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Power Consumption Optimization for Sustainable Subtractive Manufacturing Operation

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Abstract

Subtractive manufacturing, especially traditional material removal processes, is considered one of the heavily power consumption operations. Integrating sustainability principles into the process engineering and technology in response to environmental challenges is highly demanded and the key to improve the manufacturing for energy consumption optimization. A wide array of research directions to address manufacturing sustainability; from environmentally friendly designs the operational conditions to optimizing the outcomes. This research emphasizes the need to integrate sustainability in manufacturing technology aspects. The approach of this research work focuses on experimentally test the impact of main operational conditions on power consumption in turning manufacturing processes. Four critical operational factors—rotational speed, feed rate, tool angle, and lubrication—are examined for their influence on process power consumption. The work used a lathe machine and a wireless three-phase clamp meter placed into the machine's motor to measure the voltage output along with tools and steel workpiece samples. Full factorial design of experimentation is applied to test and analyze the relationships between the factors and response function of power consumption. The results reveal significant effects for the main factors and the interactions as follows: rotational speed, and feed rate, lubrication, and rake tool angle. Increasing the rotational speed and applying oil to lubricate the cut zone during the process decrease operational power consumption supporting the hypothesis for the lubrication. Surprisingly, increasing the rotational speed decreases operational power consumption and increasing the rake tool angle increases the operational power consumption - not as expected. Interaction effects emphasize the additive and subtractive influences of the factors on operational power consumption. While the full factorial design of experimentation application allows for comprehensive factor effects analysis, it acknowledges limitations in the specific selected levels for machine rotational speed, tool feed rate, and the tool cutting angles. This research provides valuable insights into the impact of various operational conditions on electrical power consumption in material removal manufacturing processes. Main and interaction effects contribute to the knowledge in sustainability manufacturing and undergraduate independent research. The study paves the way for further investigations on optimal experimental conditions and effective teaching and mentoring strategies in the field of sustainable manufacturing engineering and technology.

Keywords

Power Consumption, Optimization, Subtractive Manufacturing, Operation

1. Introduction

Manufacturing operations; especially subtractive process, need to continuously optimize operational power consumption, to minimize environmental impact and avoid possible costs regulatory agencies may apply – several research have been published line out with that objective (Di et al, 2024), (Do Carmo et al., 2023) and (Lyer et al., 2024). Many of the suggested solutions for power are about the type of supplied energy including the array of renewable energy. While solutions like streamline manufacturing operations to consume less and set the process machining conditions to the required levels are less covered in the research body (Kibira et al., 2017), (Li et al., 2018), and (Mahanta et al., 20218). One of the challenges faced by all manufacturing operations worldwide is the process conditions set to consume less power and produce new environmentally efficient products. This research work studies the intersection of manufacturing sustainability in terms of operation power consumption and manufacturing process variables, and exploring the significance of incorporating sustainability principles. This approach provides with the skills and knowledge needed to reveal complexities and implications of modern manufacturing and foster prioritizing the environmental responsibility of manufacturing enterprises. Sustainability in manufacturing is usually investigated based on similar types of manufacturing processes and experiences to develop a standard condition for the process features and conditions (Na et al., 2022) and (Nyamekye et al., 2024).

Many methodologies are analyzing toward integrating sustainability principles into machining setup such as replacing the energy used by a renewable kind and lowering the CO2 emission and, are often not accounted power consumption sustainability (Raoufi et al., 2018). This paper presents an empirical-based approach to experimentally test manufacturing main operation conditions and analyze their impact on Operation Power Consumption (OPC) using a lathe machine, wireless clamp meter with set of hand probes, and machine tools to conduct turning process. Several researches focus on sustainable manufacturing frameworks (Venkatarao, 2021), (Yang et al., 2023), (Yuwono and Schwung, 2023), and (Zhang et al., 2024) only pointing out challenges and opportunities, in this research work, four main factors - rotational speed, feed rate, tool angle, and lubrication - have been selected with specific levels of variability to experimentally investigate their optimal setup that minimizes the OPC using Minitab visual algorithms for analysis and optimization. The paper is organized as follows: Sec. 1 is the introduction to provide a background on the topic and methodology used, Sec. 2 is the experimentation setup discussing the equipment and tools used to run the experimentation, the material and samples of the tests, and the manufacturing operation factor and full factorial design of the experimentation matrix. Section 3 results and analysis describing the application of the standard through three use factors and data results, and analyzes the data in terms of each factor effect and the regression-based optimization results. Section 4 discusses the results and finally, Sec. 5 concludes the research work with some insights for future work.

