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Formulation of a Customer-Oriented Product and Determination of Optimum Design Parameter Using Response Surface Methodology

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ABSTRACT

The development of a product demands numbers of consideration and customer-based product dominates the present market. This study aims to formulate a customer-oriented product and investigate the optimum design parameters level for this formulation. The customer-oriented product named 'CNC PCB Plotter' – is proposed as a handy tool to make a single PCB within a short time and cost. In the sophisticated art of product design, the desires of the customer should be the only constraint. With this in mind, an organized approach is conducted to formulate the product. Suitable design parameters with their optimum ranges provide the sustainability of the product. Response Surface Methodology (RSM) is applied to determine the optimum level of design parameters. A 2-level 3 factorial Central Composite Design (CCD) provides the experimental trails. This research involves the customer demand and specifies the design parameter, such as cutting speed, feed rate, and depth of cut. The average dimensional accuracy is taken as a response and found 0.027 µm with a combination of cutting speed 53.676 m/min, feed rate 253.272 mm/min, and depth of cut 0.49.mm, which is found to be the optimum value.

Keywords: CNC PCB plotter, RSM, CCD, Customer-oriented product.

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1. Introduction

Product design is the way toward formulating a framework, segment, or approach to address required issues. It is a dynamic cycle (regularly iterative) in which the fundamental sciences, arithmetic, and designing sciences are conducted to change over assets ideally to meet an expressed target. The planning cycle is the foundation of targets, investigation, development, testing, and assessment [1].

A Printed Circuit Board (PCB) precisely underpins and electrically associates electronic segments utilizing conductive tracks, cushions, and different highlights carved from at least one sheet of copper layers covered onto and between layers of a non-conductive substrate [2]. So sometimes, for testing or prototyping, a small quantity of PCB is required.

Quality can be characterized as an item or an administration's ability to continually meet or surpass customer desires. Customers are keen on different parts of value contingent on necessities, which may shift broadly from case to case [3]. Customers might not have a total thought regarding quality, yet it ought to be our concentration to give them administration (designing details) relating to their apparent thought regarding quality. There are numerous methods used to characterize designing determinations.

In this paper, the House Of Quality (HOQ) and functional decomposition are combined to develop the product. The results of this paper can provide a standard tool for the sustainable development of a customer-oriented product. Response Surface Methodology (RSM) is incorporated to evaluate the interactions and the optimum value of design parameters.

RSM must be conducted at the product design phase of a product's development process. RSM consists of a group of mathematical and statistical techniques based on the fit of empirical models to the experimental data obtained with experimental design [4]. "RSM represents the relationships between several explanatory variables and one or more responses" [5, 6]. Box-Behnken, Plackett Burman, full factorial are some experimental designs available, including Central Composite Design (CCD). RSM includes some significant steps such as experimental design, estimating the test region for independent variables, ANOVA analysis.

The unpredictability of customer desire has expanded significantly, bringing about the uncertainty of product demand. Investigating customer demand would be essential for predicting the market and developing any particular product. This study addresses the following research motivation:

- What are the customer's desires?
- What will be the technical specification depending on the customer's desires?
- How accurately will the product satisfy customer demand?
- What will be the design parameters for that particular product?
- What will be the design parameter’s optimum level?

This paper is organized as follows: Section 2 considers the literature review and the research gap. Section 3 and 4 consider a detailed study of the HOQ, black box model, cluster function decomposition, and component hierarchy. Section 5 is presented to illustrate the design of experiment for finding the optimum level of design parameters.

2. Literature Review

Customer prerequisites assume a significant function in ensuring an organization's new item improvement tries' competitive advantages. Lin et al. [7] conducted a study based on the Analytic Hierarchy Process (AHP) and Interpretive Structural Modeling (ISM) for developing a customer-oriented product.

Joung et al. [8] conducted a study for finding the market-oriented product. They have presented the utilization of text mining analysis of customer protests to distinguish customers' actual necessities by utilizing the Outcome-Driven Innovation (ODI) technique.

