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# Study to Determine the Effect of Blade Distance and Chain Speed on the Productivity of Trench Excavators Using Taguchi Method

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## ABSTRACT

Chain trench excavators are widely used in the world for trenching in agriculture, laying underground cables, digging trenches. In this study, the research object is a small chain-type trench excavator. The purpose of the study is to evaluate and select the parameters of the chain loader to the machine productivity and evaluate the results of the experimental machine theory calculation. Experimental measurement parameters include machine speed when working, chain speed, blade distance adjustment on the chain. Research method is to conduct experiments using Taguchi method to design experiments and Minitab software to analyze data. Experimental results and numerical analysis determined that the optimal set of parameters was the distance of 2 cutting edges on the chain, the active sprocket rotation speed for the highest productivity. Compared with the results from the theory using the design, the deviation of the optimal parameters is less than 5%. Experimental process design and parameter influence analysis by Taguchi method, ANOVA analysis have identified reasonable parameters, highest productivity target.

**Keywords**: cutting edge, experimental design, trenching machine, Taguchi method, optimal parameters.

## INTRODUCTION

Trenching machine is widely used in the world due to its many advantages, it is suitable for jobs such as digging trenches in agriculture, digging trenches for laying underground cables, digging trenches [1, 2]. According to the structure of the working equipment, the excavator is mainly found in two types, the chain type and the rotor type.

Research in [1] has made recommendations on structural characteristics of trenching machines, guiding theoretical issues for machine design. This study provides basic knowledge for trenching machine design and operation. The author in [2] outlines the design process, calculates the blade strength of the trench excavator theoretically and gives examples of experimental calculations. An example in [2] is a trench excavator using a hydraulic drive, taking into account special local conditions. The machine is designed to have a maximum depth of 1 m, a width of 30 cm and an adjustable chain length. The theory of calculating shear resistance and excavation, blade shape is also shown in [3]. The study in [4] investigates the soil destruction by the soil cutting process of the chain excavator blade. The calculated dependencies determining the scraper middle part width rational values and the scraper middle part boom rational parameters are obtained [4].

Theoretical study in [5] analyzes the influence of some factors on trenching machines in terms of structure, assembly, trench depth, efficiency. In the same research direction as [5], in [6], the main factors affecting the performance of the chain excavator were found. The study in [6] also builds mathematical expressions and mathematical relationships to predict the speed and performance of the chain excavator. In order to design a trench excavator in water with minimum power consumption and minimum weight, in [7] studied the theory and used genetic algorithm for the optimization problem. The optimal parameters in [7] are blade distance on chain, active sprocket radius, chain length. The study in [8] is to determine the operating mode of the excavator to achieve the minimum energy based on different specification and working mode. The study in [9] refers to some factors affecting the wear resistance of cutting parts in chain excavators. It provides some recommendations to ensure the most cost-effective operation with cutting tools in chain excavators. Research, design, and adjust the transmission system of the small chain excavator mentioned in [10]. The problem of adjusting the drive system of the chain excavator has also been developed and investigated in [10], the goal is to maximize the power of the drive source. Research results [10] have theoretically determined the technical parameters and data for adjusting each machine working mode. Based on the method in [10] and in local conditions, this study designed and fabricated a trench excavator 150 mm wide and 915 mm deep.

A mathematical analysis was performed to find out the factors affecting the digging force and capacity of the chain trench trenching in the study [11]. Mathematical analysis shows that the digging force and capacity of the chain excavator are affected by the tool cutting speed, the tool cutting angle, the angle between the cutting motion and the vertical, the depth and width, coefficient of friction between soil and metal, adhesive resistance and specific gravity of soil. The field test results in [11] show that the theoretical digging force is lower than the actual digging force. The theoretical digging capacity is 3.8% and 2.8% lower than the actual digging capacity at the trench depth of 1.2 m and 1.5 m respectively. The study in [12] presented experimental research results for the manufacture of continuous working earthmoving machines. The research carried out in [12] and the results obtained allows to confirm the effectiveness of the technical proposals to create the design.

In [13–15], the experimental research method was presented and the application of Taguchi method was presented in various fields. Taguchi method was introduced by engineer Genichi Taguchi (1924–2012). Taguchi method is mainly in the parameter design stage based on assessing the influence of factors on the objective function, and at the same time determining the optimal parameters. Taguchi method has the advantages of simplicity, small number of trials, and it can be quantitative or qualitative. However, this method has the disadvantage that the data is discrete, so the obtained solution is only close to the optimal, does not introduce constraints, and is difficult to solve the multi-objective problem [13, 14].

