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Operation Conditions Empirical Optimization for Sustainability Manufacturing

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Abstract

Considerable percentage of greenhouse gas emissions comes from industry, and needs to be managed to avoid climate crisis around the world. Manufacturing as a key sector has a share to contribute in solving climate change problems. These challenges redefine the skillset of 21st century workforce and it is increasing demand on the education to integrate sustainability principles into engineering and technology programs in a response to environmental challenges and future jobs skillset. This research emphasizes the central role of engineers in shaping the future of industries, highlighting the need to integrate sustainability into education, particularly in manufacturing engineering and technology. It advocates for mentoring independent studies as another approach beside developed curriculum with sustainability to foster a culture of sustainability excellence in manufacturing engineering and technology, supporting the development of sustainability education in both teaching and research. From sustainability principles integration, and environmentally friendly designs to optimizing production processes to leveraging Industry 4.0 technologies, this array is seen as key to reshaping the future of manufacturing. The approach of this work focuses on an independent research-based study to experimentally test the impact of main operational conditions on Carbon Dioxide (CO_2) production to optimize turning manufacturing processes. Three critical factors—rotational speed, feed rate, and lubrication—are examined for their influence on CO_2. The work used a lathe machine and a set of three sensors strategically placed around the machine along with tools and workpiece samples. Full factorial design of experimentation is used to test and analyze the relationships among factors and the response function of CO_2 production. The technical results reveal significant main effects for the factors as follows: lubrication, rotational speed, and feed rate, along with interaction effects. Lowering rotational speed and high feed rate decrease CO_2 production supporting the hypothesis. Surprisingly, within-oil lubrication decreases CO_2 production, not as expected. Interaction effects emphasize the additive and subtractive influences of the factors on CO_2 production. While the full factorial design of experimentation applied allows for comprehensive factor effects analysis, it acknowledges limitations in the specific selected levels for machine rotational speed and tool feed rate. The research provides valuable insights into the impact of various operational conditions on CO_2 production in material removal manufacturing processes. Main and interaction effects contribute to the knowledge in sustainability manufacturing. Results of undergraduate independent research as another education approach showed how it valuable is to get students to explore the impact of re-adjusting engineering situations to solve problem and improvement objectives along with challenges and how experimental results are facts to change theoretical perspectives and assumptions. These findings contribute to advancing knowledge of sustainability manufacturing in student independent research, supporting the current groundwork for further exploration of optimal education approaches for effective teaching and mentoring strategies for sustainable manufacturing engineering and technology learning. The students' thoughts and learning developments about the topic were stunning, from learning the fundamentals and exploring the real-world constraints to practically challenging the theoretical aspects. This work shares an engineering student's impression of practicing sustainability in a research work project.

1. Introduction

The demand to educate sustainability principles and practices in engineering and technology programs has become more pronounced especially with the escalated environmental challenges around the world. Focusing the central role of engineers in shaping industries' future and the required skillset for the 21st century workforce, show there is a considerable consensus in the education community that the integration of sustainability principles into engineering and technology education is undeniably required. Manufacturing engineering and technology field is at the forefront of education transformative towards more sustainability in curriculum and research [1] and [2]. Mentoring independent research studies can be considered a technical approach to developing a culture of inclusive education to support the development of sustainability education across engineering and technology programs, especially in manufacturing. As the engineering education community explores strategies, challenges, and opportunities associated with teaching sustainability in engineering courses, manufacturing engineering, and technology educators can play the central role in steering the transformation by integrating sustainability principles with the aspiring manufacturing engineers for a better future and career. This approach can strongly contribute to mentee success in the sustainability manufacturing field and ultimately the readiness for future jobs. From conceptualizing environmentally friendly product designs and optimizing production processes for minimal environmental impact, to using industry 4.0 technology such as IIoT, digital cloud computation, and smart sensors, it is the range of sustainability principals' integration that holds the key to reshaping the future of manufacturing education curriculum [3] and [4].