A quantitative survey and qualitative consumer interviews were conducted for conceptualizing Customer-Oriented Product Returns Service (COPRS) performance by Sajjanit and Rompho [9].

A weighted interval rough number based approach was developed for determining the Relative Importance Rating (RIR) of consumer desires in Quality Function Deployment (QFD) product planning [10].

An integrated design framework was developed for virtual enterprise-based customer-oriented product service systems by Guan et al. [11]. With the precise feeling of customer prerequisites, organizations can respond straightforwardly to these necessities to improve their items. To handle the issue, the proposed method obtained customer prerequisites utilizing a Fuzzy Kano Model (FKM) and Benchmarking hypothesis for the degree of fulfillment improvement of every item quality from the part of customer observation and contender execution can be both estimated [12]. A dominance-based rough set approach was conducted in product development [13].

Many researchers have already conducted considering different approaches. However, there remains some research gap in integrating customer-oriented product development and its performance. This study is focused on conducted a detailed study in integrating the product development process and product performance.

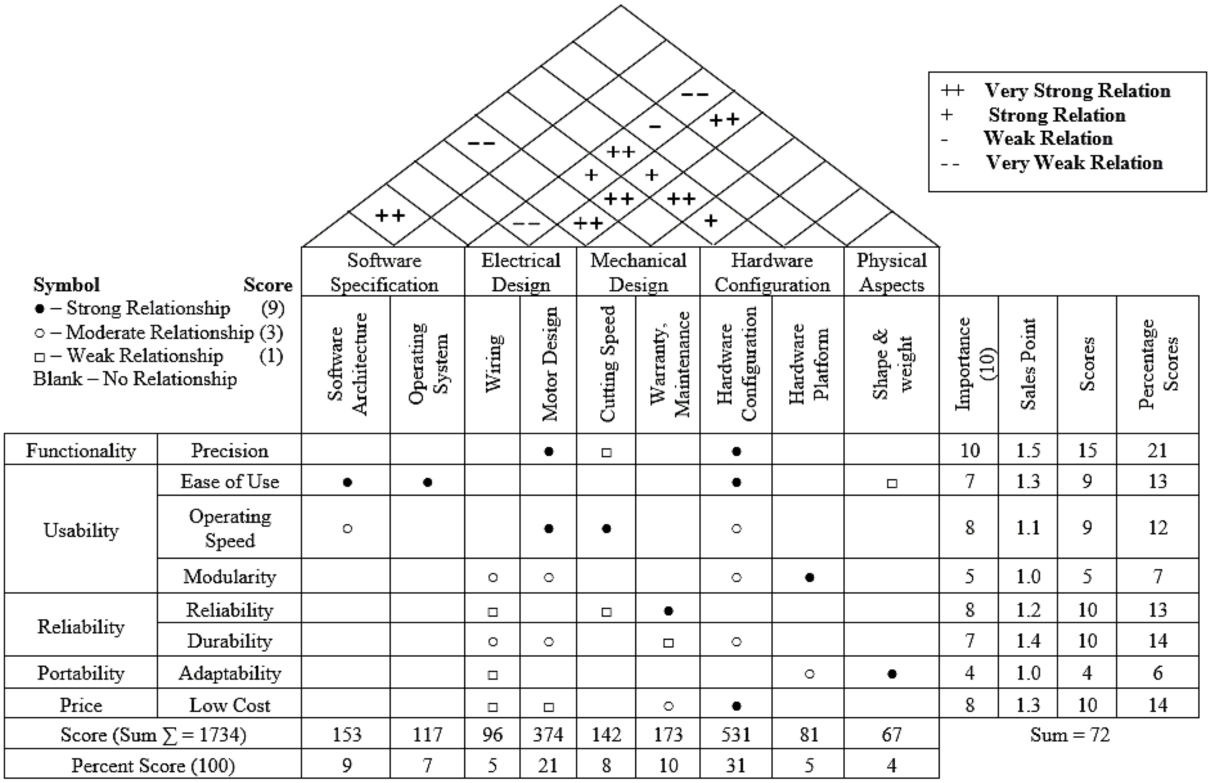
3. Methodology

QFD process starts with feedback from potential customers, is a structured process to evaluate customer desires, and transferring them into appropriate processes to meet those needs [14]. QFD utilizes a cross-practical group to decide customer wants and convert them into a product's design process through an organized and very much archived system [15]. HOQ is a sort of calculated guide that gives way between utilitarian arranging and correspondences, and it is the primary metric for QFD [16].