In the above studies, the chain excavator is the subject of research in [1, 2, 4–7, 10]. In which the studies are theoretical studies related to the research object or the calculation of parameters for experimental fabrication [1–10]. The studies in [11, 12] are experimentally verified studies to evaluate the theoretical and experimental computational force, the influence of load variation on the operation. In this study, the research object is a small chain-type trench excavator, whose structure and principles are calculated and designed in [10]. The article will present experimental research to evaluate some parameters of chain-type actuators to machine productivity and evaluate the results of theoretical calculations in [10] by experiment. The content of the report will present the working equipment and productivity of small chain excavators. Then analyze the influence of the parameters by Taguchi method, ANOVA analysis to determine the reasonable parameters to achieve the highest productivity goal.

## WORKING EQUIPMENT AND PRODUCTIVITY OF CHAIN TRENCH EXCAVATORS

### Chain trench excavator

The hydraulically driven small chain excavator in this study is designed as described in Figure 1. The machine consists of the main working mechanisms, which are the chain rotating mechanism for cutting and digging, the chain lifting mechanism to adjust the depth of the trench, and the machine moving mechanism. The power source is an internal combustion engine that drives the hydraulic pump through a mechanical transmission. The active sprocket that rotates the chain is mounted directly on the hydraulic motor of the mechanism, the moving mechanism is driven from the hydraulic motor through a mechanical transmission. The machine is designed for the combined or independent working modes between the mechanisms including: no-load starting mode; soil digging and cutting mode, moving and adjusting trench depth; mode of moving, digging and cutting soil constant depth; self-propelled travel mode, drifting mechanism moving mode. The speed adjustment of the machine's working structure is through the hydraulic flow

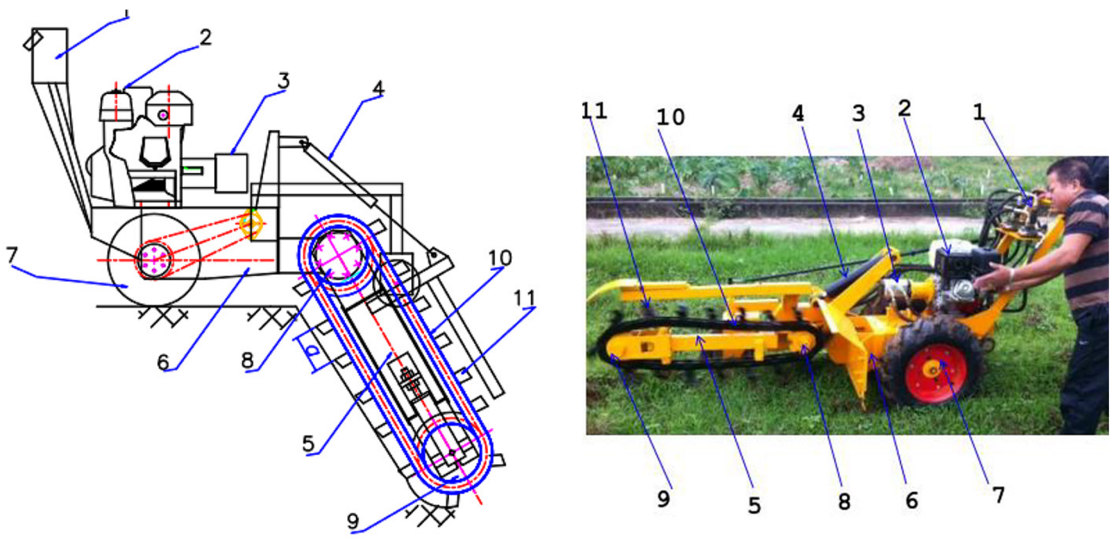


**Fig. 1.** General structure of experimental machine [10]; (1) control distribution box, (2) internal combustion engine, (3) hydraulic pump, (4) cylinder lifting chain, (5) trench excavator chain bracket, (6) machine frame, oil tank, (7) moving mechanism, (8) active sprocket, (9) passive sprocket, (10) chain, (11) cutting blade

metering valve. The chain trench excavator can dig trenches 150 mm wide and 915 mm deep, excavating grade III soil (Table 1). In terms of materials and equipment used locally, the machine uses an internal combustion engine HONDA GX340/390, with a capacity of 8.7 kW at 3600 rpm. Hydraulic actuators, chains and blades are also selected taking into account local conditions. According to the theoretical calculation in [10] for grade III soil at the maximum trench depth condition, a reasonable parameter to promote the full potential of the driving source is the motor speed to move (12 rpm), the chain motor to rotate (55 rpm). These values correspond to machine moving speed is (0.37 m/s), chain speed is (0.575 m/s).