This research work studies the technical intersection of sustainability and manufacturing engineering education to exploring the significance of incorporating sustainability principles, practices, methodologies, and ethics into an independent empirical study research project. This approach equips the next generation of engineers with the skills and knowledge needed to navigate complexities and implications of modern manufacturing and foster a mindset that prioritizes the environmental responsibility of manufacturing engineering and technology. Sustainability in manufacturing engineering and technology is usually integrated into teaching curricula based on similar types of manufacturing course and experiences to develop an implemented approach into another course which is a standard process for several reasons as has its features and conditions, especially in education setup [5]. While many education programs are taking serious steps toward integrating sustainability principles into their curriculum, research, and projects such as typical independent studies, undergraduate research studies are often not accounted sustainability education [6]. This paper presents a research-based approach implemented into an independent undergraduate study to experimentally test manufacturing main operational conditions and analyze their impact on the production of Carbon Dioxide (CO2) using a lathe machine and set of sensors and tools to conduct turning process. Several studies focus on sustainable manufacturing practices and frameworks [7, 8, 9, and 10] pointing out challenges and opportunities, in this research work, three main factors - rotational speed, feed rate, and lubrication - have been designed with specific levels of variability to empirically investigate their optimal setup that minimizes the CO_2 production using Minitab visual algorithms for analysis and optimization. The approach provided thoughtful learning experience of critical and system thinking and analysis as well as exploring computer skills and applications that all line out with the sustainability principles in the engineering manufacturing processes. The paper is organized as follows: Sec. 1 is the introduction to provide a background on the topic and methodology used, Sec. 3 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 4 technical 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 5 discusses the results and finally, Sec. 5 concludes the research work with technical and education insights for future work.

2. Experimentation Setups

In this section, experimentation setup and procedures have been covered including machining factors and machine used, factors limit, material for the experiment samples, and experiments running matrix design. It has been proposed in this work main machining conditions are the variables in the material removal manufacturing processes that affecting the CO_2 and other contaminations. It has been assumed that changes in machine rotational speed X_1, cutting feed rate X_2, and process lubrication X_3 exhibit a statistically significant effect on the observed variations in CO_2 production Y. Specifically, it is anticipate that X_1 variation from the lower limits to the higher limits reduces the CO_2 production as the process will complete faster so there is shortening for the CO_2 production, X_2 variation from lowers to the highers increases the CO_2 production as the contact area between the cutting tool and material sample will be increasing which elevate the temperatures in the process, and X_3 variation from without (NO) and within (YES) increases the CO_2 production and results of the chemical interaction from supplying the lubricant cooling oil to the process. A 13” x 40” engine lathe machine used in this work by MSC Industrial Supply Company along with right-hand carbide turning cutting tool. Three Temtop P20C CO_2 sensors are placed around the machine to measure the CO_2 production of the process and coded number 1, number 2, and number 3. Sensor number 1 was placed directly in front of the machine, sensor number 3 was placed to the side of the machine closest to the active end, and sensor number 2 was placed directly opposite sensor three to collect accuracy data and then the average of the three readings has been taken to the result analysis. 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 contamination data collected.

Figure 1: The machining setup with CO_2 sensors in three places around the lathe 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 and ambient carbon dioxide. 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

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 rigorously test and analyze intricate nuances of the X_1, X_2, and X_3 -Y relationship, exploring potential contributions to the observed outcomes and providing insights into the context of X_1, X_2, X_3 - Y interactions within the scope of our research objectives.

Table 2: Factors Design Matrix for Run and Experimentation Responses

Run #	**X_1**	**X_2**	**X_3**	**Y**
1	175	0.005	YES	7.33
2	175	0.005	NO	14.00
3	175	0.01	YES	12.93
4	175	0.01	NO	19.33
5	260	0.005	YES	17.67
6	260	0.005	NO	11.00
7	260	0.01	YES	8.67
8	260	0.01	NO	12.00

3. Technical Results Analysis

The coded regression coefficient results indicate a significant main effect for Factor X_3 (E - 2.433), Factor X_1 (E = - 1.0625), and Factor X_2 (E = 0.7325). Additionally, there is a significant interaction effect between Factor X_1 and Factor X_2 (E = - 4.732), between Factor X_1 and Factor X_3 (E = 4.103), and between Factor X_2 and Factor X3 (E = - 2.567). The significant main effects of X_3, X1, and X_2 indicate that each factor individually influences the response variable, Y. X_1, Factor X_2, and Factor C of impact the CO_2 as response variable Y is supported by the significant main effects observed. For X1, the analysis shows a CO_2 decreased rate of -1.0625 when changing the rotational speed of the machine from 175 rpm to 260 rpm which supports the hypothesis as illustrated in Figure 2. For X_2, the analysis shows a CO_2 increased rate of 0.7325 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 CO_2 decreased rate of - 2.433 when changing the machining from without oil to within oil which does not support the hypothesis as illustrated in Figure 2.