3.1. House of Quality

The first step of QFD is to extract the customer's desires [17]. This includes both the stated and the implied demands of the customers. This is termed as the Voice Of the Customer (VOC). The data is extracted from the customers using various techniques such as interviews or surveys using various questionnaires. A survey is conducted on the feasibility of the product based on the needs of the customers. This section's main objective is to translate the VOC data into engineering specifications that can be used to design and manufacture the final product.

HOQ is a product planning matrix. These matrices are an excellent communicating tool, and they act as a reliable source of information during decision-making and communication. HOQ resembles a house, leading to characterizing the connection between customer wants and product abilities [18]. QFD 's HOQ for the CNC PCB Plotter is shown in ***Figure 1***.



++ **Very Strong Relation**
\+ **Strong Relation**
\- **Weak Relation**
-- **Very Weak Relation**

Symbol **Score**
● – Strong Relationship (9)
○ – Moderate Relationship (3)
□ – Weak Relationship (1)
Blank – No Relationship

		Software Specification		Electrical Design		Mechanical Design		Hardware Configuration		Physical Aspects				
		Software Architecture	Operating System	Wiring	Motor Design	Cutting Speed	Warranty, Maintenance	Hardware Configuration	Hardware Platform	Shape & weight	Importance (10)	Sales Point	Scores	Percentage Scores
Functionality	Precision				●	□		●			10	1.5	15	21
Usability	Ease of Use	●	●					●		□	7	1.3	9	13
	Operating Speed	○			●	●		○			8	1.1	9	12
	Modularity			○	○			○	●		5	1.0	5	7
Reliability	Reliability			□		□	●				8	1.2	10	13
	Durability			○	○		□	○			7	1.4	10	14
Portability	Adaptability			□					○	●	4	1.0	4	6
Price	Low Cost			□	□		○	●			8	1.3	10	14
Score (Sum ∑ = 1734)		153	117	96	374	142	173	531	81	67	Sum = 72			
Percent Score (100)		9	7	5	21	8	10	31	5	4				

Figure 1. HOQ for CNC PCB plotter.

3.2. Relationship between Customer Requirements and Technical Requirements

Table 1. Table explaining the relationship between the customer and technical requirements.

Customer Requirement	Engineering Requirement	Relationship	Explanation
Precision	Motor Design	Strong	Good motor setup will provide high precision.
	Cutting Speed	Weak	Cutting speed may affect precision.
	Hardware Configuration	Strong	Accurate hardware configuration will assure good finishing.
Ease of Use	Software Architecture	Strong	Simple user interfaced software will make the process easier.
	Operating System	Strong	Popular operating system support will lessen user hassle.
	Hardware Configuration	Strong	Easeful hardware configuration will be efficient.
	Shape & Weight	Weak	Simple shape always preferable.
Operating Speed	Software Architecture	Moderate	Total process flow time is moderately dependent on software architecture.
	Motor Design	Strong	The optimally configured motor design will ensure more incredible operating speed.
	Cutting Speed	Strong	Cutting speed is proportional to operating speed.
	Hardware Configuration	Moderate	Hardware configuration might affect the operating speed.
Modularity	Wiring	Moderate	A systematically wired machine may offer modularity.
	Motor Design	Moderate	A systematically designed motor will also offer modularity.
	Hardware Configuration	Moderate	Easy to assemble hardware parts will provide modularity.
	Hardware Platform	Strong	Professionally designed hardware platform will ensure easier modularity.

