Use of Taguchi Method-Based Design of Experiments (DOE) in the Optimization of the Drilling Parameters of Structural A572 Steel

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Abstract

This paper presents an experimental study based on Grandspan Development Corporation that aims to find the combination of drilling parameters, namely: drilling speed, feed rate, and drill diameter, that would generate the optimal drilling time and material removal rate. A CNC FSD-1020 machine with low-carbon twist drill and a sample of A572 Steel was used for the experiment, whose data was analyzed with L9 orthogonal array. The Taguchi-based Design of Experiments was utilized in finding the optimal setting of the drilling parameters. Analysis of Variance (ANOVA) and Signal-to-noise ratio (S/N) were also utilized to determine and analyze which among the independent variables has significant effects and contributions on the response variables. Power Test was applied to check if the Power of the input parameters are acceptable. As generated by Stat-Ease, 1.8 mm/rev is the most optimum feed rate for all settings. Meanwhile, using Minitab, the drilling parameters with the minimum drill time are as follows: 390 rpm for cutting speed, 1.8mm/rev for feed rate, and 25mm for drill diameter; and, the optimal set of parameters with the highest material removal rates: cutting speed of 400 rpm, feed rate of 1.8mm/rev, and drill diameter of 25mm. ANOVA shows that drill diameter is the parameter with the most significant impact on drill time, and feed rate for material removal rate. The two most optimal sets of parameters for each drill diameter were also determined in the study.

Keywords

Drilling, Taguchi Design of Experiments (DOE), Analysis of Variance (ANOVA), drilling time, material removal rate (MRR)

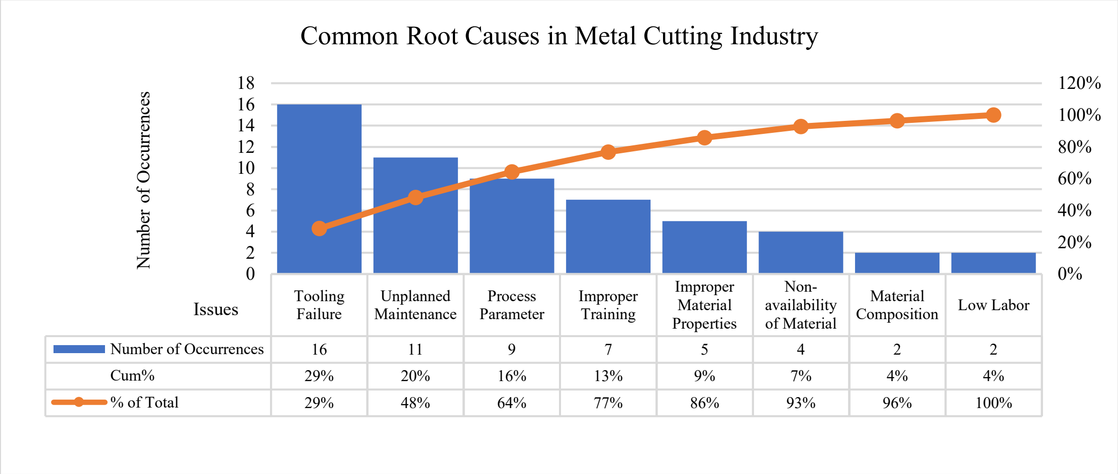
1. Introduction

Drilling operations is a metal cutting activity that makes up 25% of all machining processes and plays a critical role in structural steel production and fabrication (Black and Kohser 2012). In fact, drilling is done on structural steels such as plates, beams, and columns to connect them to other steel members. Drill holes are also normally drilled near supports to attach fasteners and connectors. In Grandspan Development Corporation, drilling is a key production activity and is used in all metal pieces processed by the company. Hence, many resources are focused on its drilling processes.

Manufacturing companies like Grandspan consistently monitor their production processes to ensure that operations are continuous and efficient, but there are several factors that can hinder a production line. One of these factors is time. Time is a critical variable in the manufacturing environment and is often used as a performance indicator in manufacturing processes due to its decisive effect on the flow of operations. For that reason, businesses value time not only to satisfy client demand timely but also to minimize costs associated with time. For instance, downtimes like machine breakdown can disrupt production schedules reducing productive capacity by 5 to 20% (Deloitte 2017) and can potentially cause failure to meet customer demands, resulting to revenue loss.

In the metal processing industry, coordination and management of time is crucial in achieving a holistic operation of procedures, machines, and labor. As such, Grandspan Development Corporation strives to fulfill its customer demands by planning compact schedules and allocating reasonable time for its production activities, especially its drilling activities. Therefore, studying the time of manufacturing processes is an important activity that can be used to identify issues and gaps, improve production efficiency, and set a standard to control performance.