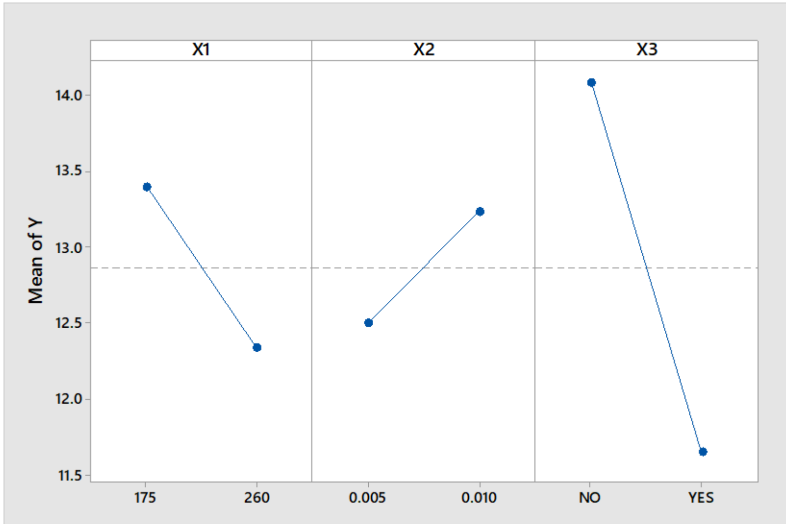

Figure 2: The main effects plot of rotational speed (X_1), feed rate (X_2) and lubrication (X_3)

The interaction effect between X_1, X_2, and X_2, X_3 shows that the combined influence of these factors is subtractive and X_1 and the combined influence of X_1 and X_3 is additive. Further emphasizing the interaction effect analysis shows the combined influence of multiple factors does not significantly influence the CO_2 at both the lower limit of rotational speed, X_1= 175 rpm, and the higher limit at X_1 = 260 rpm as illustrated in Figure 3. The same influence of X_3 effects has been observed that there is no significant effect observed on both X_2 and X_1. In this experimentation setup, 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 an increased effect rate on the CO2, and a decreased effect rate on the CO2 at the higher limit of the feed rate when X2 = 0.01 in/min has 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 project.

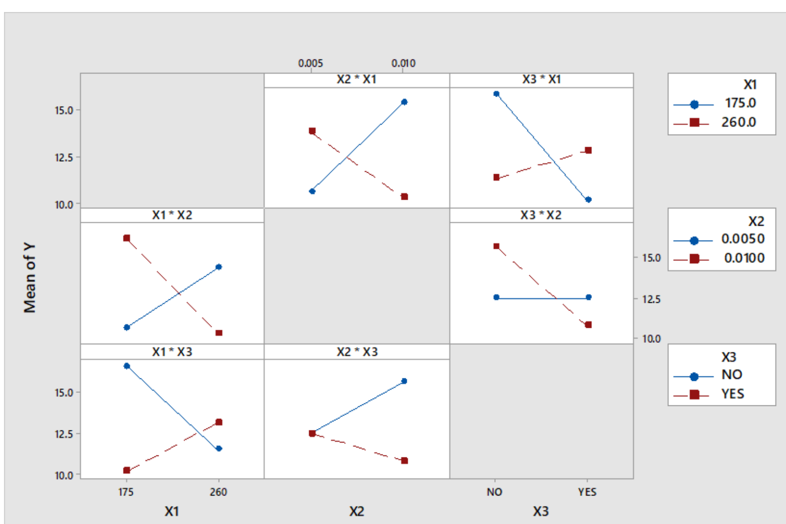

Figure 3: The interaction effects plot of rotational speed and feed rate (X_1 X_2), rotational speed and lubrication (X_1 X_2), and feed rate and lubrication (X_1 X_2).