2. Experimentation Setups

This section covers the research experimentation setups and procedures for each run including operation factors and machine used, factors limit, material for the experiment samples, and experiments running matrix design. Main machining conditions are the variables used in this material removal manufacturing process that proposed to affecting the OPC. In this experimental research work, it has been assumed that changes in machine rotational speed X_1, cutting feed rate X_2, process lubrication X_3, and tool rake angle X_4 exhibit a statistically significant effect on the observed variations of Y_{OPC}. Specifically, it is anticipate that X_1 variation from the lower limits to the higher limits increase the OPC as the process will complete faster so the rotational speed is the main source that the motor is requiring more voltage for, X_2 variation from lowers to the higher increases the OPC as the contact area between the cutting tool and material sample will be increasing which elevate the temperatures as result of consuming the energy in the process, X_3 variation from without (NO) and within (YES) reduces the OPC and results from lowering the friction load between the tool and the contact surface of the workpiece from supplying the lubricant oil to the process, and X_4 variation from the lower to higher level reduces the OPC. A 13″ x 40″ engine lathe machine used in this work by MSC Industrial Supply Company along with right-hand carbide turning cutting tool. UEi DL 599 Wireless three-phase clamp meter

(600 A AC/DC, 9999 µF) is used to measure the voltage output from the machine main motor with two probes directly connect the lathe motor in backside of the machine. And then the voltage is taken prior to cutting process be done for each run to get voltage for no cutting and voltage recorded during the cutting process. Figure 1 show the experimentation setup used to test and collect the data. When the machine turned on to the set to the prescribed experiment run, then the cutting process began, and the OPC data collected.

Figure 1: The machining setup with UEi DL 599 Wireless three-phase clamp meter and tool cutting angle for the experimentation

A 1-inch circular 1018 carbon steel stock used to prepare 8 samples with 0.8″-inch length of cut at room temperature. Table (1) illustrates the experimentation factors with the measuring units and lowers and higher limits of each.

Table 1: Experimentation Factors Higher and Lower Limits Values

Factor (unit)	**Code**	**Min Value**	**Max Value**
Rotational Speed (rpm)	X_1	175	260
Feed Rate (in/min)	X_2	0.005	0.01
Lubrication (thread oil and air)	X_3	NO	YES
Tool Rake Angle (degrees)	X_4	0	30

Table 2 illustrates the design of experimentation matrix and collected results for each run of experimentation. The experimental setups designed using full factorial approach to test and analyze intricate nuances of the X_1, X_2, X_3, and X_4 -Y relationship, exploring potential contributions to the observed outcomes and providing insights into the context of X_1, X_2, X_3, and X_4 - Y interactions within the scope of the research objectives.

Table 2: Factors Design Matrix for Run and Experimentation Responses

Experiment #	X_1	X_2	X_3	X_4	$Y_{(OPC)}$
1	175	0.005	YES	0	5.1
2	175	0.005	YES	30	5.2
3	175	0.005	NO	0	5.1

4	175	0.005	NO	30	5.2
5	175	0.01	YES	0	5.0
6	175	0.01	YES	30	5.2
7	175	0.01	NO	0	5.2
8	175	0.01	NO	30	5.2
9	260	0.005	YES	0	4.9
10	260	0.005	YES	30	5.0
11	260	0.005	NO	0	5.0
12	260	0.005	NO	30	5.1
13	260	0.01	YES	0	5.0
14	260	0.01	YES	30	5.0
15	260	0.01	NO	0	5.1
16	260	0.01	NO	30	5.2

3. Results Analysis

The coded regression coefficient results indicate a significant main effect for the factors following the order of Factor X_1 (E = 0.057), Factor X_3 (E = 0.044), X_4 (E = - 0.044), and Factor X_2 (E = - 0.019). Additionally, there is a significant interaction effect between Factor X_1 and Factor X_2 (E = 0.019), between Factor X_1 and Factor X_3 (E = - 0.019), between Factor X_1 and Factor X_4 (E = - 0.007), between Factor X_2 and Factor X_3 (E = - 0.019), between Factor X_2 and Factor X_4 (E = - 0.007), and between Factor X_3 and Factor X_4 (E = 0.007). The significant main effects of X_1, X_3, X_4, and X_2 indicate that each factor individually influences the response variable, Y. Factor X_1, Factor X_3, Factor X_4, and Factor X_2 are impacting the OPC as response variable Y that is supported by the observed significant main effects. For X_1, the analysis shows a OPC decreased rate of 0.057 when changing the rotational speed of the machine from 175 rpm to 260 rpm which does not support the hypothesis as illustrated in Figure 2. For X_2, the analysis shows a OPC increased rate of 0.019 when changing the feed rate of the machine from 0.005 in/min to 0.01 in/min which supports the hypothesis as illustrated in Figure 2. For X_3, the analysis shows a OPC decreased rate of 0.044 when changing the machining from without oil to within oil which does support the hypothesis as illustrated in Figure 2. For X_4, the analysis shows a OPC increased rate of 0.044 when changing the rake cutting angle of the tool from 0.0^o to 30.0^o which does not support the hypothesis as illustrated in Figure 2.