Figure 1 is a pareto chart of common root causes in the metal cutting industry. In the study conducted by Tayal et al. (2021), the determined significant few issues (under 80%) are tooling failure, unplanned maintenance, process parameter, and improper training. These issues are needed to be properly and promptly addressed to mitigate losses and to ultimately avoid affecting efficiency and performance.



Issues	Tooling Failure	Unplanned Maintenance	Process Parameter	Improper Training	Improper Material Properties	Non-availability of Material	Material Composition	Low Labor
Number of Occurrences	16	11	9	7	5	4	2	2
Cum%	29%	20%	16%	13%	9%	7%	4%	4%
% of Total	29%	48%	64%	77%	86%	93%	96%	100%

Figure 1. Common Root Causes in Metal Cutting Industry

The presented issues in Figure 1 can result to speed loss, minor stoppages, and reject/ rework causing delays in schedule which is highly discouraged in the industry (Tayal et al. 2021). On the bright side, resolving these significant issues will also settle issues that are directly and indirectly related. Among the significant few issues, issues related to process parameter can be immediately rectified by setting a standardized set of parameters. It is necessary to address issues related to process parameters because these process parameter issues can cause delays in the cutting operations affecting the succeeding operations like furnishing and assembling. In a highly intensive production, delays from machine breakdowns may occur due to different reasons. One of these is incompatible drilling parameters. Entering incompatible drilling parameters onto the CNC machine gives rise to premature tool wear, chip control problems, low surface quality, low accuracy, and machine breakdowns (Popan et al. 2017). These repercussions, especially operation delays, can be avoided or reduced by having appropriate drilling parameters. This illustrates the importance of controlling drilling time through the modification of cutting parameters.

To meet project schedules and satisfy customer demands, time spent for drilling should be kept at a minimum while ensuring accuracy, considering machine capacity, and producing quality drill hole. In the case of Grandspan, its production department practices an outdated and pragmatic approach to their steel drilling and inspection. The engineers and staff predominantly utilize visual inspection of the process and residuals to assess if the drilling parameters, specifically the feed rate (FR) and cutting speed (CS), and drill diameter (DD), are optimal for the given piece. They follow the drilling parameters dictated by the American Society for Testing and Materials (ASTM) Handbook, a piece published by a third-party analyst. Grandspan's inspection routine lacks a data-driven method for its drilling processes. Hence, studying to optimize drill times and drilling parameters will aid the company set their own drilling standards and drive improvement efforts to contribute increase productivity.

1.1 Objectives

The primary objective that this study wishes to achieve is to determine the optimal drilling parameter sets, which are drilling speed (DS), feed rate (FR), and drill diameter (DD), to achieve the least required drilling time. The datasets for these parameters will be supplied by the production department of Grandspan Development Corporation.

Furthermore, the study also aims to determine the optimal drilling operation in respect to the parameters of A572 Grade 50 Structural Steel to attain the maximum MRR. The secondary objectives that the study wishes to attain is to determine the parameters that significantly affects drill time and MRR. Another is to identify other possible areas of study, that the present paper failed to address due to the lack of measuring equipment and practicality in the industry.

2. Literature Review

2.1 Application of Taguchi Method for Parameter Optimization

Manufacturers these days use techniques to optimize processes, without the need for costly and time-consuming experimentation. Design of experiment (DOE) methods are widely used optimization techniques in the manufacturing process improvement (Suthar et al. 2021). For instance, a study by (Patel 2015) used both full factorial method and Taguchi method DOEs to investigate the MRR and compare the results from both methods. However, compared to a full factorial method, Taguchi-based DOE is considered as one of the most powerful and attractive DOE methods for analyzing experiments as it allows a simple, efficient, and systematic method in addressing steel machining issues and optimizing a process by improving both performance and reducing cost (Yuvaraj et al. 2012). Genichi Taguchi developed a framework for statistics-based design of experiments to be able to adapt specific requirements of an engineering design (Kıvak et al. 2012). Taguchi's approach in DOE is effective for when one or more factors are suspected to have influence on the performance of a product or process (Samleti and Potdar 2018).

A Taguchi-based orthogonal array design is utilized for finding optimal settings of the input, or control, variables to make a product or process robust to uncontrollable factors (Sumesh and Shibu 2016). Uncontrollable factors are also called noise factors, which are difficult or expensive to control during manufacturing (Minitab 2017). Moreover, the Taguchi method investigates a smaller number of experiments and aims to reduce sensitivity of engineering designs to uncontrollable factors, it introduced the use of loss function or the signal-to-noise (S/N) ratio to evaluate the improvement quality through variability reduction and improvement of measurement.

