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METHOD AND MODEL DEVELOPMENT FOR MANUFACTURING COST ESTIMATION DURING THE EARLY DESIGN PHASE RELATED TO THE COMPLEXITY OF THE MACHINING PROCESSES

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ABSTRACT

Product manufacturing cost estimation in the early stages of the design process is useful for accelerating product time to market, reducing costs, and increasing quality in order to obtain products with a high level of competitiveness in the free market. Complexity and machining cost are important variables to estimate the final cost of the product. However, current cost estimation models only consider their calculations based on the design which has been determined beforehand, so that it is difficult to apply a cost estimation model early on in the design process because of minimal information. Therefore, in this research, a new method to produce a cost estimation model during the early stage of the design process is proposed. The new model was developed by correlating the cost calculation with the complexity of the machining process based on product features. By using this model, the designers are able to put through design changes quickly by modifying revisions at the manufacturing stage. In this paper, the development and implementation of the proposed cost estimation model which involves the milling process is known as the SPMF (Single Product Multi-Features) Product model is explained in detail. The proposed method shows that the SPMF Product model can be used to produce a manufacturing cost estimation based on process complexity.

Keywords: Complexity; Cost estimation; Machining; Process

1. INTRODUCTION

Manufacturers are being driven to produce products quickly with high quality and low cost so that they can compete in the global market. The endeavor to accelerate the process of design has attracted researchers because 70-80 % of the product cost is generated in the design and manufacturing stage (Shehab & Abdalla, 2001; Asiedu & Gu, 2010; Dewhurst & Boothroyd, 1988). A design for a product feature consists of geometrical parts put in order and these become the main factors in determining the complexity and the cost of the product. The design changes may be made by altering various features, so that the structure of the product could be simpler (Boothroyd, 2011) in order that the production time will be shorter. However, simplification of the product structure may have an impact by creating new complexity.

Cost estimation in the early stages of the design process is an endeavor towards estimating the cost of product where the product design has not been determined as yet. Budget estimates must be identified early on in the design process to enhance speed and accuracy.

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Yang and Lin (1997) has succeeded in developing a framework to facilitate cost estimation by utilizing product features obtained from CAD information in the early phases of the design process. The fact that geometrical parts are unlimited has encouraged classification of product features to assist in the performance of cost estimation methods, which, in this particular case, concerns machining product features (Jung, 2002). Any changes applied to geometrical parts will, of course, have an impact on the final value and the product complexity. El Maraghy has succeeded in developing a calculation model which can be used to assess the complexity of the product manufacturing process, although this model does not propose a correlation with the cost calculation and the manufacturing process (El Maraghy & Urbanic, 2003). Development of information technology especially in recognition of product features has simplified the automation process, resulting in a reduction of time in the planning process (Nasr & Kamrani, 2006).

This research proposes a new cost estimation model that can be applied in the early design process which considers the complexity of the manufacturing process. The model in this research is generated for parts manufactured by a milling process. However, by using this particular method, an extension of the model can be developed for other parts beyond those involved in the milling processes.

2. COST ESTIMATION

Cost estimation plays an important role in the product development cycle (Duverlie & Castelain, 1999). Proper cost estimation will simplify the process to determine the profit that will be obtained, evaluation against competitors, and to simplify the investment of a new tool. There are many techniques that have been developed by researchers such as the one shown in Figure 1 (Niazi et al., 2006).

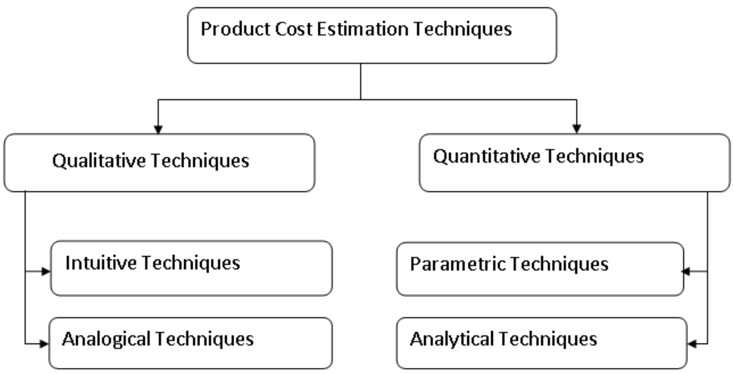


Figure 1 Product cost estimation technique (Niazi et al., 2006)

Qualitative cost estimation techniques are used for estimating costs by relying on the experience of the estimator (intuitive basis) or by searching for product similarity (analogy basis). On the other hand, quantitative cost estimation may be based on a detailed analysis of the product design. The latter technique consists of two kinds of approaches, i.e. parametric and analytical. The difference between the parametric and the analytical technique lies on the level of the data completeness (Niazi et al., 2006).

The analytical technique is based on a detailed analysis of the manufacturing process required. The detailed cost data are collected from the smallest component level to an aggregate of the total product level (Roy et al., 2011). One of analytical techniques used is to identify high cost products through a feature-based cost estimation method (Niazi et al., 2006). The method allows for the selection of a particular design or the form of a feature that is able to characterize the shape, geometry, tolerance, etc. which can be attributed to the manufacturing activity and its techniques. Since the feature itself plays an important role in the product design and manufacturing, it will be beneficial to use it as a basis for cost estimation. However, the cost of the product in the early stages of the design process is not easily calculated, because at this stage the final design has not been decided as yet, so a calculation of product complexity is required.

3. COMPLEXITY

Complexity is a term normally used in day-to-day situations to describe product characteristics. Complexity can be defined as complications of the manufacturing production process.