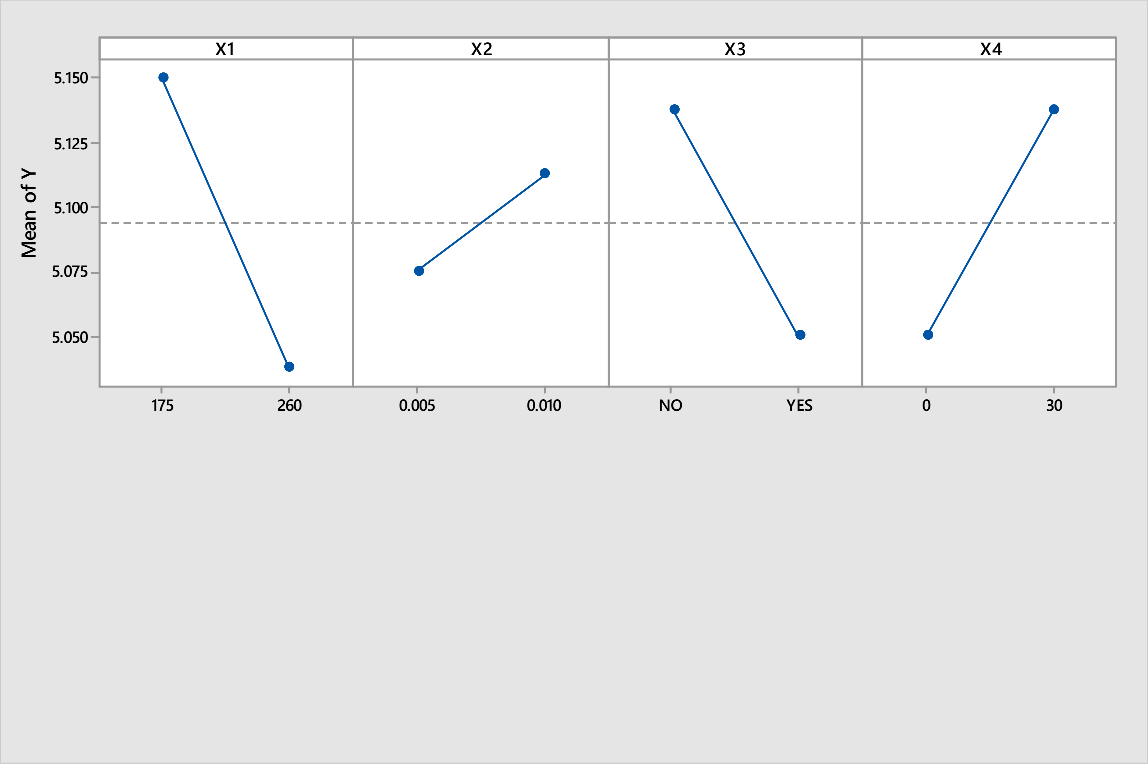

Figure 2: The main effects plot of rotational speed (X_1), feed rate (X_2), lubrication (X_3), and rake tool angle (X_4)