Figure 1 shows the general structure of the trenching machine used for testing. Cutting and digging work group 5 consists of a chain 10 that is matched with an active sprocket 8 above and a passive sprocket 9 below, on the chain 10 with 2-blade distance cutter *a*. Blade mounting distance can be adjusted at different distances. The machine designed in [10] is available to excavate soil up to grade III.

## Machine productivity

Diagram of the excavation process of the machine as shown in Figure 2, the thickness of the soil chip is *c* (mm). When the machine is working, at the same time the cutting blades are digging the ground and the machine is moving. Thus, there

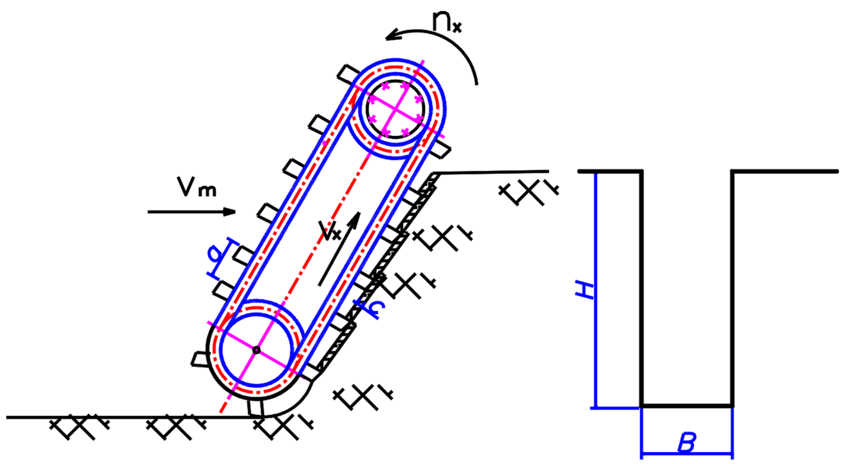


**Fig. 2.** Diagram of the excavation process

is a very close relationship between the machine moving speed and the blade speed.

Machine technical productivity $Q$ (m³/s).

$$Q = v_m BH \tag{1}$$

$$v_m = \frac{\pi D_{bx} n_{bx}}{60} \tag{2}$$

where: $v_m$ – the machine speed (m/s),
$B$ – the width of the trench (m),
$H$ – the depth of the trench (m),
$D_{bx}$ – the diameter of the wheel (m),
$n_{bx}$ – the rotational speed of the wheel (rpm).

Thus, the machine productivity can be determined when the experimental value $v_m$ is measured. On the other hand, the machine productivity depends on the number of cutting blades out of the excavation per minute $z$:

$$z = \frac{60 v_x}{a} \tag{3}$$

where: $a$ – the step of the blade attached to the chain (m).

In order to increase productivity, $z$ must be increased, which here depends on the relationship between the speed of chain $v_x$ and the distance of the cutting net attached to chain a. With the drive source constant, it can be seen that increasing $v_x$ causes a change in $v_m$.

## RESEARCH ON EXPERIMENTAL METHODS

### Experimental purpose

The purpose of experimental research is to evaluate and select a number of chain working parameters to machine productivity and evaluate the results of theoretical calculations in [10]. Experimental measurement parameters include: machine speed $v_m$ (m/s), chain speed $v_x$ (m/s), blade pitch adjustment on the chain $a$ (cm). The chain speed $v_x$ is determined by the rotation speed of the active sprocket $n_x$ (rpm).

The goal of the problem is to determine a reasonable parameter for maximum productivity through the value of $v_m$.

$$v_m = max\, f\,(a, v_x) \tag{4}$$

In field experiments, there are many interference factors affecting the results such as soil type, working mode, operator level, blade type, measurement method error. In order to limit these factors, it is necessary to have a reasonable process such as experimenting on the same type of soil, setting up and adjusting the correct working mode according to the design [10], using only 1 operator, using 1 type of blade for an experimental procedure.

### Experimental process

The experimental sequence has a diagram as shown in Figure 3, including 6 steps. Step 1 is the experimental design according to Taguchi method. Step 2 is to measure and determine the land level required by the problem. Step 3 is to select and adjust the blade distance. Step 4 is to adjusts and measures the blade speed at idle through the sprocket rotation speed. Step 5 is to excavate and cut the soil with the trench of width B and height H and measure the machine speed. Steps 2 to 4 above are repeated for $n$ experiment. Step 6 is to process experimental results according to Taguchi method.

