Dry Machining Process of Milling Machine using Axiomatic Green Methodology

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Abstract. Most of companies know that there are strategies to become green industry, and they realize that green efforts have impacts on product quality and cost. Axiomatic Green Methodology models the relationship between green, quality, and cost. This methodology starts with determining the green improvement objective and then continues with mapping the functional, economic, and green requirements. From the mapping, variables which affect the requirements are identified. Afterwards, the effect of each variable is determined by performing experiments and regression modelling. In this research, axiomatic green methodology was implemented to dry machining of milling machine in order to reduce the amount of coolant. Dry machining will be feasible if it is not worse than the minimum required quality. As a result, dry machining is feasible without producing any defect. The proposed machining parameter is to reduce the coolant flow rate from 6.882 ml/minute to 0 ml/minute, set the depth of cut at 1.2 mm, spindle rotation speed at 500 rpm, and feed rate at 128 mm/minute. This solution is also resulted in reduction of cost for 200.48 rupiahs for each process.

Keywords: Axiomatic Green, Dry-Machining, Experiments, Regression Modelling

1. Introduction

Manufacture get 8th rank as the sector that generate most poison pollutant in the world [1]. This condition make most of stakeholder ask to manufacture to produce green products which are some product that has lowest impact to environment in all of their value chain. Manufactures should minimize the using of poison or unrenewable material by changing them with renewable material then use it as efficient as possible [2].

A strategy that could be implemented by manufacture is to minimize the number of waste produced. In manufacture, waste could be generated from the coolant used in machining process. Coolant has a potential to cause some environmental problems that are generated by fluid disposal activity. The amount of fluid waste should be minimized to make greener machining. Several ways used for solving it are filtration system and dry machining strategy [3]. A research compare the performance between dry and wet machining of stainless steel rods on CNC lathe. The main outputs monitored were cutting tool temperature and the surface roughness. The main cutting parameters were cutting speed, feed rate, and depth of cut [4]. Another study use novel chromium based coatings to realize dry machining. The
results show that the incorporation of silicon increases the wear and oxidation resistance as well as the micro hardness [5]. Using coolant not only causes environmental problem, but also causes higher of manufacturing cost. Coolant cost can contribute to 16% of manufacturing cost [6]. Coolant cost is consists of used cost, removal cost, buying cost, storage cost, etc [7].

Manufacturers know that they should reduce using coolant to minimize the environmental impact. But, they usually doubt to apply this improvement because it will influence product quality and production cost. In the other side, some researchers has developed many green improvement methods to assist in implementation of green in process production phase. A research has been conducted using Axiomatic principle to reduce the number of coolant used in lathe machine with the name of Axiomatic Green Methodology [8]. This methodology will also be used in this research to be implemented in milling machine.

2. Theoretical Background

2.1. Axiomatic Green

Axiomatic Green consists of 6 steps of implementation, see Fig. 1. Firstly, collecting the green objective from the stakeholder and state it to be modelled in axiomatic mapping. Secondly, creating axiomatic map by attaching green objective from the first step to the general product axiomatic quality. By using this map, relationship between several kinds of factor with the objectives could be known. Then, response and control variable should be defined based on process condition. Uncontrollable factor should be eliminated from the list [8].

![Figure 1. Axiomatic Green Methodology [8].](image)

There are 4 sub steps in the third step. All of the defined variables should be mapped for their actual condition. After that, experiment plan is built by defining measurement method, number of replication, and sequence of experiment. The experiment is executed then the result will be analysed using ANOVA to find significant relation between response and control variable. Each response variable that has relationship with specific control variable is modelled using regression methodology in the fourth step. After that NLP modelled is built to be optimize in fifth step. Solution got from it will be transferred to be implementation plan in last step.
3. Implementation
This research was conducted at Polytechnic of Manufacture in Bandung city of Indonesia whose students have a practicum to make a based metal product. One type of product produced is mini vise, see figure 2. Mini vise has capability to clamp thing with maximum thickness of 25 millimetres. This product is made by ST-37 stainless steel and consists of 4 part which are fixed jaws, movable jaws, slider, and countershaft.

