radius in %	Weight loss in g	Weight loss in %
A	0.70 ± 6.56%	1.00 ± 16.21%	43.63	4.00 ± 20.45%	2.76
B	0.59 ± 5.40%	0.98 ± 20.97%	67.07	4.62 ± 27.51%	3.36
C	0.79 ± 3.11%	1.02 ± 17.23%	28.05	4.23 ± 25.55%	3.02
D	0.64 ± 4.19%	0.98 ± 19.65%	53.97	4.57 ± 17.05%	3.29
E	0.39 ± 22.68%	1.14 ± 23.28%	192.83	5.53 ± 14.83%	3.99
F	0.51 ± 11.95%	1.01 ± 23.22%	98.73	3.97 ± 8.48%	2.69
G	0.60 ± 9.09%	1.05 ± 24.49%	75.27	4.60 ± 21.00%	3.27

Although the disc mower blades from manufacturer C performed best on average after changing the substitution radius, they already had a larger substitution radius before they were worn out, and therefore have less cutting ability. Furthermore, despite the small increase in substitution radius, this manufacturer's blades are among the three most lest worn and rank third in terms of weight/material loss.

When comparing by weight/material loss alone, the disc mower blades from manufacturer F are the best. It is remarkable that the blades of this manufacturer show a very high increase in the substitution radius at the cutting edge despite the low weight loss. This is followed by manufacturers G, B and D. As a result, they quickly become dull and lose their cutting ability. However, the new disc mower blades from manufacturer F have the second smallest substitution radius on average.

The disc mower blades from manufacturer E show the lowest wear resistance when evaluated accordingly to the two wear methods. Compared to the blades of other manufacturers, however, the blades of this manufacturer dull faster and their cutting ability decreases rapidly. It is probably because these blades have a lower surface hardness and have been sharpened. On the other hand, the disc mower blades from manufacturer E have the lowest average substitution radius when new compared to the blades from other manufacturers. As a result, the disc mower blades from this manufacturer should increase the area output when mowing in the short term. In addition, when using these blades, lower fuel consumption per hectare can be expected for a shorter period of time.

When evaluating the blade manufacturing quality, the degree of scatter of the measured values of the unworn disc mower blades was considered. Overall, all blades have a high dispersion of measurements of substitution radius apart from blades from manufacturer C (less than 5 %). Some disc mower blades examined showed various defects on the cutting edge, such as small cracks, deep grinding marks, severely bent blade tips and etc. The blades from manufacturer E show the greatest scatter in the measured values for substitutional radius. This is probably due to the fact that they are ground during production and not rolled like the blades from other manufacturers. When looking at the scatter of the weight measurements of the new blades from all manufacturers, it can be said that due to the lower scatter dimensions, no manufacturing defects can be determined (Figure 17a).

In this paper, a correlation between the mass loss and the geometry shape change of the disc mower blades was also sought. The correlation could not be determined (Table 6). In addition, the phenomena behind the differences in wear behaviour cannot be explained at present due to missing information, such as on the microstructure of disc mower blades before and after wear.

Conclusions

The test results confirm that the wear test bench and the developed method of high-speed wear tests on disc mower blades together with the wear medium examined make it possible to examine the wear process of both blades qualitatively and quantitatively. In addition, the wear test bench is a fast and effective method of researching the wear behavior of disc mower blades. It is possible to examine a wide variety of blades variations. Numerous blade coatings and blade materials in combination with different blade geometries can be compared with each other.

The disc mower blades examined in the basic tests can be used as references in the future. With the help of references and the reproducible operating conditions, it is possible to make statements about the profitability of blade variations without extensive field tests. The research has shown that the production quality of the disc mower blades varies greatly. For example, they have various production defects on the cutting edge and material defects that are highly likely to have a negative effect on the cutting pattern and area performance. In addition, all blades examined today do not have sufficient wear resistance. All of this has a negative impact on productivity, and therefore on the sustainability and efficiency in agriculture.

In order to reduce wear on the cutting edges and achieve a long service life, disc mower blades could be hardened or coated with wear-resistant layers. The coating has to be adjusted to the different environmental conditions for the fields and plants which depend on the regions. Thus you need more knowledge about the different conditions that are important for the mower blades in relation to environmental influences. For the coating, you have to validate with separately field tests caused by the different reaction of wear medium. It is also important to recognize the state of wear of the blades at an early stage and, if necessary, to replace the badly worn blades in good time. Innovative technologies like AI-powered automation can help solve these challenges. For this reason, the FMDauto Institute is currently using the data obtained for the predictive detection of the wear status of the disc mower blades with the help of a neural network.

Further potential for improvement lies in the characterization of the cutting edges. A coated cutting edge can consist of several different radii and chamfers. Wear parameters can be derived based on an algorithm that clearly characterizes different cutting edges. However, different measuring devices use different calculation algorithms, on which the results are heavily dependent. This is due to the lack of standards. After the further development of the evaluation method, the test method presented here can be established as a standard for the wear analysis on blades from agricultural machinery.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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