To determine the soil level in this study, use a tool as shown in Figure 4. Place the working head on the ground, raise the hammer head to the upper

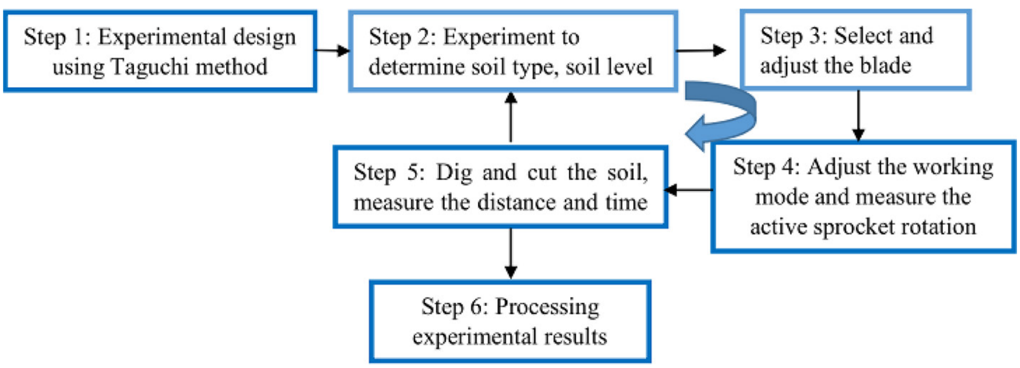


**Fig. 3.** Experimental procedure

**Table 1.** Soil classification test equipment

| Level of soil and rock | Number of collisions |
|---|---|
| I | 1÷4 |
| II | 4÷8 |
| III | 8÷16 |
| IV | 16÷32 |

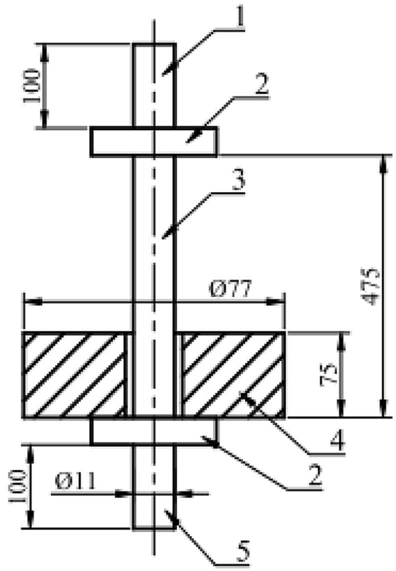


**Fig 4.** Soil level measuring instrument, (1) handle, (2) stop ledge, (3) navigation, (4) hammer head $G = 2.5$ kg, (5) working head ϕ11

ledge and drop the impact to make the working head sink into the ground, the hammer head creates a work A = 0.4·2.5 kgm, working head has a cross section of $F = 1$ cm$^2$ and is 100 mm long. Count the number of hits of the hammer head until the working head sinks into the ground to the stop (100 mm). According to the number of collisions counted, we can determine the soil level according to Table 1.

The blade pitch with distance $a$ was changed after each experiment. This distance for each test is taken as a step of the chain.


**Fig. 5.** Measuring machine moving speed

In step 4, raise the chain high and adjust the machine to a steady value. Use a non-contact ring tachometer to measure the rotational speed of the active sprocket $n_x$, measuring position as shown in Figure 6. The value of the chain speed is converted according to the formula (5).

$$v_x = \frac{\pi D n_x}{60} \tag{5}$$

where: $D$ – the diameter of the active sprocket ring (m);
$n_x$ – the rotational speed of the active sprocket (rpm).

Average travel speed $v_m$ is measured by measuring distance and velocity using a stopwatch and length measuring instrument (Fig. 5). Then the average speed of the machine is determined by formula (6).

$$v_m = \frac{L}{t} \tag{6}$$

where: $L$ – the length of the trench used for testing (m);
$t$ – the corresponding travel time (s).