As a result of using the oil lubrication X_3 as non-numerical factor in the turning process is reducing the CO_2 production, and knowing it has been originally added intentionally to the process to lower the cutting force load which is consequently lowering the process power consumption, then it is approved that adding lubrications to the material removal processes will make significant positive impact not only on cutting the process CO_2 but also saving energy consumption. This are both definitely manufacturing sustainability features and adding lubricant oil into the process is highly recommended based on the project exploration. Therefore, it leaves the CO_2 optimization formula to be changed relative to two factors X_1 and X_2 as illustrated in the regression equation (1). 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.

$$Y = 12.87 - 0.532X_1 + 0.366X_2 \cdots (1)$$

Figure 4 shows a counter plot for the X_1 and X_2 changing with relative to Y using Minitab graphical algorithm to visually and numerically trace the lowest possible areas of CO_2 within the effective ranges of X_1 and X_2 variability. Two blue areas are observed at the top right corner and low left corner with a range of 10 ppm to 12 ppm of CO_2. The following are the optimal values of rotational speed of the machining X_1, and feed rates of the tool X_2 measured at three corners of each area that will provide the minimal values range between 10 ppm – 12 ppm of CO_2 productions: $(0.0090$ in/min, 237 rpm$)_1$, $(0.0080$ in/min, 260 rpm$)_1$, $(0.0088$ in/min, 244 rpm$)_1$, $(0.0060$ in/min, 178 rpm$)_2$, $(0.0050$ in/min, 205 rpm$)_2$, and $(0.0057$ in/min, 195 rpm$)_2$.

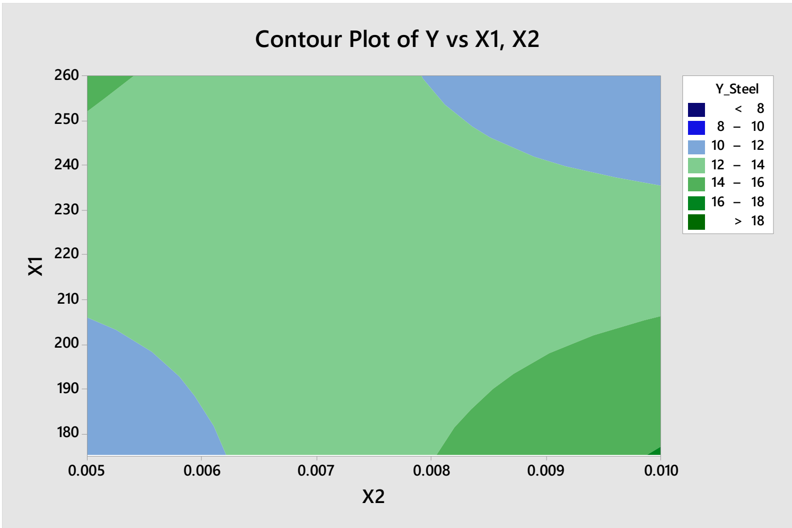

Figure 4: The main effects plot of rotational speed (X_1), feed rate (X_2) and lubrication (X_3)

Figure 5 is the three-dimensional representation of surface response methodology by Minitab to verify the that the tow mammal areas for the possible optimizable solutions are located at the ends of the possible solution to equation (1). Darkest areas represent the optimal solutions of minimal CO_2 (Y) relative to the rotation speed (X_1) and feed rate (X_2).