Customer Requirement	Engineering Requirement	Relationship	Explanation
Reliability	Wiring	Weak	Better grade wire may be a key factor for reliability.
	Cutting Speed	Weak	Adaptable speed may ensure reliability.
	Warranty, Maintenance	Strong	After-sale services will provide reliable customers.
Durability	Wiring	Moderate	Quality grade wire will increase the product's durability.
	Motor Design	Moderate	A long-lasting motor will serve for a more extended period.
	Warranty, Maintenance	Weak	Unwanted failure may be minimized through warranty and maintenance.
	Hardware Configuration	Moderate	The materials used in hardware needs to be standard for the long life of the product.
Adaptability	Wiring	Weak	Wiring is a factor for adaptability.
	Hardware Platform	Moderate	Easy to carry platform ensure adaptability.
	Shape & Weight	Strong	The physical aspects are the key factors to the adaptation to any situation.
Low Cost	Motor Design	Weak	Powerful motor costs more.
	Warranty, Maintenance	Moderate	Warranty may increase the price
	Hardware Configuration	Strong	Better hardware configuration will cost more

3.3. Importance Rating

Table 2. Importance rating.

Observation Number	Engineering Requirement	Importance Rating	Percentage Rating (%)
1	Software Architecture	153	9
2	Operating System	117	7
3	Wiring	96	5
4	Motor Design	374	21
5	Cutting Speed	142	8
6	Warranty, Maintenance	173	10
7	Hardware Configuration	531	31
8	Hardware Platform	81	5
9	Shape & Weight	67	4

HOQ is the technique to estimate technical specifications to design a product based on the customer's voice. ***Table 2*** represents that the precision and durability of the product should be focused on the marketing purpose.

For technical specifications, hardware configuration (31%) and motor design (21%) are prioritized. On the other hand, the hardware platform (5%) and shape & weight (4%) are the least essential engineering requirements.

4. Functional Decomposition

Functional decomposition is the decomposition of the functional process under specific consideration [19]. Functional decomposition allows the designer to work on each component one at a time that simplifies even the most complex machines.

4.1. Black Box Model for CNC PCB Plotter

The black box represents the inputs as well as outputs, with no information on its interior activities. The black box model for CNC PCB Plotter is shown in ***Figure 2***.

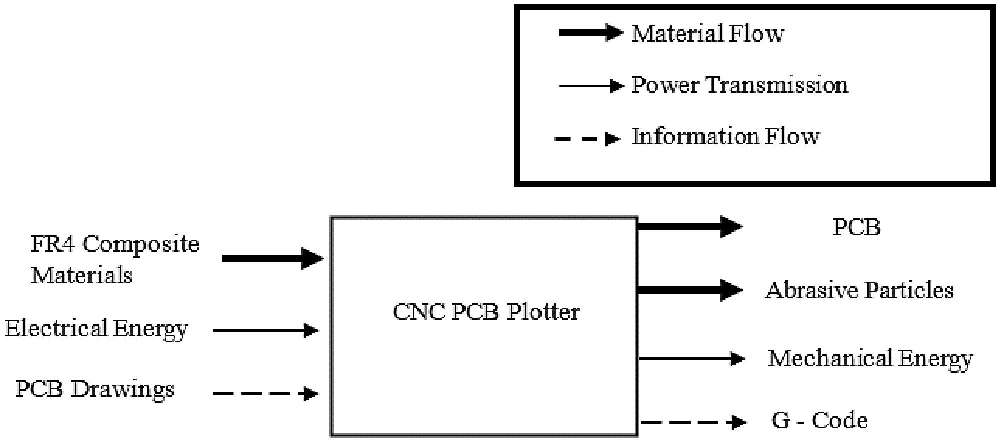


Figure 2. Black box model for CNC PCB plotter.

4.2. Component Hierarchy for CNC PCB Plotter

Component hierarchy expresses the relationship between components of the product considering structure and function. It divides the components into influential groups and subgroups to relate them. The component hierarchy of CNC PCB plotter is shown in ***Figure 3***.