The interaction effect between X_1 X_2, X_1 X_3, X_1 X_4, and X_3 X_4 shows that the combined influence of these factors is subtractive and, X_2 X_3 and X_2 X_4 the combined influence is additive. Further emphasizing the interaction effect analysis of a set of combined influence factors shows the following: X_1 X_3 does not significantly influence the OPC at both the lower limit of rotational speed, X_1= 175 rpm, and the higher limit at X_1 = 260 rpm and at both the lower limit of the lubrication X_3 from without oil (NO) to within oil (YES), X_1 X_4 does not significantly influence the OPC at both the lower limit of rotational speed, X_1= 175 rpm, and the higher limit at X_1 = 260 rpm, X_2 X_4 does not significantly influence the OPC at both the lower limit of feed rate, X_2= 0.005 in/min, and the higher limit at X_2 = 0.01 in/min and both the lower limit of rake tool angle, X_4= 0.0°, and the higher limit at X_4 = 30.0°, X_3 X_4 does not significantly influence the OPC at both the lower limit of the lubrication X_3 from without oil (NO) to within oil (YES) and both the lower limit of rake tool angle, X_4= 0.0°, and the higher limit at X_4 = 30.0°, and X_1 X_4 does not significantly influence the OPC at both the lower limit of rake tool angle, X_4= 0.0°, and the higher limit at X_4 = 30.0° as illustrated in Figure 3. On the other side, a set of combined influence factors shows significantly influence the OPC as follows: X_1 X_2 results in higher decreasing influence of E = 0.019 when heigh rotational speed X_1 = 260 rpm at the higher limit of feed rate at X_2 = 0.01 in/min while lower decrease of E = 0.005 observed and at both limits of X_1 are indifferent at X_2 = 0.005 in/min, X_2 X_3 results in increase influence of E = 0.019 at the lubricant without oil (NO) at the lower limit of feed rate at X_2 = 0.005 in/min while almost results in no change in the influence at higher limits of X2 when change lubricant from without oil (NO) to within oil (YES), and X_2 X_1 results in increase influence at higher limit X_2 = 0.01 in/min when change rotational speed from X_1 = 175 rpm to X_1 = 260 rpm while almost results in no change in the influence at lower limit of X_2 when change the rotational speed as illustrated in Figure 3.At the lower limit of feed rate X_2 = 0.005 in/min, changing the lubrication X_3 from without oil (NO) to within oil (YES) shows less decrease effect rate than higher limit of X_2 = 0.01 in/min on the OPC, and becomes indifferent when the lubricant within oil (YES) for both lower and higher feed rates have been observed as illustrated in Figure 3. However, the observed interaction effects analysis provides a unique contribution to the literature, emphasizing the importance of exploring factor interactions in empirical research projects.

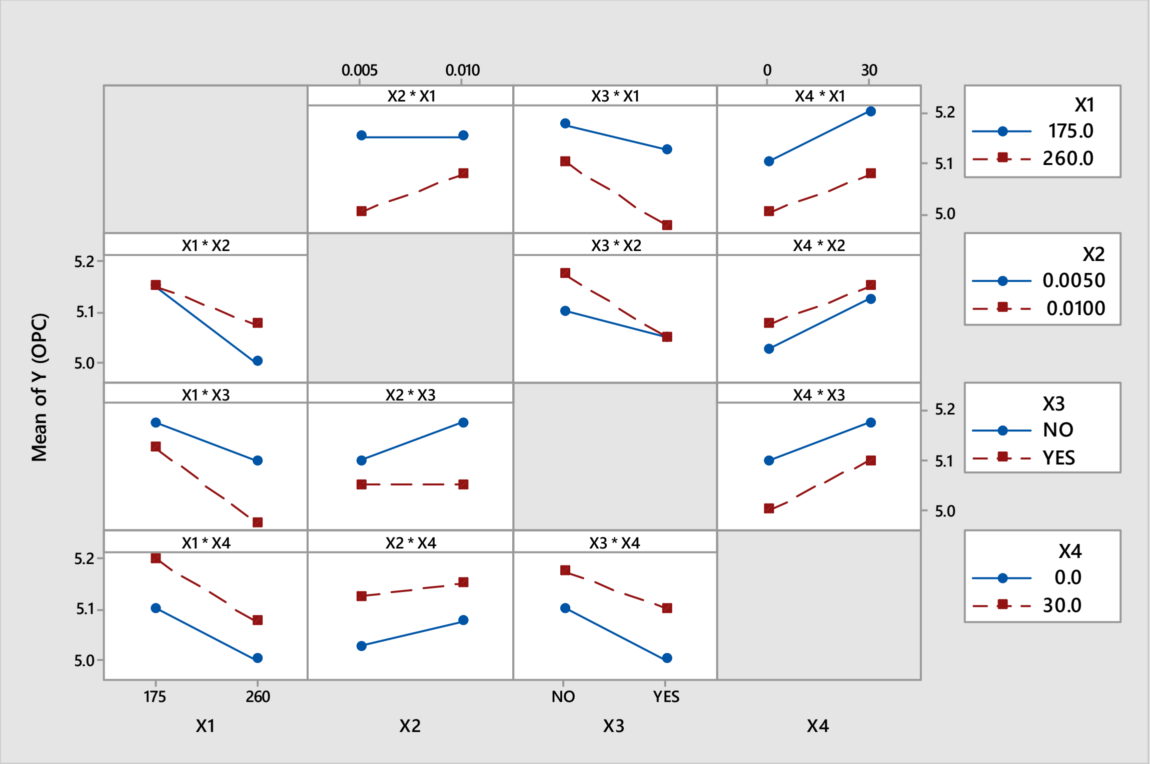

Figure 3: The interaction effects plot of rotational speed and feed rate (X_1 X_2), rotational speed and feed rate (X_1 X_2), rotational speed and lubrication (X_1 X_3), rotational speed and rake tool angle (X_1 X_4).