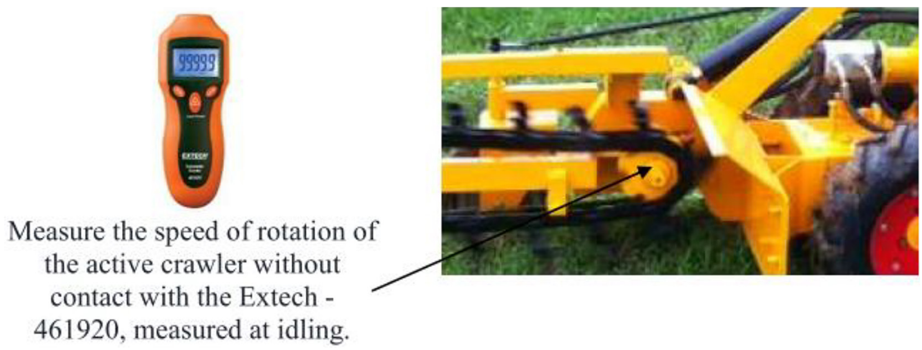


**Fig. 6**. Active sprocket tachometer position

### Taguchi method

The idea of the Taguchi method is to determine the factors in order to achieve the highest efficiency by detecting and eliminating the effect of disturbance as much as possible. A design variable that affects the results in two directions, the effect that moves the results closer to the goal is a useful signal, called "Signal", the effect that makes the result move away from the goal is "Noise". The S/N (Signal/Noise) ratio represents the performance indicator, used to evaluate and select parameters. The parameter set is good for large S/N. The optimal set of parameters when giving the largest S/N [13-15].
Maximum problem (Larger better).

$$S/N = -10\,lg\left(\frac{1}{n}\sum_{u=1}^{n}\frac{1}{v_{mu}^{2}}\right) \tag{7}$$

where: $u$ – the experimental sequence number;
$n$ – the number of experiments;
$v_{mu}$ – the response value.

Regardless of the type of problem, the goal to be optimized is always to maximize the *S/N* ratio. The steps to use Taguchi method include determining the independent factors and influencing parameters, determining the objective function, choosing the original matrix to conduct the Taguchi method, conducting the method and analyzing the results. The parameters $\{X_i\}$ that affect the process are being optimized. These are controlled parameters that vary according to the Taguchi method level. More levels allow for greater parameter variations. The objective function can have any variable. The objective function in this study is determined by the actual experimental results. Depending on the number of parameters affecting the process, a orthogonal matrix will be selected according to Taguchi method. Performing calculations can be done by creating algorithms or calculation programs, or in some software that supports the Taguchi method. Taguchi method in this paper is used to find the maximum possible objective function.

## DETERMINE THE INFLUENCE OF THE PARAMETERS USING TAGUCHI METHOD

### Experimental design

The independent factors determined according to [10] include the parameters of the mechanical transmission, the engine power, the specifications of the pump and the hydraulic motor. Here the form of the blade, the level of the experimental soil and operator ability is also considered as an independent factor. Machine operating mode in the heaviest conditions, the depth is maximum. Independent factors such as power, track width and depth, wheel and chain sizes are given in Table 2 [10].
Influence factor:

$$\{X_i\} = \{a, n_x\} \tag{8}$$

The influencing factors choose the design at 3 levels of values based on the machine structure and the results calculated in [10]. The experimental design is as in Table 3. The response value is the machine moving speed $v_m$ (m/s), this is an indirect value to evaluate the machine productivity through formula (1). The objective function of the problem is according to formula (4). According to the Taguchi method with 2 influencing factors, 3 levels of values, we choose the experimental planning table L9, the number of times experiment $u$ in this study is repeated 3 times. Conduct the experiment according to the procedure outlined in the diagram in Figure 3, collect data and get the results in Table 4.

**Table 2.** Independent factors

| *P* (kw) | *B* (m) | *H* (m) | *D* (m) | $D_{bx}$ (m) |
|---|---|---|---|---|
| 8.7 | 0.15 | 0.915 | 0.2 | 0.6 |

**Table 3.** Influential factors and value levels

| Influential factors | Symbol | Unit | Value level | | | Range of change |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | |
| Active sprocket rotation speed | $n_x$ | rpm | 40 | 55 | 70 | 30 |
| Step of the blade attached to the chain | *a* | cm | 18.9 | 25.2 | 31.5 | 12.6 |

**Table 4.** Matrix of planning L9 and experimental results

| *N* | $n_x$ (rpm) | *a* (cm) | Response value $v_m$ (m/s), times of experiment *u* | | |
|---|---|---|---|---|---|
| | | | 1 | 2 | 3 |
| 1 | 40 | 18.9 | 0.215 | 0.216 | 0.225 |
| 2 | 40 | 25.2 | 0.322 | 0.296 | 0.301 |
| 3 | 40 | 31.5 | 0.195 | 0.196 | 0.192 |
| 4 | 55 | 18.9 | 0.301 | 0.301 | 0.296 |
| 5 | 55 | 25.2 | 0.348 | 0.355 | 0.356 |
| 6 | 55 | 31.5 | 0.241 | 0.238 | 0.241 |
| 7 | 70 | 18.9 | 0.31 | 0.325 | 0.301 |
| 8 | 70 | 25.2 | 0.345 | 0.351 | 0.346 |
| 9 | 70 | 31.5 | 0.228 | 0.23 | 0.229 |

## Analyze experimental results

The S/N ratio represents the performance indicator, which is the machine moving speed, which is the largest. The S/N ratio is used to evaluate and select parameters. The S/N ratio is calculated according to the problem of Maximum problem (Larger better) by formula (7). Response values calculated at 3 times of experiment are shown in Table 4.