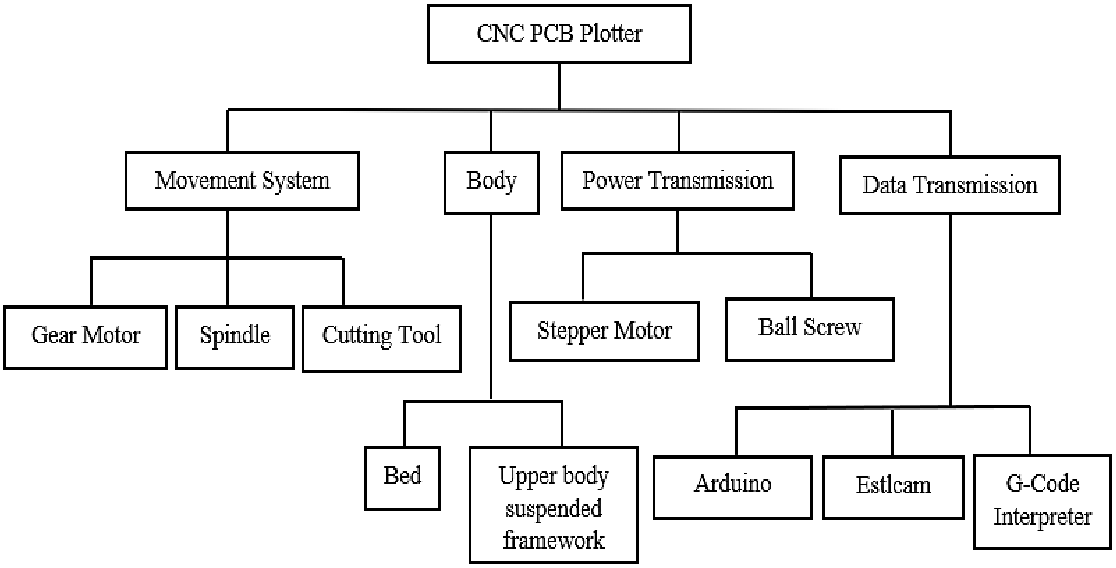


Figure 3. Component hierarchy for CNC PCB plotter.

4.3. Cluster Function Structure for CNC PCB Plotter

The cluster function structure represents the overall mechanisms of a product and shows the relationship among them. The cluster function structure of the CNC PCB Plotter is shown in ***Figure 4***.