The results support the assumption of using the oil (YES) and (NO) lubrication X_3; as non-numerical factor in the turning process, has reduced the OPC and it has been intentionally added to the process to lower the cutting force load which is consequently lowering the process power consumption based on equation (1). Then it is now experimentally approved that adding lubrications to the material removal processes will make significant positive impact not only on cutting force but also on the process's OPC which is also saving process energy consumption. These are both definitely manufacturing sustainability features and adding lubricant oil into the process is highly recommended based on the project exploration.

$$P\left(in.\frac{lb}{min}\right) or\ (Watt) = F(lb) or\ (N) v \left(\frac{in}{min}\right) or \left(\frac{m}{sec}\right) \sim F\ \pi\ D(in) or\ (m) N(r.p.m)\ldots (1)$$

Where P is the cutting power, F is the main cutting force, v is the cutting surface velocity, D is the average dimensions of before and after diameters of machining rounded bar, and N is the machine rotational speed. Therefore, these set of experimental facts leave the OPC optimization formula to be changed relative to two factors X_1 and X_2 as illustrated in the regression equation (2). The optimization objective is to minimize the CO_2 in the workplace as much as zero difference between before and after work at the ambient CO_2 of 529.5 ppm before running the material removal processes.

$$Y = 5.01 + 0.057X_1 - 0.019\ X_2 + 0.044\ X_3 - 0.044\ X_4 + 0.019\ X_1X_2 - 0.019\ X_2X_3 \cdots (2)$$

Figure 4 shows a counter plot for the two predictor variables X_1 and X_2 changing with relative to Y using Minitab graphical algorithm to visually and numerically trace the lowest possible areas of OPC within the effective ranges of X_1 and X_2 variability. One blue area is observed at the top left corner with a range of 5.00 volte to 5.05 volte of OPC. The following are the optimal suggested values of rotational speed of the machining X_1, and feed rates X_2 measured at four corners of each area that will provide the minimal values range between 5.00 volte – 5.05 volte of OPC: (0.005 in/min, 231 rpm), (0.008 in/min, 260 rpm), (0.005 in/min, 260 rpm), and (0.005 in/min, 250 rpm).

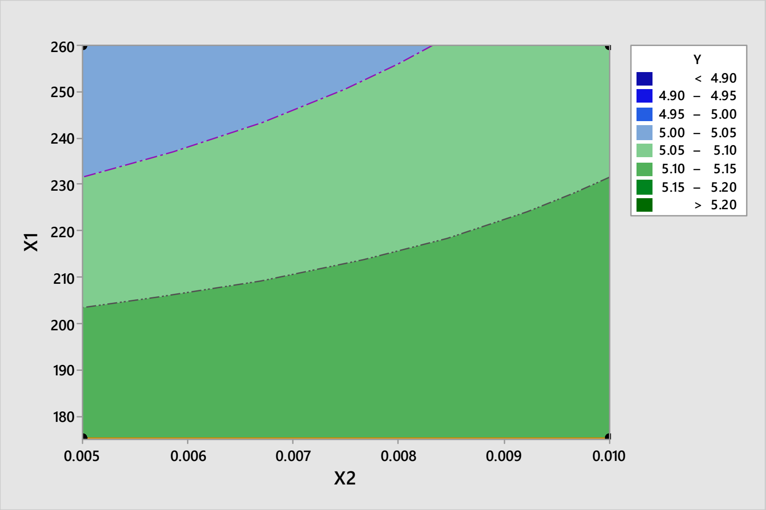

Figure 4: The main effects response plot of rotational speed (X_1) and feed rate (X_2)

Figure 5 is the three-dimensional representation of surface response methodology by Minitab to verify the that the two mammal areas for the possible optimizable solutions are located at the ends of the possible solution to equation (2). Darkest surface represents the optimal solutions pool of minimal OPC(Y) relative to the rotation speed (X_1) and feed rate (X_2).