Furthermore, the S/N ratio to be used depends on the quality characteristics of the process to be optimized. There are three categories of S/N ratios, namely: smaller-the-better, larger-the-better, and nominal-is-best. Studies by Patel et al. (2021) and Kıvak et al. (2012) utilized the larger-the-better criteria in evaluating material removal rate (MRR), and smaller-the-better for cycle time (Ramesh 2015).

A study by Samleti and Potdar (2018) also implemented the Taguchi DOE to identify the optimal levels of drilling parameters. The study conducted an L9 Taguchi orthogonal design with MRR and surface roughness as its output variables, applying ANOVA on the S/N ratios of the outputs. The study applied S/N ratio to consider the mean (signal) and variability (noise) of the experimental result in determining the control factors that reduce variability. ANOVA was then used to analyze the effects of the drilling parameters on the outputs and to determine the optimal parameter sets. The study concluded that FR and DD had significant effect on maximizing MRR. It was observed that DD followed by FR had the most contributory effect for obtaining the optimum MRR. Ramesh (2015) utilized a Taguchi methodology to minimize the cycle time in machining of stainless steel, with spindle speed, feed rate and depth of cut as parameters and used a smaller-the-better S/N to analyze the experimental results. ANOVA results show that spindle speed and feed rate have a significant effect on the cycle time, and in minimizing cycle time, spindle speed had the most contribution percentage of 83.69%.

Similarly, Sumesh and Shibu studied the optimal values of the input parameters in the drilling of cast iron that and used the Taguchi method with L9 orthogonal design accompanied by ANOVA. The experiment had SR as its output parameter. ANOVA is utilized to study the effects of the input parameters on the output variables. They also utilized the S/N ratio which is defined in the study as the combined performance measurement of the mean and variance of the response or experimental result. The study used a smaller-the-better S/N for surface roughness and larger-the-better for MRR.

Patel et al. (2021) conducted a study on IS 10,343 Gr. 2A carbon steel with the use of Taguchi method and ANOVA to determine the optimal drilling parameters and significant effect on the response. The carbon steel is produced as a gear shifter used in gearbox assembly. The company produces around 7500 to 8000 gear shifters in a month by drilling process. The study aims to improve the quality of surface finish by examining the parameter through an experiment since the company experienced a problem with multiple product rejection. It is estimated that approximately 10.88% of the gear shifters were rejected due to high surface roughness. With the use of design of experiments such as response surface methodology (RSM) and Taguchi method along with statistical techniques like ANOVA and regression, the optimal machining parameters were found, and this resulted into a 3.0006% reduction in the rejection of the gear shifter and increase in overall productivity after parametric optimization. It was concluded that Taguchi's orthogonal design method is a completely suitable and efficient method to analyze the problem and optimize the cutting for improved productivity.

2.2 Analysis of Performance of Drilling Operations

Various studies investigated the impact of parametric optimization of different machining processes and materials on certain response variables, using Taguchi techniques such as Orthogonal Array and Signal-to-Noise Ratio (S/N) paired with Analysis of Variance (ANOVA). Material removal rate (MRR) is the primary response variable while considering productivity during machine operation. The primary objective of optimization analysis during the drilling operation is to optimize the input parameters. Optimization is to improve the MRR and reduce the surface roughness value (Sumesh and Shibu 2016). In this study, drilling parameters are optimized for multiple performances to achieve a good quality of holes in drilling. It is found that feed rate is directly proportional to MRR.

Similarly, a study conducted by Abdullah et al. (2016) conducted several drilling experiments on AISI 1015 Carbon steel using the L9 orthogonal array on a conventional drilling machine with control variables such as feed rate, spindle speed, and drill diameter. The study concluded that drill diameter is the most important effect with 64.08% and 76.12% on the MRR and surface roughness. Results show that an increase in tool diameter leads to an increase in MRR.

Furthermore, Manickam and Parthipan (2020) conducted various drilling process parameters to cut AISI SS317L stainless steel based on given input parameters of speed, feed rate, and selected drill tool, the paper mainly focused on the MRR and surface roughness as its output variables. The control factors utilized for the orthogonal array are allocated to every section. The optimum value of different input parameters to ensure that the specified confines for MRR is speed = 800 rpm, feed rate = 0.012 mm/rev, and drill tool = 8mm.