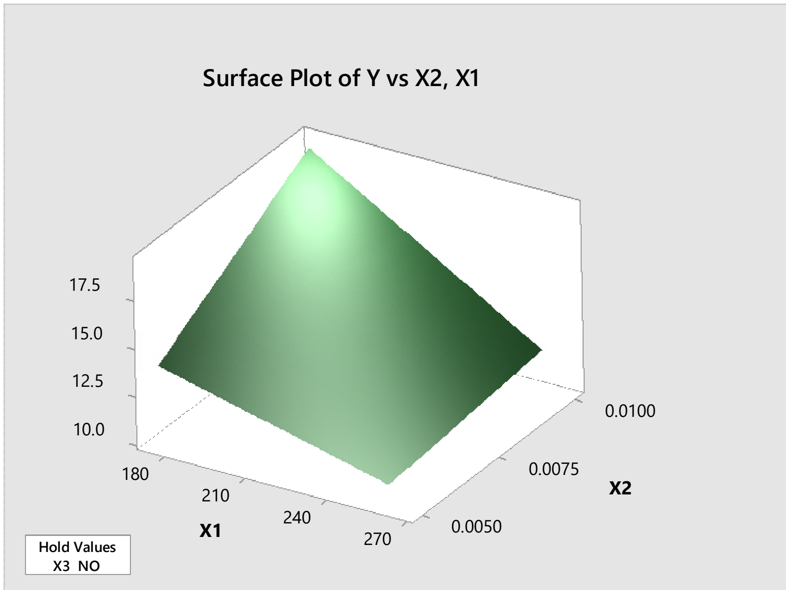

Figure 5: The main effects plot of rotational speed (X_1), feed rate (X_2) and lubrication (X_3)

4. Discussion

While the full factorial design of experimentations allows for a comprehensive exploration of factor effects and analysis, the research work is not without limitations. The specific levels selected for each factor, especially, X_1 and X_2 may limit the generalizability of the finding results. Future research works are highly recommended to explore additional levels and more factors to further refine the understanding of turning process operational conditions and how possibly can influence the CO_2. The identified factors X_1, X_2, and X_3 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 power consumption as another sustainability function.

The research project contributes technically to the existing literature by emphasizing the importance of exploring factor interactions in empirical research projects and it is considered calls attention to the often-overlooked role of independent studies in sustainability education. Educationally, this research work uniquely investigates the intersection of sustainability aspects and manufacturing engineering and technology education by considering undergraduate independent research study as another avenue to implement sustainability knowledge and practices into engineering and technology students learning. By exploring the significance of incorporating sustainability principles, practices, and empirical methodologies into an independent study project, this approach is considered a learning trial to challenge the theoretical assumptions and understand the real-world constrains practically. This research work contributes to equipping the next generation of engineers with essential skills and knowledge of the 21st century skillset. Participant student has been questioned to express: How does this independent study impact you or change their engineering education experience? The following is the students answer.

> *"This study impacted me personally in many aspects. It first showed me that carbon dioxide emissions can be created from inconspicuous places. Even simple processes such as creating a bolt on a lathe machine can produce small amounts of emissions that can quickly add up when done on an industrial scale. For me, this highlighted a need to consider sustainability and emissions in all designs and solutions that I create. In addition, I am planning to begin my master's degree in mechanical engineering in the fall, and having experience in conducting research will benefit me greatly as I enter a research-oriented graduate program."*

As an educator evaluating student learning outcomes, nothing more than seeing how students feel confident about their knowledge and excited to put their skills and tools to use at the first possible opportunity is reflecting that we are contributing to workforce excellence in the 21st century.

5. Conclusion

In conclusion, manufacturing engineering and technology education has a role in driving transformative changes toward sustainability in both curriculum and research. It emphasizes the importance of educators in steering this transformation and molding aspiring manufacturing engineers with a sustainability mindset. It experimental approaches used equip the next generation of engineers with a robust understanding of sustainability practices, methodologies, and ethical considerations. This research work emphasizes the need to incorporate sustainability principles in engineering and technology education, particularly in the field of manufacturing engineering and technology. Technically concluding the empirical results of full factorial DOE experimental of this research, it provides valuable insights about the impact of various operational conditions of a material removal manufacturing processes on the CO_2 as a response variable of the empirical analysis. It clearly showed the difference between the theoretical understanding about an engineering situation and the experimental facts. It is presented experimental exploration focusing on three critical factors – rotational speed (X_1), feed rate (X_2), and lubrication (X_3) – to empirically investigate their impact on CO_2 production during the turning manufacturing process. The identified main and interaction effects contribute to the growing body of knowledge in sustainability manufacturing and undergraduate independent research studies and, pave the way for further investigations into optimal experimental conditions in teaching and mentoring strategies. Acknowledging the limitations of specific levels of selected factors, this paper not only suggests future research to explore additional levels and factors for a more refined understanding but is an apply avenue to demonstrate the real-world constrains to students.

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