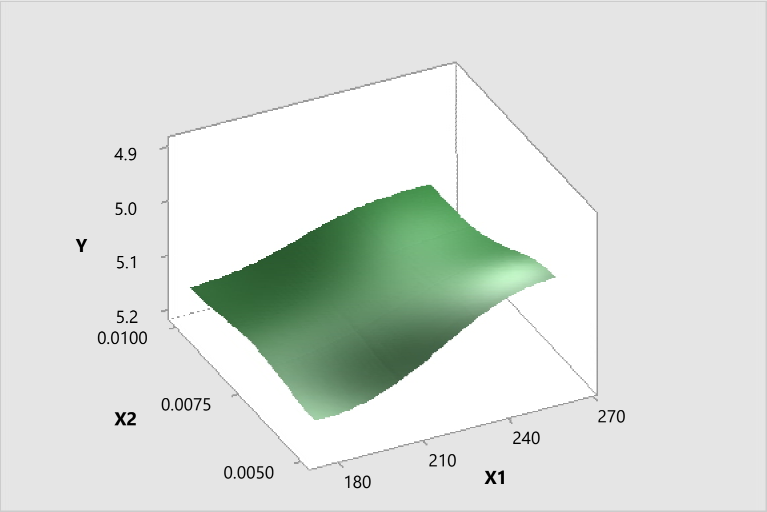

Figure 5: The main effects plot of rotational speed (X_1), feed rate (X_2)

Figure 6 shows a counter plot for the two predictor variables X_1 and X_4 changing with relative to Y using Minitab graphical algorithm to visually and numerically trace the lowest possible areas of OPC within the effective ranges of X_1 and X_4 variability. One blue area is observed at the top left corner with a range of 5.00 volte to 5.05 volte of OPC. The following are the optimal suggested values of rotational speed of the machining X_1, and feed rates X_4 measured at four corners of each area that will provide the minimal values range between 5.00 volte – 5.05 volte of OPC: (0.08°, 219 rpm), (20°, 260 rpm), (0.2°, 260 rpm), and (8°, 237 rpm).

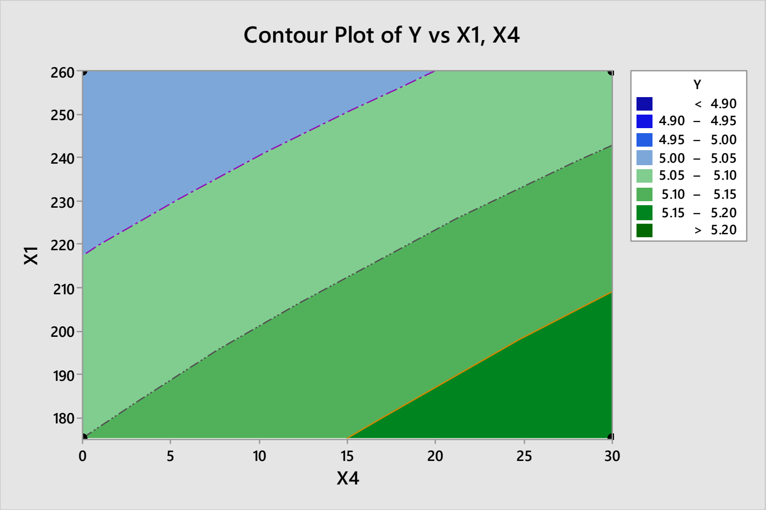

Figure 6: The main effects response plot of rotational speed (X_1) and feed rate (X_4)

Figure 7 is the three-dimensional representation of surface response methodology by Minitab to verify the that the two mammal areas for the possible optimizable solutions are located at the ends of the possible solution to equation (2). Darkest surface represents the optimal solutions pool of minimal OPC(Y) relative to the rotation speed (X_1) and feed rate (X_4).

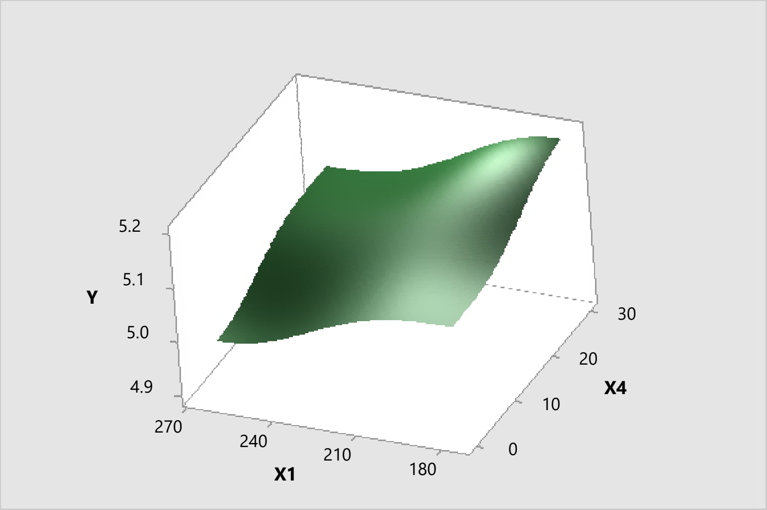

Figure 7: The main effects plot of rotational speed (X_1), feed rate (X_4)

Figure 8 shows a counter plot for the two predictor variables X_2 and X_4 changing with relative to Y using Minitab graphical algorithm to visually and numerically trace the lowest possible areas of OPC within the effective ranges of X_2 and X_4 variability. One blue area is observed at the lower left corner with a range of 5.00 volte to 5.05 volte of OPC. The following are the optimal suggested values of rotational speed of the machining X_2, and feed rates X_4 measured at four corners of each area that will provide the minimal values range between 5.00 volte – 5.05 volte of OPC: (0.03°, 0.007 in/min), (7.4°, 0.005 in/min), (0.15°, 0.005 in/min), and (4°, 0.006 in/min).