Drill time is a tool engaged from the beginning of chip production to the end for uninterrupted machining. A study conducted by Tolouie-Rad and Aamir (2021), states that proper selection of machine tools and equipment, cutting tools, and parameters are needed in reducing the drill time which is one of the most important factors in achieving greater productivity. Likewise, Ramesh (2015) conducted an experimental study to optimize cutting parameters during the machining of SS304 for simultaneous minimization and maximization of Surface roughness (Ra), machining time, and geometrical tolerance of stainless steel. He stated that it is essential to select the best combination values of process parameters to minimize as well as maximize the responses. An orthogonal array, signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) were employed to analyze the effects of control variables such as depth of cut, feed rate, and cutting speed on the response variables. The experiments utilized an L9 orthogonal array with each experiment performed under different conditions of the depth of cut, feed rate, and cutting speed. Optimal values of cutting parameters were identified to minimize cycle time and surface roughness during the machining process. The most significant factor in cycle time is spindle speed, followed by feed rate and depth of cut. The most optimal results were found when spindle speed = 500 rpm, feed rate = 155 mm, and depth of cut = 0.35mm. Higher spindle speed, feed rate, and depth of cut lead to minimum cycle time.

3. Methods

3.1 Experimentation

3.1.1 Work Material Properties

The work material used in the study is an ASTM A572 Grade 50 Plate 22 or Steel A572 with a yield strength of 50 ksi and width of 22 mm. ASTM A572 is a high-strength low-alloy (HSLA) steel, which is steel designed to bear more weight. A572 is lighter compared to other steel grades with similar compositions (Leeco Steel 2019). Hence, ASTM A572 is mostly used for structural foundation or “bones and muscles” to construct the form and shape of structures such as buildings, bridges, and other structures (George Washington University 2022). Structural Steel A572’s chemical composition is as follows: Carbon at 0.23%, Manganese at 1.35%, Phosphorus at 0.03%, Sulfur at 0.03%, and Silicon at 0.15 to 0.40% (Leeco Steel 2019).

3.1.2 Machine and Tool Properties

Grandspan Development Corporation has several machines involved in their drilling operations. One of their drilling machines is the CNC FSD-1020 which will be used in this study. According to Asia Machine Group Co., LTD, this standalone unit is one of the popular hydraulic drilling machines designed to be compact for steel structure fabrication and is widely used in both small and large engineering and manufacturing companies. Figure 2 shows the drilling machine, drilling during operation, and machine controls.

Figure 2. CNC FSD-1020 Drilling Machine

This machine is highly capable of changing drill bits of different diameters, cutting speed, and feed rate in between drilling operations. Since this machine is a computer numerical control (CNC) equipment, CNC FSD-1020 is programmed by an engineer on site, and the engineer is tasked to control and input the desired parameters and pick which drill bit to be used for the required process. The machine has a maximum drilling diameter of 50mm and a maximum drilling thickness of 100mm, allowing users to possibly raise efficiency by stacking and drilling multiple workpieces at once without compromising speed or accuracy (Asia Machine Group Co., LTD). Table 1 shows the Technical Specifications of the CNC FSD-1020.

Table 1. CNC FSD-1020 Technical Specifications

Technical Specification	Description
Model	FSD 1020
Working Area WxL (mm)	1000x2000
Drilling Thickness	100mm (stackable)
Drilling Capacity (mm)	14-100
Variable RPM	100-600
Motor Horsepower	7.5HP

The type of drill bit used for the CNC FSD-1020 is a low-carbon twist drill. This type of drill bit is best used with the machine according to the production engineer at Grandspan Development Corporation. The twist drill is one of the most widely used drill bit type as this is known to cut anything from steel to concrete. According to Rockler, twist drills are also low cost and offer the widest selection of sizes.

3.1.3 Machining Parameters

As the subject of the study, the accustomed machining parameters and setting by Grandspan Development Corporation for drilling, which are cutting speed, feed rate, and drill bit diameter, will be adapted in this study as the control parameters to be analyzed and optimized. Sumesh and Shibu (2016), Manickam and Pathipan (2020), and Samleti and Potdar (2021) tested the same drilling parameters for improvement. Table 2 shows the levels of the drilling parameters to be considered for optimization.

Table 2. Drilling Tool Parameters and Levels

	Level 1	**Level 2**	**Level 3**
Cutting Speed (rpm)	380	390	400
Feed Rate (mm/rev)	0.3	1.3	1.5
Diameter (mm)	22	24	25

The output parameter to be considered to measure and analyze the quality and productivity of the optimized input parameters applied to the ASTM A572 workpiece is the MRR. MRR refers to the amount of material, or metal in this case, removed per unit time during the drilling process. It is considered as a primary indicator for productivity of the drilling operation (Manickam and Pathipan 2020). The formula to compute for the MRR based on Black and Kohser (2012) is shown below and will be followed for this study.

$$MRR = \frac{\pi}{4} \times D^2 \times FR \times CS$$

Equation 1. Material Removal Rate Formula

where: MRR = material removal rate
D = drill diameter, mm
FR = feed rate, mm/rev
CS = cutting speed, rpm

3.2 Taguchi-based Design of Experiments

This study will employ a Taguchi-based Design of Experiments which is has been widely used in quality improvement of various process designs and product designs because it is utilized in finding the optimal setting of the input parameters (control factors) to make the process robust to noise factors (Sumesh and Shibu 2016) — parameters that are difficult or expensive to control during the manufacturing operation. Hence, to reduce sensitivity of engineering designs to uncontrollable factors, the signal-to-noise ratio (S/N ratio) is introduced in Taguchi method to consider the mean and variability of the response variable (output variable) at each setting of parameters in the orthogonal array (Kıvak et al. 2012).