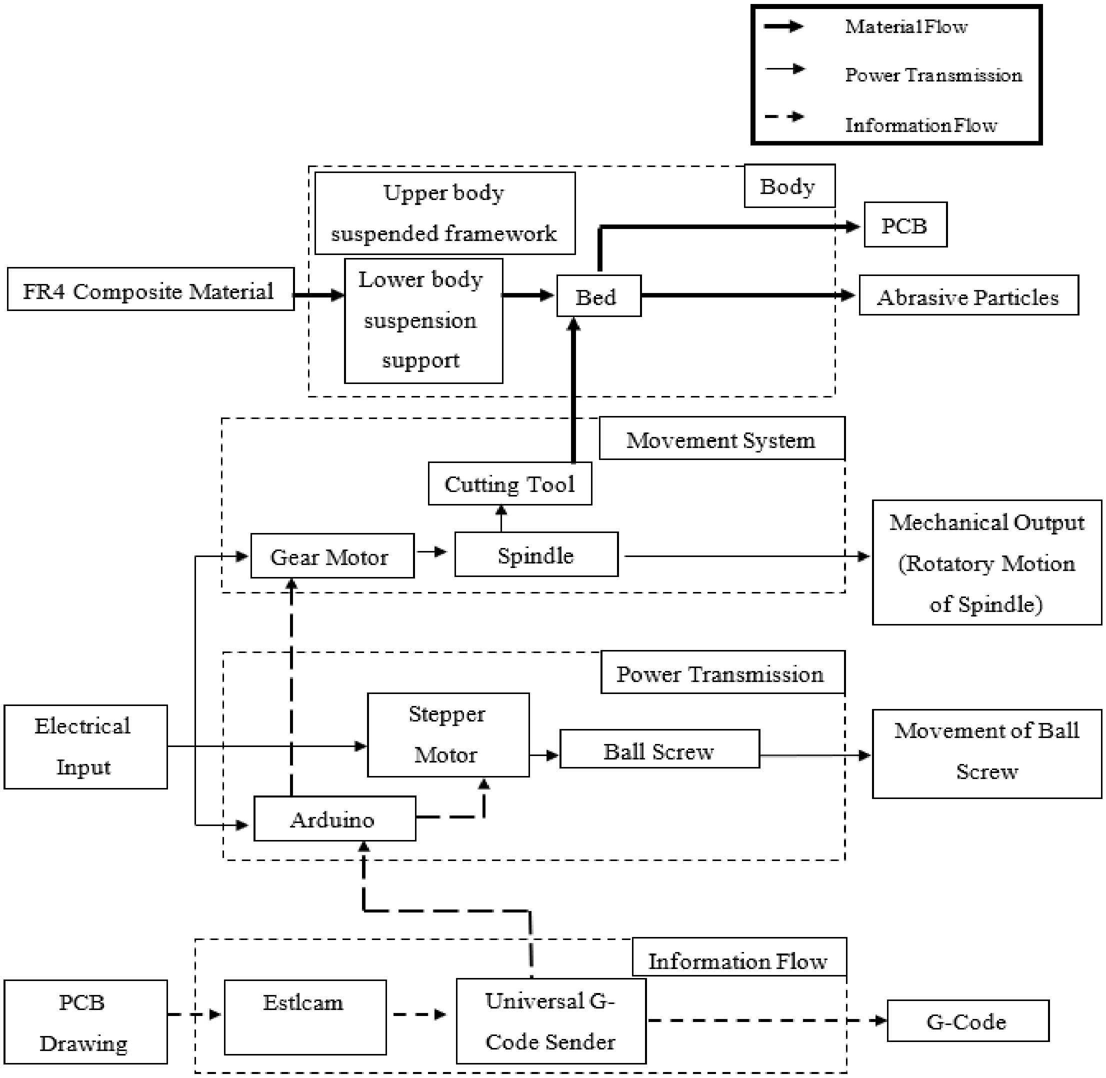


Figure 4. Cluster function structure for CNC PCB plotter.

5. Design of Experiments

Engineering experiments aim at determining the conditions that can lead to optimum performances [20]. RSM was developed by Box and Draper [21] and is a combination of the mathematical and statistical approaches used for the modeling of problems where the output (response) of interest is influenced by several inputs (factors) [21]. RSM responds to the entire factor space and locates the region of interest where the response reaches its optimal or near-optimal value [20]. To study the effects of the designing parameters on the response, a second-order polynomial response surface mathematical equation below by Box and Hunter [22] is used:

$$Y_u = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i<j}^{n} b_{ij} x_i x_j.$$

Where,

Y_u is the corresponding response.

x_i (1, 2, 3, ……………....., n) are machining parameters.

b_0, b_1.... are second-order regression coefficients.

5.1. Experimental Condition

The DESIGN-EXPERT software of version 12.0.5 is used to develop the experimental plan. Experiments are designed based on the three-factor two levels small factorial design concept of RSM. In this study, the cutting speeds are used as a factor and range from 50 m/min to 100 m/min. The choice of this interval is made from previous research. Along with this, the independent variables are coded, considering the capacity of the CNC PCB plotter [23]. Levels of independent variables and coding identification are shown in ***Table 3***.

Table 3. Coding of independent variables with their level.

Level	Low	High
A: Cutting Speed, m/min	50	100
B: Feed Rate, mm/min	240	600
C: Depth of Cut, mm	0.1	0.5

5.2. Experimental Layout

The response that is considered for model development is average dimensional accuracy. The Mitutoyo Surftest SJ-210 is used to measure the average dimensional accuracy after each operation. The average dimensional accuracy on the operating surface is measured perpendicular to the feed marks after every cut [24]. An average of three readings is taken as the final result of dimensional accuracy. ***Table 4*** presents the experimental layout for this study.

Table 4. Experiment layout.