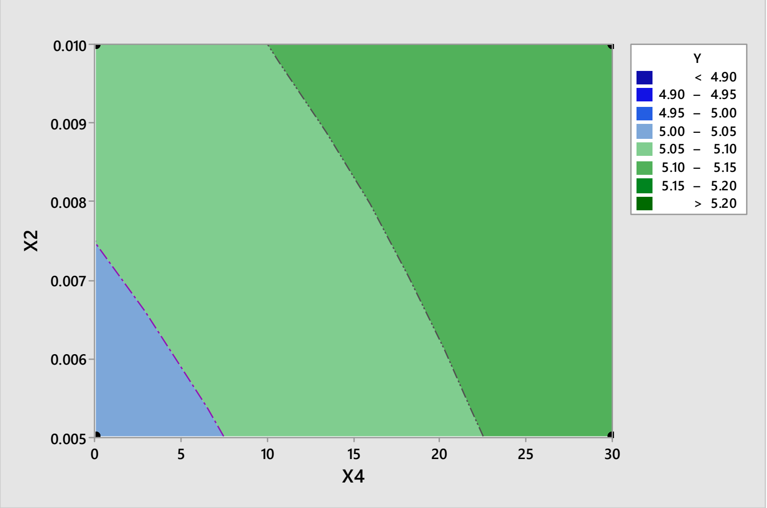

Figure 8: The main effects response plot of rotational speed (X_2) and feed rate (X_4)

Figure 9 is the three-dimensional representation of surface response methodology by Minitab to verify the that the two mammal areas for the possible optimizable solutions are located at the ends of the possible solution to equation (2). Darkest surface represents the optimal solutions pool of minimal Y (OPC) relative to the rotation speed (X_2) and feed rate (X_4).

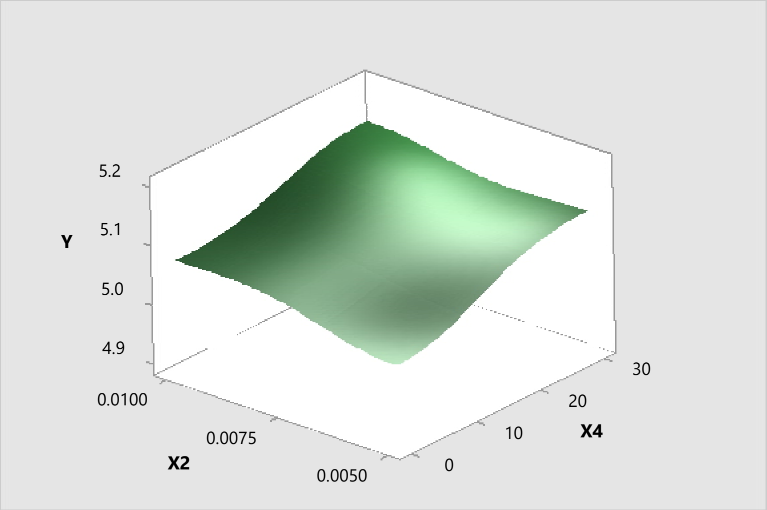

Figure 9: The main effects plot of rotational speed (X_2), feed rate (X_4)

4. Discussion

While the full factorial design of experimentations allows for a comprehensive exploration of the factor effects and analysis, the research work is not without limitations. The specific levels selected for each factor, especially, X_1, X_2 and X_3 may limit the generalizability of the finding results. Future research works are highly recommended to explore additional levels and more focus on the factors showed significant impact and promising results to explore to further refine the understanding of turning process operational conditions and how possibly can influence the OPC. The identified factors X_1, X_2, X_3, and X_4 influencing the response variable Y have practical implications for using lower rotational speed for the carbon steel samples, it has a relatively higher density 7750 kg/m^3 which may cause machine damage if higher speeds selected, therefore a wider range of rotational speed of the machine is valuable to further the analysis. Future research projects recommended to delve deeper into understanding the mechanisms underlying the observed effects and, explore optimal combinations of factors for CO2 and other contaminations generated during the process as another sustainability function.