The Taguchi-based Design of Experiments will also be accompanied by Analysis of Variance (ANOVA) to analyze the effect of the three input parameters (independent variables) on the dependent variable and to test which among the independent variables has a significant effect on the dependent variable. Stat-Ease was used to form the array and to generate the statistical results (i.e. ANOVA and numerical optimization) from the experimental results. Minitab was used to generate the interaction plot and main effects plot.

3.2.1 Signal-to-Noise Ratio (S/N Ratio)

The use of signal-to-noise ratio allows to identify control factor setting that minimizes the variability caused by noise factors. The S/N ratio to be used depends on the quality characteristics of the process to be optimized. The following are the three S/N ratios along with their respective formula:

- **Smaller-the-better:** S/N = $-10\log_{10}(mean\ square\ of\ the\ response)$

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{n=1}^{n} y_i^2\right)$$

Equation 2. S/N Ratio for Smaller-the-better

- **Larger-the-better:** S/N = $-10\log_{10}(mean\ square\ of\ the\ inverse\ of\ the\ response)$

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{n=1}^{n} \frac{1}{y_i^2}\right)$$

Equation 3. S/N Ratio for Larger-the-better

- **Nominal-is-best:** S/N = $-10\log_{10}(the\ square\ of\ the\ mean\ divided\ by\ the\ variance)$

$$S/N = 10\,log_{10}\left(\frac{y^2}{s^2}\right)$$

Equation 4. S/N Ratio for Nominal-is-best

where: n = number of measurements in trial/row; hence, n = 1, 2, …, 9
y_i is the i^{th} measured value in a run/ row; n = 1, 2, …, 27

In this study, the Taguchi method is utilized to analyze the result of response of machining parameters. The S/N ratios for MRR are calculated based on the larger-the-better criteria (Kıvak et al. 2012); and drill time based on smaller-the-better criteria (Ramesh 2015).

3.2.2 Orthogonal Design

With the input parameters given in Table 2, the study will have an L_9 orthogonal array. The orthogonal array of the experiment tabulated which is shown below.

Table 3. Orthogonal Array of the Taguchi-based Design of Experiments

Experiment No.	Cutting Speed (rpm)	Feed Rate (mm/rev)	Diameter (mm)
1	380	0.3	22
2	380	1.3	24
3	380	1.8	25
4	390	0.3	24
5	390	1.3	25
6	390	1.8	22
7	400	0.3	25
8	400	1.3	22
9	400	1.8	24

4. Data Collection

The experiments were conducted with their respective factors and levels as tabulated in Table 3. Each of the experiment were conducted with two trials to account for the variations that may occur caused by noise factors. The drill time was gathered using a stopwatch, and the MRR was determined using Equation 1.

5. Results and Discussion

5.1 Statistical Test for Model Validation

The Design Power was determined using the Optimal (Custom) Design in Stat-Ease. The power for the parameters were generated as shown in Table 4. A, B and C signify Cutting Speed, Feed Rate, and Diameter, respectively. A signal-to-noise ratio was automatically set at 10dB by the software. Statistical power should be approximately 80% or greater to detect true effects (Bhandari 2021). The powers of all factors are greater than 80%; hence, this model is acceptable and can be used to determine the effects of the parameters.

Table 4. Design Power

Name	Units	Delta (Signal)	Sigma (noise)	Signal/Noise	Power for A	Power for B	Power for C
Drill Time	s	20	2	10	91.1%	91.1%	91.1%
MRR	mm^3/min	300,000	30,000	10	91.1%	91.1%	91.1%

5.2 Experimental Results

Table 5 shows the drill times and MRR obtained from the experiments.

Table 5. Experimental Results for Drilling

Experiment No.	Cutting Speed (rpm)	Feed Rate (mm/rev)	Diameter (mm)	Drill Times (s)	MRR (mm^3/min)
1	380	0.3	22	25.95	43,335.13
2	380	1.3	24	30.52	223,480.34
3	380	1.8	25	21.39	335,757.71

4	390	0.3	24	33.44	52,929.55
5	390	1.3	25	21.97	248,873.04
6	390	1.8	22	20.50	266,853.16
7	400	0.3	25	25.39	58,904.86
8	400	1.3	22	24.49	197,669.01
9	400	1.8	24	29.33	325,720.33

5.3 Taguchi Analysis for Drill Time

Analysis of Variance (ANOVA). Analysis of variance is a commonly used statistical tool to determine significant parameters on the response and to measure the effects of the parameters. The ANOVA result for drill time is illustrated in Table 6. The percentage contribution of each process parameter was also computed and shown at the table.