Critical part of this product based on the product expert experience is fixed jaws, see figure 3. It is because this part has two mandatory functions for clamping a thing and stabilizing the others part. Fixed jaw is processed from raw material using milling machine. When the processed executed, students brush manually coolant to the material processed. The coolant type used is Emulcut S50 which is put in the little glass. Students frequently brush it to keep the temperature below the limit. After first used, the coolant will be collected in the 200-litres-drum to be remove. Approximately, three hundred litres of coolant waste is generated in one semester. The school is usually pay removal cost each drum for 400,000 rupiah.

3.1. Step I – State the Green Objective
Green objective of this research was to minimize of using hazardous material which is coolant waste that is generated by the production process of fixed jaw.

3.2. Step II – Axiomatic Mapping
Axiomatic tree diagram used for mapping the relationship between quality, cost, and green objective with the process parameter value from machining process, see Appendix A. Firstly, quality objectives
are mapped to the functional requirements (FR’s), physical domains (DP’s), until process parameter values (PV’s). All of them are mapped in the form of 77 orange rectangles. Then, cost and green objective is also mapped to cost requirement (CR), green requirement (GR), and each of their physical domain (DP). After that, the parameter values (PV’s) from machining process is connected to cost and green objective. From the mapping, it can be inferred that most of the process needed to create fixed jaw are milling processes. So, this research is limited only for milling machining process. This research is also select several feature that critical for this part. The product expert informed that there were two critical feature which were clamping edge and moving line as you can see from Figure 3. Quality aspect of these feature are surface fineness and flatness.

Green objective is depend of the coolant waste which is depend on coolant debit from process parameter value. This parameter value influence the tool life which is influence the cost objective and also influence fineness and flatness of surface section from quality objective. Coolant debit also has interaction with other process parameter values that influence the quality and cost objective. The others are feed rate, depth of cut, and cutting speed.

Response variable is defined by quality and cost objective. Variable from quality objective are height surface flatness (y2). Meanwhile, variable from cost objective is tool area reduction (y3) to estimate the tool life. Another response variable is process temperature (y1) as a technical constraint to be compared with the temperature limitation. Control variable is defined by process parameter values which are coolant debit (x1), depth of cut (x2), cutting speed (x3), and feed rate (x4).

3.3. Step III – Execute Design of Experiment (DOE)

After all of the response and control variable have been defined, experiment should be planned and executed to show what kind of control variable that has significant relation with each response variable. The DOE method used for this research was factorial experiment 2k. It means that each of control variable has 2 level which are low and high. Number of replication of the experiment is two times. It was because the limitation of time and raw material existed in the machining plant. The sequence of experiment is random, see Table 1. Then, the result from this experiment could be seen in Table 2.

| Sequence Number | Coolant debit (x1) | Depth of cut (x2) [mm] | Cutting speed (x3) [m/ min.] | Feed rate (x4) [mm/ min.] | Sequence Number |
|-----------------|-------------------|------------------------|-----------------------------|---------------------------|-----------------|
| 1               | High              | 0.5                    | 400                         | 128                       | 9               |
| 2               | High              | 0.5                    | 400                         | 76                        | 10              |
| 3               | Low               | 0.5                    | 400                         | 128                       | 11              |
| 4               | Low               | 0.5                    | 400                         | 76                        | 12              |
| 5               | Low               | 1.5                    | 400                         | 76                        | 13              |
| 6               | Low               | 1.5                    | 400                         | 128                       | 14              |
| 7               | High              | 1.5                    | 400                         | 76                        | 15              |
| 8               | High              | 1.5                    | 500                         | 76                        | 16              |

To know the existence of relation between response and control variable, Analysis of Variance (ANOVA) was used. Table 3 shows p-value from each control variable and their interaction for each response variable by using Minitab©. Control variables/interactions that have p-value less than α would have significant relationship with the response variable. Tool area reduction variable (y3) using α value of 10%, but the others variable use 5% value. So, for an example, control...
variables/interactions that have significant relationship with Tool area area reduction \( (y_3) \) are depth of cut \( (x_2) \); and interaction between depth of cut \( (x_2) \) and feed rate \( (x_4) \).