As the main operational conditions of the subtractive manufacturing are motived by the machine physical power, analytically estimating the motor consumed energy for sustainability featured operation becomes complicated process especially if the quality and cost are critical factors. Based on equation (1), rotational speed X_1 hypothesized to be additive influence on the OPC, and the experimentation results do not support the hypothesis. The cutting power *P* is a working power (mechanical torque) required to remove the material which required another measurement setup and tool to be experimentally result-collected. The UEi DL 599 Wireless three-phase clamp meter (600 A AC/DC, 9999 µF) used in this project is measuring the electric power generated by the motor (electric torque) in terms of voltage which subjected to equation (3).

$$P = K_t \left[\frac{30\,V - K_v\,\pi\,N}{30R}\right] \ldots (3)$$

Where K_t is the motor torque constant, *V* is the input voltage supplied by the motor, *R* is the motor armature resistance, K_v is constant of the motor generated voltage at the armature coil terminals (Electro-magnetic Power) resulted from rotating the motor, which is dropping the voltage supply as it increases with the speed of the motor. This analysis explains the reason what experimental results shows decreasing the OPC at increasing the rotational speed X_1 as illustrated in Figure 1. In the experimentation setup of this research project, it is also hypothesized that X_4 to be subtractive influence on the OPC, and the experimentation results do not support the hypothesis as illustrated in Figure 1. The resultant analysis for the cutting force at 30° where it will be in the parallel direction of the cutting line slop is less than the cutting force at 0° where the cutting force normally (horizontal axis) on the cutting surface and cutting speed of the part which results in applying the complete force without projecting parallelly with the direction of the cutting speed causing loss of the apply force and requiring more load to be applied to remove the material. Figure (10) described the forces resultant analysis of the material removing zone of the subtractive manufacturing operation.

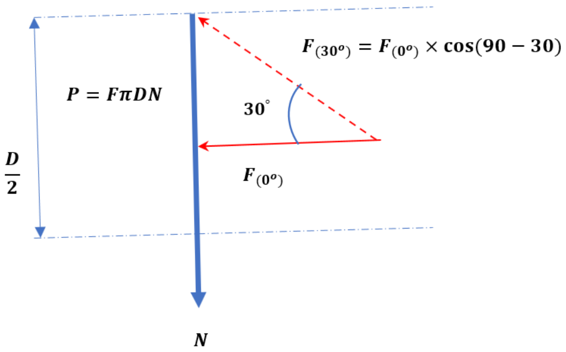

Figure 10: Main cutting force analysis for P, F, and the tool rake angle X_4.

The research project contributes to the existing literature by emphasizing the importance of exploring factor interactions in empirical research projects. It uniquely navigates the intersection of sustainability and manufacturing engineering and technology. By exploring the significance of incorporating sustainable principles, practices, and empirical methodologies into an experimental research project. This research work contributes to provide the next generation of engineers with essential analytical and experimental skills and knowledge of the 21st century manufacturing engineering and technology qualities.

5. Conclusion

In conclusion, the results of full factorial DOE experimental research provide valuable insights into the impact of various operational conditions of a material subtractive manufacturing processes on the OPC as a response variable of the empirical analysis. It is presented experimental exploration focusing on four critical factors – rotational speed (X_1), feed rate (X_2), lubrication (X_3), and rake tool angle (X_4) – to empirically investigate their impact on OPC during the turning manufacturing process. The identified main and interaction effects contribute to the growing body of knowledge in sustainability manufacturing and technology and, pave the way for further investigations into optimal experimental conditions in analysis strategies. As the results of examining the lubrication; from (NO) to (YES), and rake tool angle; from (0°) to (30°), showed almost equal opposite influence on the OPC, both can be recommended to work together in designing the work plan of turning manufacturing operation. This is very helpful finding for quality cutting surfaces If product quality is required in the resulting surfaces of the subtractive manufacturing process, which requires soft cutting forces F_{x°, applying cutting oil will help to cancel any increase in the power consumption to finish the cut. In other words, the same OPC level can be applied for smoother cutting surface by changing the cutting line angle and lubrication.

This research work emphasizes the need to incorporate sustainability principles in engineering and technology, particularly in the field of manufacturing systems and processes. Manufacturing engineering and technology have a role in driving transformative changes toward sustainable future. It emphasizes the importance of researchers in steering this transformation and molding aspiring manufacturing engineering and technology researchers with a sustainability mindset. It experimental approaches used equip the next generation of researchers with a robust understanding of sustainability practices, methodologies, and ethical considerations. Acknowledging the limitations of specific levels of selected factors, this paper suggests future research to explore additional levels and factors for a more refined understanding. Further recommendations include investigating mechanisms underlying observed effects and exploring optimal combinations of factors for power consumption and environmental contaminations.

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