According to Table 6, diameter and feed rate have P-values lower than 0.05. Hence, diameter and feed rate have significant effect on drill time with 75.33% and 21.24% percent contribution, respectively. There is a direct relationship between diameter and feed rate and drill time. Increasing diameter and feed rate will also increase drill time. In a manufacturing setting, drill diameter is the first to be determined, and the feed rate and cutting speed will depend on the chosen drill diameter (Oberg et.al. 2020). Furthermore, the Model F-value of 34.70 implies the model is significant. There is only a 2.83% chance that an F-value this large could occur due to noise.

Table 6. Analysis of Variance for Drill Time

Source	SS	df	Mean Square	F-value	p-value	
Model	155.66	6	25.94	34.70	0.0283	significant
Cutting Speed	1.84	2	0.9175	1.23	0.4490	1.17%
Feed Rate	30.88	2	15.44	20.65	0.0462	19.65%
Diameter	122.95	2	61.47	82.22	0.0120	78.24%
Residual	1.50	2	0.7477			
Cor Total	157.15	8				

Interaction Plot. The interaction plot displays the interactions between factors. The interaction plot for drill time is shown in Figure 3. It can be seen from the plot that there is interaction between cutting speed and feed rate, and the least drill time was obtained at 390 rpm and 1.8 mm/rev. Likewise, cutting speed and diameter interacts with each other, and a setting of 390 rpm and 22 mm has the least drill time. Meanwhile, there is no interaction between feed rate and diameter, but minimum drill time is observed at 22 mm and 1.8 mm/rev.

Main Effects Plot. The main effects plots illustrate how the cutting parameters affect the response, in this case, the S/N ratio of drill time. A main effect exists when the levels of a factor have different effects on the response factor. Figure 4 shows the main effects plot for drill time. When a factor has a large difference in the vertical position of the plotted points, its magnitude of main effect is also large, for instance, the diameter parameter in Figure 4. The main effects plot can also be utilized to determine the optimal set of parameters. Based on Figure 4, the cutting speed of 390 rpm, feed rate of 1.8 mm/rev, and 25 mm are the optimal combination to achieve low drill time.

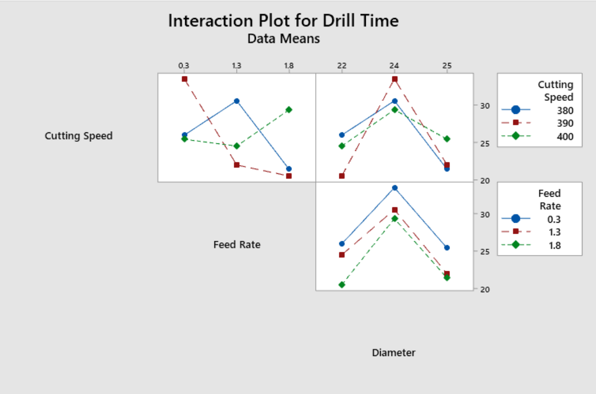


Figure 3. Interaction Plot for Drill Time

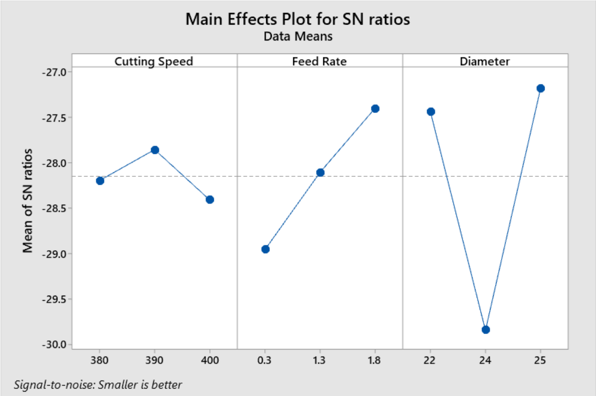


Figure 4. Main Effects Plot for Drill Time

5.4 Taguchi Analysis for Material Removal Rate (MRR)

Analysis of Variance (ANOVA). The ANOVA result for MRR is illustrated in Table 7. The percentage contribution of each process parameter was also computed and shown at the table.