Using Minitab software to calculate the effect of factors according to Taguchi method, a large response value is good. The results are shown in Tables 5 and 6, the graphs Figure 7 and Figure 8. Analytical results when 40rpm < $n_x$ < 55 rpm the S/N ratio increased rapidly, when $n_x$ > 55 rpm, the S/N ratio was almost unchanged but tended to decrease. With a factor of cutting edges on the chain *a* < 25.2 cm, S/N ratio increases rapidly, *a* > 25.2 cm, S/N ratio

**Table 5.** Calculation table of (a) S/N ratios **(**Larger is better) and (b) response value by Minitab software

| Response table for signal to noise ratios | | | Response table for means | | |
|---|---|---|---|---|---|
| Level | $n_x$ | *a* | Level | $n_x$ | *a* |
| 1 | -12.578 | -11.272 | 1 | 0.2398 | 0.2767 |
| 2 | -10.640 | -9.508 | 2 | 0.2974 | 0.3356 |
| 3 | -10.706 | -13.143 | 3 | 0.2961 | 0.2211 |
| Delta | 1.938 | 3.635 | Delta | 0.0577 | 0.1144 |
| Rank | 2 | 1 | Rank | 2 | 1 |

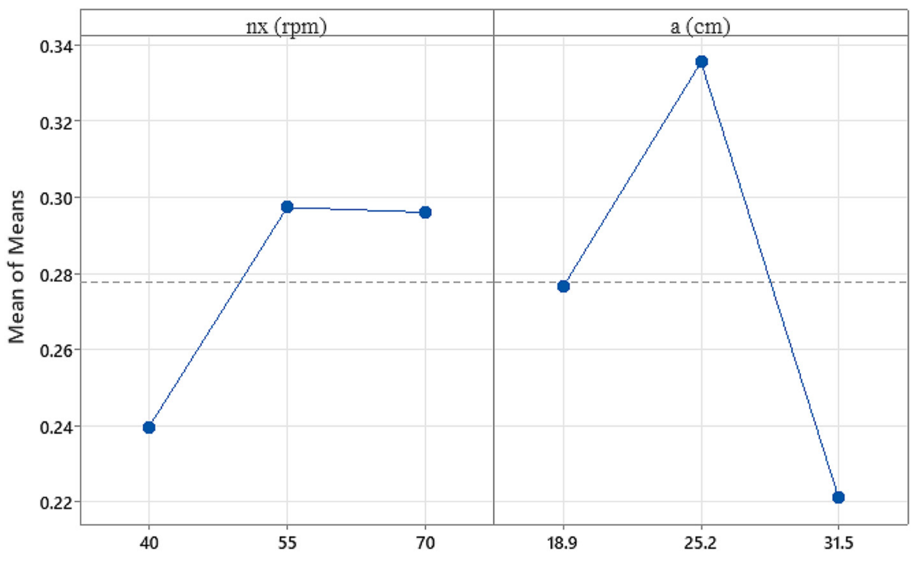


**Fig. 7.** The main factors affecting the objective function

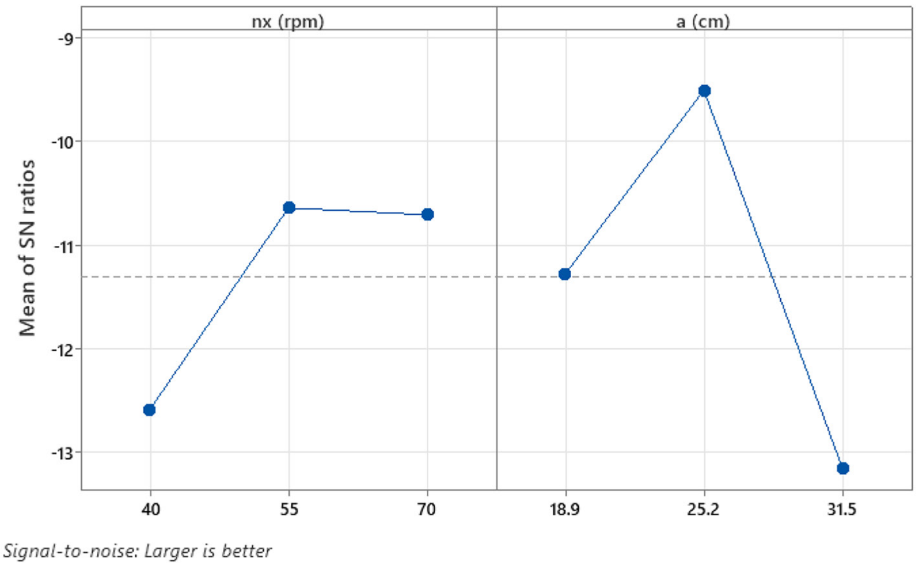


**Fig. 8.** Effect of each factor on the S/N ratio

**Table 6.** Summary of results of one-way ANOVA model using Minitab software

| Factor | S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|---|