### Table 2. Experiment Result

| Sequence Number | Process temperature \( (y_1) \) \[°C\] | Surface flatness \( (y_2) \) \[mm\] | Tool area reduction \( (y_3) \) \[mm\^2\] |
|-----------------|---------------------------------|---------------------------------|---------------------------------|
|                 | \#1                              | \#2                             | \#1                              | \#2                             |
| 1               | 30.7                             | 26.7                            | 0.03                             | 0.02                            | 0.00018348                      | 0.00049090                      |
| 2               | 26.1                             | 26.6                            | 0.05                             | 0.05                            | 0.00035442                      | 0.00053596                      |
| 3               | 24.8                             | 26.9                            | 0.05                             | 0.04                            | 0.00022372                      | 0.00010140                      |
| 4               | 26.6                             | 31.4                            | 0.03                             | 0.02                            | 0.00027200                      | 0.00020119                      |
| 5               | 44.1                             | 32.3                            | 0.03                             | 0.03                            | 0.00010623                      | 0.0005955                       |
| 6               | 56.3                             | 54.1                            | 0.03                             | 0.04                            | 0.00001609                      | 0.0009013                       |
| 7               | 45.1                             | 38.8                            | 0.03                             | 0.04                            | 0.00007404                      | 0.0009818                       |
| 8               | 39.6                             | 32.2                            | 0.03                             | 0.04                            | 0.00006277                      | 0.0001609                       |
| 9               | 43.1                             | 55.3                            | 0.02                             | 0.01                            | 0.00003702                      | 0.0004668                       |
| 10              | 51.5                             | 39.1                            | 0.06                             | 0.06                            | 0.00006599                      | 0.0006599                       |
| 11              | 33.1                             | 29                               | 0.04                             | 0.04                            | 0.00009496                      | 0.0009174                       |
| 12              | 30.1                             | 28.6                            | 0.04                             | 0.04                            | 0.00004507                      | 0.0007082                       |
| 13              | 32.6                             | 33.4                            | 0.02                             | 0.01                            | 0.00039111                      | 0.0014646                       |
| 14              | 42.3                             | 45.7                            | 0.03                             | 0.04                            | 0.00022372                      | 0.00027039                      |
| 15              | 59.5                             | 63.1                            | 0.03                             | 0.04                            | 0.00020602                      | 0.00025430                      |
| 16              | 33.1                             | 31.6                            | 0.02                             | 0.03                            | 0.00002253                      | 0.0009818                       |

### Table 3. ANOVA Result

| Source of variance | Response variable’s p-value |
|-------------------|-----------------------------|
|                   | Surface flatness \( (y_2) \) | Process temperature \( (y_1) \) | Tool area reduction \( (y_3) \) |
| Coolant debit(X1) | 0.000                        | 0.004                       | 0.577                       |
| Depth of Cut (X2) | 0.379                        | 0.000                       | 0.075                       |
| Cutting speed (X3)| 0.379                        | 0.039                       | 0.112                       |
| Feed Rate (X4)   | 0.004                        | 0.005                       | 0.747                       |
| X1 X2            | 0.767                        | 0.022                       | 0.496                       |
| X1 X3            | 0.000                        | 0.047                       | 0.116                       |
| X1 X4            | 0.004                        | 0.447                       | 0.436                       |
| X2 X3            | 0.051                        | 0.780                       | 0.492                       |
| X2 X4            | 0.015                        | 0.005                       | 0.065                       |
| X3 X4            | 0.004                        | 0.737                       | 0.676                       |
| X1 X2 X3        | 0.767                        | 0.202                       | 0.605                       |
| X1 X3 X4        | 0.004                        | 0.059                       | 0.778                       |
| X1 X2 X4        | 0.015                        | 0.479                       | 0.922                       |
| X2 X3 X4        | 0.151                        | 0.962                       | 0.300                       |
| X1 X2 X3 X4     | 0.151                        | 0.238                       | 0.214                       |