According to Table 7, feed rate has a P-value less than 0.05. Hence, feed rate is determined to have a significant effect on MRR. Feed rate has the most percentage contribution of 96.09% followed by diameter and cutting speed. This result suggests that adjusting to increase feed rate will majorly increase MRR. Feed rate's high influence on MRR can be explained by its influence on the material. Feed rate refers to the rotating motion of the tool with contact on the material. Feed rates are usually used in drilling troubleshooting, and incompatible combination of feed rate and cutting speed can immediately affect MRR (Black and Kohser 2012). For instance, feed rate too high or too low in relation to cutting speed can affect the quality of the drilled hole or the MRR. Moreover, the Model F-value of 45.13 implies the model is significant. There is only a 2.18% chance that an F-value this large could occur due to noise.

Table 7. Analysis of Variance for MRR

Source	SS	df	Mean Square	F-value	p-value	
Model	1.067E+11	6	1.778E+10	45.13	0.0218	significant
Cutting Speed	1.942E+08	2	9.709E+07	0.2464	0.8023	0.18%
Feed Rate	1.033E+11	2	5.164E+10	131.06	0.0076	96.09%
Drill Diameter	3.223E+09	2	1.612E+09	4.09	0.1965	3.00%
Residual	7.881E+08	2	3.940E+08			
Cor Total	1.075E+11	8				

Interaction Plot. The interaction plot for MRR is shown in Figure 5. It can be seen from the plot that there is interaction between cutting speed and diameter, and the maximum MRR was at 380 rpm and 25 mm. Likewise, cutting speed and feed rate interacts with each other, and a setting of 380 rpm at 1.8 mm/rev maximized the MRR. Meanwhile, there is no interaction between feed rate and diameter, but maximum MRR is observed at 25 mm and 1.8 mm/rev. Since no interaction is seen between feed rate and diameter, there is a linear relationship. Increasing the diameter will also require increasing the feed rate.

Main Effects Plot. The main effects plots illustrate how the cutting parameters affect the response, in this case, the S/N ratio of MRR. A main effect exists when the levels of a factor have different effects on the response factor. As shown in Figure 6, feed rate has a large difference in the vertical position of its plotted points and has a steep slope; thus, this result is consistent with the ANOVA analysis of MRR wherein feed rate has a large main effect. Diameter and cutting speed also have a main effect on MRR, but it can be inferred that cutting speed has minimal effect since it has a near-horizontal plot. Furthermore, the optimal set that has maximum MRR is the 400 rpm, 1.8 mm/rev, and 25 mm.

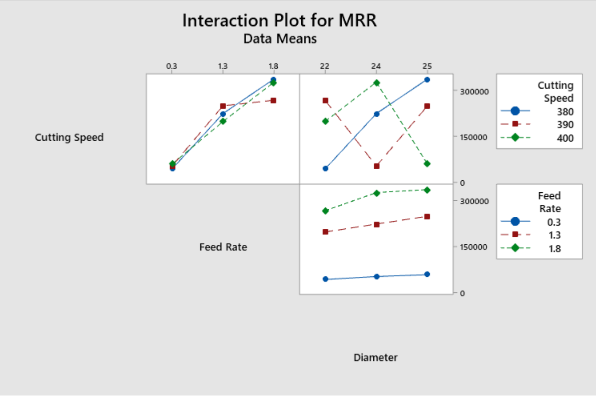


Figure 5. Interaction Plot for MRR

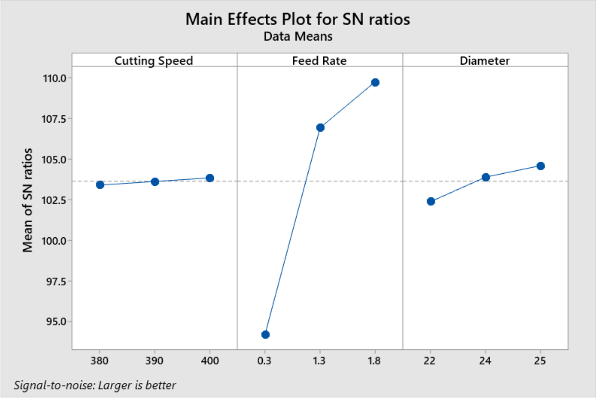


Figure 6. Main Effects Plot for MRR

5.5 Numerical Optimization

The optimal combinations for each drill diameter were generated since drill diameter is the first parameter to be decided in the manufacturing setting. Two optimal combinations with the most desirability from each drill diameter were taken and presented in Tables 8, 9 and 10. For drill diameter of 22mm, a cutting speed of 390 rpm with 1.8 mm/rev is best to achieve the minimum drill time and maximum MRR, but a cutting speed of 380 rpm with 1.8 mm/rev can also be used.