Run	A: Cutting speed (m/min)	B: Feed rate (mm/min)	C: Depth of Cut (mm)	Average Dimensional Accuracy (μm)
1	75	420	0.3	0.4490
2	75	420	0.3	0.5870
3	75	420	0.582843	0.5657
4	75	420	0.0171573	0.7020
5	75	674.558	0.3	0.6457
6	75	165.442	0.3	0.4657
7	75	420	0.3	0.4800
8	50	240	0.1	0.5330
9	100	600	0.1	0.03763
10	100	240	0.5	0.5320
11	75	420	0.3	0.4473
12	110.355	420	0.3	0.4320
13	75	420	0.3	0.5100
14	39.6447	420	0.3	0.5233
15	50	600	0.5	0.6923

RSM has been exploited to develop the mathematical models in terms of the investigated design parameters, i.e., cutting speed, feed rate, and depth of cut. According to the fit and summary tests, the quadratic model is suggested. The fitted dimensional accuracy model for this study is found to be as:

Average Dimensional Accuracy = 0.170289 + 0.009614 × cutting speed + 0.002783 × feed rate -3.98783× depth of cut - 0.000047 × cutting speed × feed rate + 0.029481 × cutting speed × depth of cut + 0.003657 × feed rate × depth of cut.

5.3. Effect of Design Parameters

The experimental trials found that the depth of cut tends to have the most significant effect on the response for a specified range of design parameters followed by cutting speed and feed rate. The response tends to decrease with an increase in depth of cut and increase with an increase in both cutting speed and feed rate. The interaction between cutting speed and depth of cut has a significant effect on average dimensional accuracy.

Figure 5 illustrates the effect of cutting speed (A) versus feed rate (B) for a constant depth of cut of 0.3 mm. "The surface plot has been developed based on the regression model developed using the experimental data" [25]. It is cleared from the surface plot that the decrease in cutting speed (A) at the lower depth of cut (C) increases the possibility of finding more stable dimensional accuracy. An acceptable response can be observed at a lower feed rate (B) and lower depth of cut (less than 0.3 mm). So, for the most acceptable dimensional accuracy, the cutting speed (A) (from 50 to 75 m/min) and feed rate (B) (closer to 240 mm/min) should be lower at a lower depth of cut (less than 0.3 mm).