### 3.4. Step IV – Set Relationship Model using Regression Setting

Regression equation was generated by using Minitab© which the result could be seen in Table 4. Each regression coefficient shows influence level from factor and/or factor interaction to the response variable. Only factor or interaction with significance influence that will be used in regression equation model.
Table 4. Regression Coefficient

| Source of variance | Response variable’s p-value |
|--------------------|-----------------------------|
|                    | Surface flatness ($y_2$) | Process temperature ($y_1$) | tool area reduction ($y_3$) |
| Constant           | 0.0340625                 | 37.91875                  | 0.000078 |
| Coolant debit (X1) | 0.0059375                 | -2.59375                  | 0.000010 |
| Depth of Cut (X2)  | 0.0009375                 | 8.4625                    | -0.000032 |
| Cutting speed (X3) | -0.0009375                | 1.7625                    | -0.000028 |
| Feed Rate (X4)     | 0.0034375                 | 2.55                      | -0.000005 |
| X1 X2              | 0.0003125                 | -2                        | 0.000012 |
| X1 X3              | 0.0046875                 | -1.6875                   | -0.000028 |
| X1 X4              | -0.0034375                | -0.6125                   | 0.000013 |
| X2 X3              | 0.0021875                 | -0.21875                  | 0.000012 |
| X2 X4              | 0.0028125                 | 2.51875                   | 0.000033 |
| X3 X4              | 0.0034375                 | 0.26875                   | -0.000007 |
| X1 X2 X3           | 0.0003125                 | -1.04375                  | 0.000009 |
| X1 X3 X4           | 0.0034375                 | -1.59375                  | 0.000005 |
| X1 X2 X4           | 0.0028125                 | 0.56875                   | 0.000002 |
| X2 X3 X4           | 0.0015625                 | 0.0375                    | -0.000018 |
| X1 X2 X3 X4        | -0.0015625                | 0.9625                    | -0.000022 |

The yellow cells indicate all of coefficients and intercepts used in the equation. Table 5 shows three regression equation which describe about relationship between three variable response to their factors and factor interactions.

Table 5. Converted Regression Equation

| No | Response Variable | Relationship Model |
|----|-------------------|--------------------|
| 1  | Process Temperature ($y_1$) | $y_1 = 37.91875 - 2.59375 + 1.7625 + 2.55x_1 - 2x_1x_2 - 1.6875x_1x_2 + 2.51875x_1x_2$ |
| 2  | Surface flatness ($y_2$) | $y_2 = 0.0340625 + 0.0059375 + 0.0009375 - 0.0009375 + 0.0034375 + 0.0003125 + 0.0046875x_2 + 0.00028125x_2x_4$ |
| 3  | Tool area reduction ($y_3$) | $y_3 = 0.000078 - 0.000032 + 0.000033x_3$ |

Minitab© automatically simplifies all of control variables value to be 1 for high level and -1 for low level. Because of that, all of those values must be converted to their real values. The final equation could be seen on Table 6.

Table 6. Real Regression Equation

| No | Response Variable | Relationship Model |
|----|-------------------|--------------------|
| 1  | Process Temperature ($y_1$) | $y_1 = -1.704 + 0.822362685 + 1.1625 + 0.069 + 0.095673077 - 1.162452775x_1 + 0.00980195x_1 + 0.19375x_1x_4$ |
| 2  | Surface flatness ($y_2$) | $y_2 = 0.004334146 + 0.035069188 - 0.00009375 + 0.0000442 + 0.000065114x_4 + 0.0004471x_4 + 0.000000077x_4x_4 + 0.000006287x_4x_4x_4$ |
| 3  | Tool area reduction ($y_3$) | $y_3 = 0.0000401 - 0.0000325 - 0.0000025 + 0.0000254x_4$ |

3.5. Step V – Optimize Green Objective using Non-linear Programming

Objective function of this model was equal to the green objective function that is to minimize the coolant used. It means that the other objectives would be constraints of the model. From the axiomatic mapping, it is known that surface flatness ($y_2$) of fixed jaw not exceed 0.05 mm. Cost constraints is depend on tool volume reduction ($y_3$) and number of coolant volume used. Coolant used cost consists
of material cost and removal cost. Materials used in the coolant were Emulcut S50 and Aquades with 50:50 proportion. The price of Emulcut S50 and Aquades were 162.921 rupiahs per litre and 700 rupiahs per litre. It means that a litre coolant need material cost of 81.810 rupiahs. Removal cost of coolant was 200 rupiahs per litre. So, the unit coolant used cost was 82.010 rupiahs per litre.