Table 8. Optimal Combinations for Drill Diameter 22mm

Number	Cutting Speed	Feed Rate	Drill Diameter	DT	MRR	Desirability
1	390	1.8	22	20.917	278609.610	0.894
2	380	1.8	22	21.567	289915.420	0.885

For drill diameter 24mm, cutting speeds 390 rpm with 1.8 mm/rev and 380 rpm with 1.8 mm/rev are appropriate to attain the optimal drill time and MRR. These settings are similar with the optimal combinations with drill diameter 22mm.

Table 9. Optimal Combinations for Drill Diameter 24mm

Number	Cutting Speed	Feed Rate	Drill Diameter	DT	MRR	Desirability
1	390	1.8	24	28.367	310033.917	0.563
2	380	1.8	24	29.017	321339.727	0.530

For drill diameter 25mm, cutting speed of 380 rpm with 1.8 mm/rev is more suitable to reach the optimal drilling time and MRR. The difference in desirability between combinations 1 and 2 are minimal with a value of 0.002. There is also minimal difference in drill time. Hence, combination 2 can also be used.

Table 10. Optimal Combinations for Drill Diameter 25mm

Number	Cutting Speed	Feed Rate	Drill Diameter	DT	MRR	Desirability
1	380	1.8	25	20.837	335141.523	0.984
2	390	1.8	25	20.187	323835.713	0.982

6. Conclusion

As taken from the results of the Statistical Analysis program, the most optimum feed rate, regardless of drill diameter, is 1.8 mm/rev. The optimal set of parameters for drill diameter 22 mm excluding feed rate are: 390 rpm for cutting speed, 20.917s for drill time, and 278609.610 mm^3/min for MRR. The second would be: 380 rpm for cutting speed, 21.567s for drill time, and 289915.420 mm^3/min for MRR.

Meanwhile, the optimum parameter set for drill diameter 24 mm with the highest desirability are: 390 rpm for cutting speed, 28.367s for drill time, and 310033.917 mm^3/min for MRR. The second would be: 380 rpm for cutting speed, 29.017s for drill time, and 321339.727 mm^3/min for MRR.

Lastly, the most optimal parameter sets for drill diameter 25 mm are: 380 rpm for cutting speed, 20.837s for drill time, and 335141.523 mm^3/min for MRR. The second would be: 390 rpm for cutting speed, 20.187s for drill time, and 323835.713 mm^3/min for MRR.

The most significant factor affecting drill time was found out to be feed rate and drill diameter while the most significant factor affecting MRR was feed rate alone.

The proponents of this research highly recommend that the engineers at Grandspan Development Corporation utilize the optimal parameter sets determined by this paper to reduce their overall drill time and to increase their overall productivity in the long run.

Since the proponents are currently unable to test their derived parameters, applying the optimized parameters stated in this paper will require the support of preventive maintenance to ensure that the machine can adjust to the parametric demands and check if the pairs are feasible by reviewing Grandspan’s historical records as to avoid any possible incidents. Checking the feasibility of the parameter combination is highly important during the application since infeasible combination might lead to a temporary machine breakdown which was witnessed during data gathering at Grandspan Development Corporation.

Reduced drill time due to the application of optimized parametric sets will also lead to higher capacity. Hence, during the initial application period of the new parameters, this study recommends that engineers at Grandspan review their capacity planning and make it more efficient with respect to the shorter drill time. The efficiency of capacity planning can be quantified by comparing historical production capacities of their unoptimized drilling times to the current production capacity of the new drilling parametric sets. When analyzing the new and historical data, the engineers may find patterns and redesign their capacity planning in accordance with the new production capacity data.

To reinstate, reduced cycle times can increase productivity, customer satisfaction, innovativeness, and possible profitability (Butler 2018). However, the implementation of the optimized parameter sets in the programming of the CNC FSD-1020 drilling machine must be done carefully and allow the engineers to adjust around utilizing it with the researchers recommending they use any of the methods.

The current study applies statistical analysis in investigating the drilling parameters of the machine, which offers the organization an idea to integrate the use of statistical tools and analysis to drive improvements in workplace performance and be attuned to current industry trends and innovations to manage their pragmatic approach in their drilling operations and inspections.

In general, findings from statistical analysis provides quantitative information that support the decision-making activities of the business. It gives the opportunity to examine the machine's efficacy to improve performance and determine factors that can help or harm the efficiency of the processes as well as to recognize variables that may not be apparent and can only be obtained through investigation.

To generate future improvements, it is advised for Grandspan to utilize the outcome of this research study as a supporting data for activities such as approving proposed development programs and policies, budget allocation, and production capacity planning. For instance, in the future, the company may opt to propose programs or campaigns related to improving drilling processes and variables in the production department. The extracted sufficient and correct data from this research study can be used to justify the need for the approval of the proposal. The utilization of the result or any interpretation from this research would contribute to adding value and influence in rationalizing the budget allocation or the course of action of the project.

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