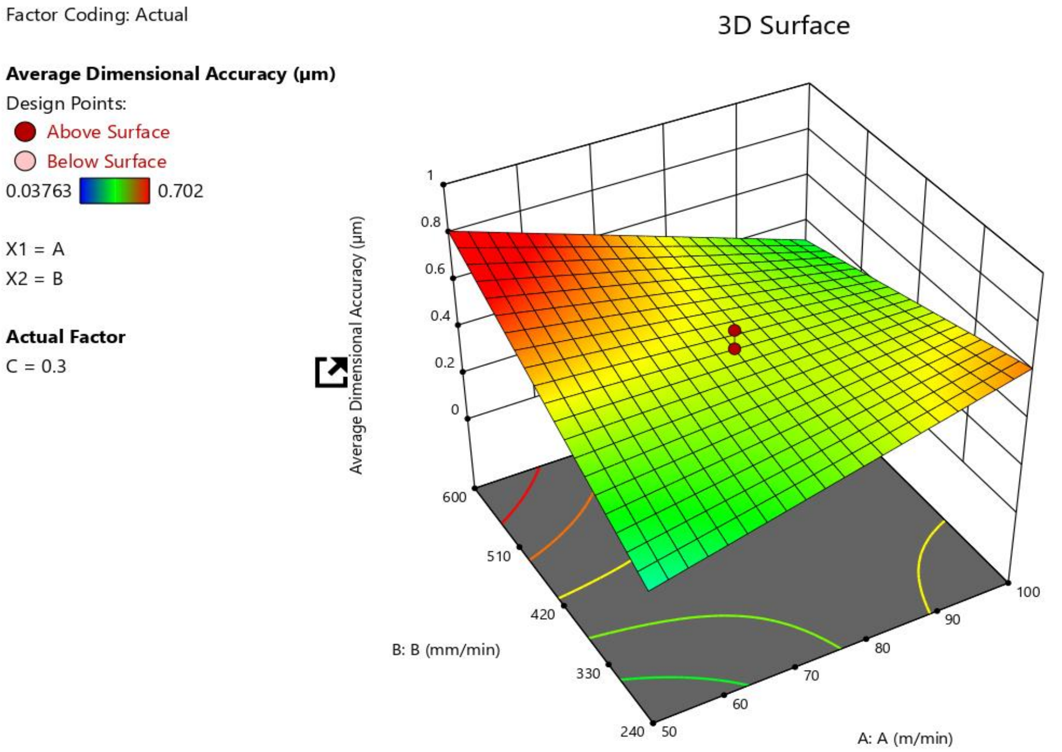


Figure 5. Effect of cutting speed (A) vs. feed rate (B). (Response as a function of cutting speed (A) and feed rate (B) for '0.3' level value of depth of cut (C) during the experimental run).

5.4. Results and Discussion

Table 5 represents the designed parameters obtained after single response optimizations, and the DESIGN EXPERT software suggests ten possible solutions. All 10 solutions are accepted, but our preference is to get higher desirability. For this, cutting speed 53.676 m/min, feed rate 253.272 mm/min, and depth of cut 0.490 mm are recommended. These combinations of parameters will provide the average dimensional accuracy (Response) of 0.027 µm. From these combinations of design parameters, the desirability of 100% can be achievable.

Table 5. Value of design parameters for optimizing the response.

Solution	Factor 1: A (m/min)	Factor 2: B (mm/min)	Factor 3: C (mm)	Response (µm)	Desirability	
1	53.676	253.272	0.490	0.027	1.000	Selected
2	53.043	250.589	0.491	0.012	1.000	
3	50.685	276.301	0.495	0.034	1.000	
4	52.501	261.092	0.485	0.036	1.000	
5	51.903	242.439	0.497	-0.029	1.000	
6	50.879	266.824	0.487	0.027	1.000	
7	50.186	244.670	0.447	0.035	1.000	
8	51.720	258.328	0.499	0.001	1.000	
9	51.525	247.838	0.463	0.032	1.000	
10	53.437	247.393	0.492	0.009	1.000	

6. Conclusion

In the process of formulating any customer-oriented product which makes the best use of electricity, a PCB is a must. Since the conventional process of getting a PCB made for a specific product is rather lengthy and is not very convenient, a CNC PCB plotter will make customized PCBs for any design project. This study will give the designers freedom, and it will make the entire designing process more customer-friendly, which makes the production process faster. Its compact size allows the integration of it into any place, and the optimum design parameters allow the customer to develop a more accurate product. Adopting this product will not only ensure the best use of a designer's visions, but it will also make the designing process more efficient. In specific, the findings of this study can be summarized as follows:

- The HOQ represents that hardware configuration (31%) and motor design (21%) should be prioritized based on the customer's demand for this particular product.
- The following model developed by RSM using the DESIGN-EXPERT 12.0.5 which can provide an accurate prediction of the values of average dimensional accuracy, with a confidence level of 100%: Average Dimensional Accuracy = 0.170289 + 0.009614 × cutting speed + 0.002783 × feed rate -3.98783× depth of cut - 0.000047 × cutting speed × feed rate + 0.029481 × cutting speed × depth of cut + 0.003657 × feed rate × depth of cut.
- The model suggests that the depth of cut has a strong individual influence on average dimensional accuracy, while the interaction effect of cutting speed and depth of cut also affects significantly. Usually, lower cutting speed (from 50 to 75 m/min) results in more acceptable dimensional accuracy. However, the feed rate (closer to 240 mm/min) should be lower at a low depth of cut (less than 0.3 mm) for finding more accurate dimensional accuracy.
- The combinations of parameters (cutting speed 53.676 m/min, feed rate 253.272 mm/min, and depth of cut 0.490 mm) will provide the average dimensional accuracy (Response) of 0.027 µm with the desirability of 100%.

The following recommendations are for future works:

- Experimentation can be done using a more comprehensive set of design parameters for considering the optimization process.
- Genetic Algorithm can be applied along with RSM for finding more accurate results.

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