Machining processing time was influenced by cutting speed, feed rate, and their interaction. The total coolant used cost could be computed by using equation (1).

\[
82x_1 \times ( (-614.97 + 1.6789 \cdot x_2 + 3.13677 \cdot x_4 - 0.00854 \cdot x_3 \cdot x_4) / 60 )
\] (1)

Total tool used cost was influenced by tool material and tool sharpening activity with the value of 1.213.000/mm². Total machining cost was summation of total coolant used cost and total tool used cost. This value could not be exceed the existing cost of 290.58 as you can see in Equation (4).

There are four technical constraints. Constraint (5) ensures that the process temperature not exceed 120°C. Constraint (6) ensures non-negative of coolant debit used. Then, constraint (7) ensures that the depth of cut only have value between 0.5 – 1.5 mm. Constraint (8) is also about the machining constraint that has cutting speed in range between 300 – 500 rpm. The last, constraint (9), ensures that the feeding rate has a range value between 48 – 128 mm/min.

**Green Objective**

Minimize \( x_1 \)

s/t.

**Quality Constraint**

\[
0.043341346 + 0.035069188x_1 \cdot -0.00009375x_4 + 0.0006442x_4 - 0.0005114x_1x_4 - 0.0004471x_4x_4 + 0.00000077x_1x_2x_4 + 0.000000287x_1x_2x_4 \leq 0.05
\] (3)

**Cost Constraint**

\[
82x_1 \times ( (-614.97 + 1.6789 \cdot x_2 + 3.13677 \cdot x_4 - 0.00854 \cdot x_3 \cdot x_4) / 60 ) + (486.3196923 - 391.7056923x_4 - 3.079153846x_4 + 3.079153846x_2x_4) \leq 290.58
\] (4)

**Technical Constraint**

\[
0 \leq -1.704 + 4.822362685x_1 + 1.1625x_3 + 0.069x_3 - 0.095673077x_4 - 1.162452775x_1x_2 - 0.09808195x_1x_2 + 0.19375x_2x_4 \leq 120
\] (5)

\[x_1 \geq 0\] (6)

\[0.5 \leq x_2 \leq 1.5\] (7)

\[300 \leq x_3 \leq 500\] (8)

\[48 \leq x_4 \leq 128\] (9)

Using LINGO© software, solution for the NLP model was computed. All of control variable were computed with the result of \( x_1 = 0 \) ml/min. \( x_2 = 1.203 \) mm, \( x_3 = 500 \) rpm, and \( x_4 = 128 \) mm/min. With this solution, the unit cost is equal to 95.10 rupiahs that is almost 1/3 times of existing value of 290.58 and the process will not use coolant, so the temperature will increasing significantly for mass production schema.

**3.6. Step VI – Design Implementation Plan**

To make greener production process, management should implement new machining parameter by changing the existing machining parameters which are \( x_1 = 6.882 \) ml/min. \( x_2 = 1.53 \) mm, \( x_3 = 400 \) rpm, and \( x_4 = 128 \) mm/min to new one which are \( x_1 = 0 \) ml/min. \( x_2 = 1.203 \) mm, \( x_3 = 500 \) rpm, and \( x_4 = 128 \) mm/min.
4. Conclusion
Axiomatic Green was developed to assist management in applying the green improvement. This method consists of 6 steps that is started from green objective that stated by management. Relationship between green, quality, and other objectives are modelled using axiomatic map. This map used to identify what kind of influence that will be generated by adding green objective to the general axiomatic quality. To quantify this relationship between response and control variables, regression model is used. Then, this relationship model converted to green objective and constraint functions to be processed in non-linear programming (NLP). The optimal solution from this model could be applied as a green improvement.

Axiomatic green has been implemented to design parameter of dry machining in production process using milling machine. Solution generated by this method was to use coolant debit of 0 ml/min., depth of cut of 1.203 mm, cutting speed of 500 rpm, and feed rate of 128 mm/min. This solution has reached the green objective that could decrease the coolant used and make the process more efficient with cost reduction of 195,46 rupiahs.

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Appendix A: Axiomatic Mapping Tree Diagram