| $n_x$ | 0.0587515 | 23.89% | 0.00% | 0.00% |
| $a$ | 0.0354947 | 72.22% | 62.96% | 37.49% |

decreases rapidly. The results show that the influencing factors give the best results in the vicinity of level 2 (maximum S/N ratios) $n_x$ = 55 rpm, $a$ = 25.2 cm. Table 6 is a summary of the analysis ANOVA. Ranking the level of influence, factor $a$ is the major influence accounting for 72.22%, factor $n_x$ is the influence accounting for 23.89%.

## DISCUSSION

From the experimental results, using Minitab software to determine the regression equation of the factors affecting the machine moving speed. The relationship equation between the machine moving speed and the distance between the two cutting edges on the chain is Equation (9).

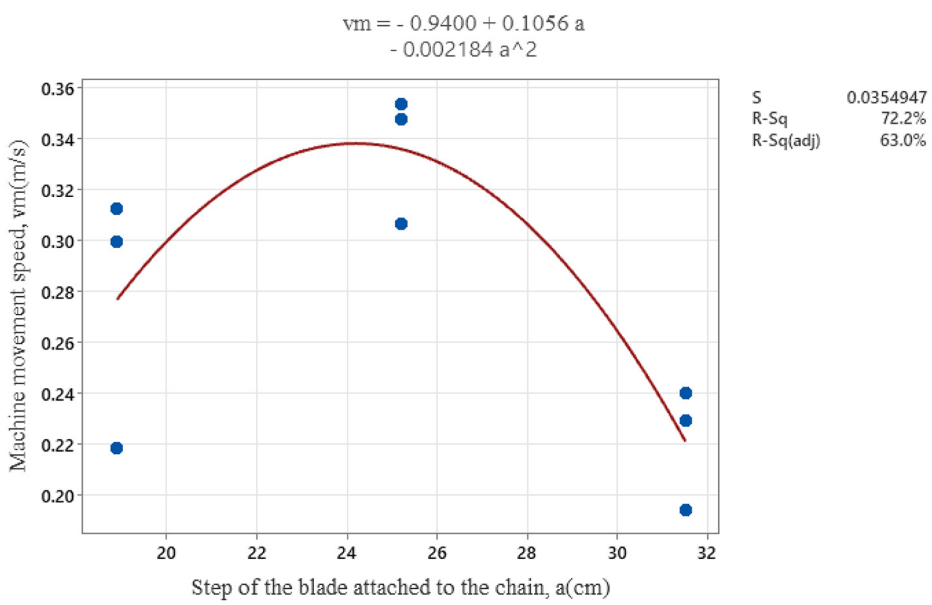


**Fig. 9.** Graph of the relationship between the distance of 2 blades on the chain with the machine moving speed

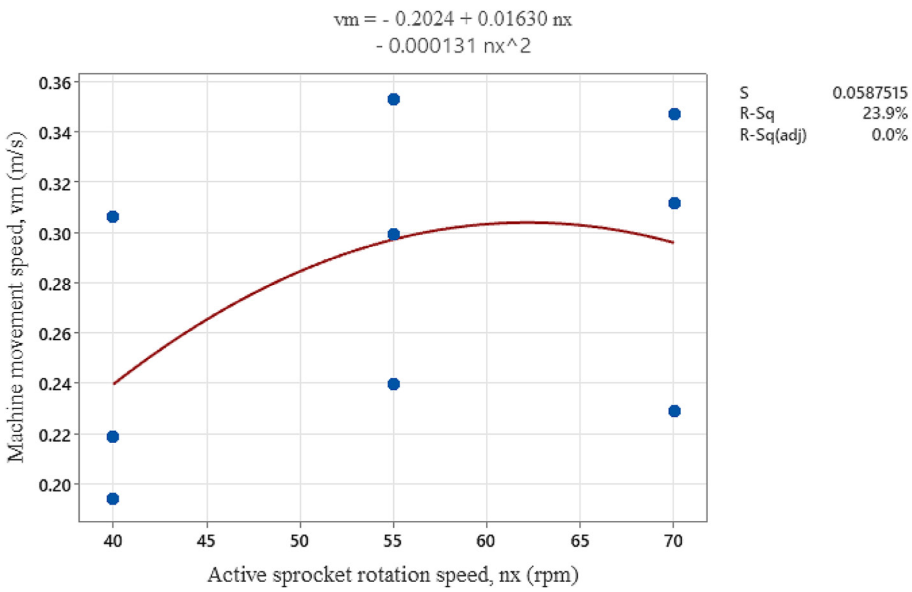


**Fig. 10.** Graph of the relationship of active sprocket rotation speed with the machine moving speed

The relationship equation between the machine moving speed and the distance between the two cutting blades mounted on the chain is Equation (10).

$$v_m = -0.94 + 0.1056a - 0.002184a^2 \quad (9)$$

$$v_m = -0.2024 + 0.0163n_x - 0.000131n_x^2 \quad (10)$$

Based on the regression equations, the graphs of Figures 9 and 10 we can determine that the optimal value of $v_m$ according to the objective function is the maximum. The corresponding results determine the optimal parameter value for the machine corresponding to the independent factors $a$ = 24 cm, $n_x$ = 62 rpm. Experiment with this optimal parameter, determine the reasonable machine moving speed $v_m$ = 0.36 m/s. When compared with the results from the selected theory, the design in [10], the deviation of the optimal parameters is less than 5%. The cause of the deviation is due to the influence of many noise factors that cannot be completely eliminated by the experiment, due to the selection of the machine efficiency coefficient when designing. The results show that the calculation and survey methods in [10] are appropriate and reliable. When changing independent factors such as soil level, blade shape, and trench size, it is possible to proceed with the method as above.

Table 8 is a comparison of specifications with studies in [2] and [5]. This study and the studies in [2] and [5] have different trench sizes and different rock types. In [2], the capacity of the internal combustion engine is equivalent, and if considering the flow rate of hydraulic pump $F_r$ (l/min), the capacity of machine $Q$ (mm$^3$/s) is almost the same. If the trench width $B$ = 150 mm, the effect of the specific resistance on both sides of the wall will be greater than in [2], so initially, it can be seen that the selected parameters are more effective [2] if the trench conditions are the same. The study in [5] refers to the large excavator, which has a high chain speed and a slow machine travel speed. The parameters [5] are much different because this is a machine used to dig complex soils, the depth and width of the trench are large. Therefore, it is possible to apply the experimental method mentioned in this study to obtain the most effective parameters for the studies in [2, 5].

**Table 7.** Comparison of optimal parameters from experiment and design selection from theory

| Parameter | Symbol | Result of design selection from theory [10] | Optimal results from experiment | False (%) |
|---|---|---|---|---|
| Active sprocket rotation speed, (rpm) | $n_x$ | 59.68 | 62 | 3.74 |
| Hydraulic motor moving speed, (rpm) | $n_{dc}$ | 12.77 | - | - |
| Machine movement speed, (m/s) | $v_m$ | 0.397 | 0.36 | 5 |
| Step of the blade attached to the chain, (cm) | $a$ | 25.2 | 24 | 4.76 |

**Table 8.** Discuss machine specifications

| Parameter | Symbol | Parameter [2] | Parameter [5] | Results from experiment |
|---|---|---|---|---|
| Depth of trench (mm) | $H$ | 1000 | 1200 | 915 |
| Width of trench (mm) | $B$ | 300 | 650 | 150 |
| Hydraulic pump flow (l/ph) | $F_r$ | 23 | - | 55.2 |
| Engine power when the number of revolutions is 3600 rpm (kW) | $P$ | 8.7 | - | 8.7 |
| Step of the blade attached to the chain (cm) | $a$ | - | 62.5 | 24 |
| Chain speed (cm/s) | $v_x$ | - | 4 - 5 | 1 |
| Machine movement speed (m/s) | $v_m$ | - | 0.05 | 0.36 |

## CONCLUSIONS

The article has studied the machine on small chain trench excavator and machine productivity. Through experimental research to evaluate some parameters of chain-type actuators to machine productivity and evaluate theoretical calculation results. The article has developed the problem and experimental procedure, designed the experiment and conducted the experiment.The experimental design method in this study used Taguchi method and Minitab software to analyze the data. Experimental results and data analysis using Minitab software from independent factors determined the optimal parameter $a$ = 24 cm, $n_x$ = 62 rpm for the highest productivity. When compared with the results from the theory using the design, the deviation of the optimal parameters is less than 5%. The research results show that the method of calculation and survey is suitable and reliable when applied to trenching machines in local conditions. The experimental method in this paper can be extended to other influencing factors and other devices.

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