3.1. Complexity of a Product ($p_{c\text{-}tot}$)

A product is a combination of many parts in which different features are contained. The Complexity of a Product index ($p_{c\text{-}tot}$) is the sum of the factors in the Part Machining Process Complexity (p_{cx}) and the Complexity of the Assembly Process (p_{ass}). Every part which is going to be assembled has a Part Machining Process Complexity index (p_{cx}) whose amount equals the sum of the factors related to the Complexity of the Set-up Process ($p_{c\text{-}su}$), the Operational Process Complexity ($p_{c\text{-}op}$) and the Non-Operational Process Complexity ($p_{c\text{-}no}$) in relation to all of the features contained in the part itself.

3.2. Part Machining Process Complexity (pc_x)

3.2.1. Operational Process Complexity ($p_{c\text{-}op}$)

The Operational Process Complexity is the function of the part entropy information ($H_{process,x}$), the information ratio of part process diversity ($D_{Rprocess,x}$) and the coefficient of the relative process complexity of the part ($c_{process,x}$). Equations 1-6 are used to calculate the Operational Process Complexity [$p_{c\text{-}op}$]. Those equations are adopted from a process complexity evaluation that was introduced by El Maraghy & Urbanic (2003).

$$p_{c-op} = (D_{Rprocess,x} + c_{process,x}) \times H_{process,x} \tag{1}$$

$$p_{c-op} = (\frac{n}{N} + c_{process,x}) \times \log_2(N+1) \tag{2}$$

$$c_{process,x} = \sum_{f=1}^{F} x_f \times c_{f,feature} \tag{3}$$

Where n is the number related to unique information, N is total number of quantifiable information, $c_{f,feature}$ is a coefficient of the relative feature of complexity, x_f is a percentage of a x^{th} factor related to dissimilar features.

The coefficient of relative complexity is on average associated with the relative complexity of various aspects of required features and specifications, and this is represented by:

$$c_{f,feature} = \frac{F_N \times F_{CF} + S_N \times S_{CF}}{F_N + S_N} \tag{4}$$

$$F_{CF} = \frac{\sum_{j=1}^{j} factor\_level_j}{j} \tag{5}$$

$$S_{CF} = \frac{\sum_{k=1}^{K} factor\_level_k}{k} \tag{6}$$

Where F_N is the number of features, F_{CF} is the feature complexity factor, S_N is the number of specifications, S_{CF} is the specification complexity factor, *j* is the number of categories that affect the feature, $factor\_level_j$ is the factor for jth category, *k* is the number of specifications that affect the feature, and $factor\_level_k$ is the factor for kth specification..

3.2.2. Complexity of the Set-up Process ($p_{c\text{-}su}$)

The complexity of the set-up process is affected by the number of workpiece planes and the cutting tools to be used. The increasing number of planes and the number of feature shapes will increase the complexity of the set-up process. Equation 7 shows the model for calculating the Complexity of the Set-up Process, where m is the number of planes and o is the number of different tools used.

$$p_{c-su} = \sum_{i=1}^{o} \sum_{j=1}^{m} (plane + tool) \tag{7}$$

3.2.3. Non-Operational Process Complexity ($p_{c\text{-}no}$)

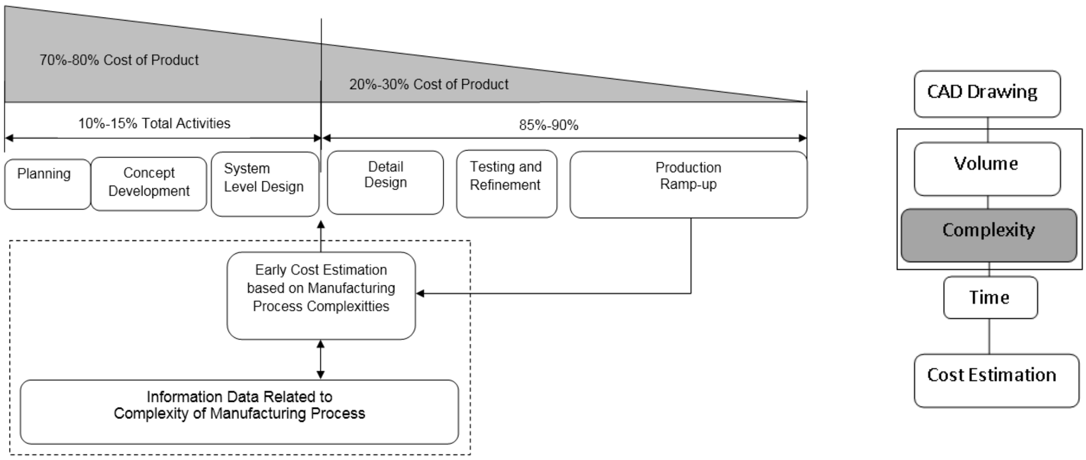
Non-Operational Process Complexity is associated with the process of loading and unloading from one process to another in the production process. The features used in this study are standard features and the influence of the non-operation attributes is considered as not being significant compared to the machining process (Shehab & Abdalla, 2001).

3.2.4. Complexity of the Assembly Process (p_{ass})

To determine the complexity of a manufacturing process such as the part machining process, complexity information data about the variations in shape, geometry and tolerance of all features are required. In this study, the standard feature is classified into four different classes such as Class I (step, groove, chamfer, round, neck, and cylinder), Class II (plain, stair, and slot), Class III (notch, depression, and pocket) and Class IV (hole) (Jung, 2002).

4. DEVELOPMENT OF THE COST ESTIMATION MODEL RELATED TO THE PART MACHINING PROCESS COMPLEXITY

Figure 2(a) shows the schematic diagram of the proposed product cost estimation model in the early stage of the design process by taking into account the complexity index in a manufacturing process. The cost estimation is obtained by correlating the manufacturing process index with manufacturing process time calculation based on the volume of materials removed as shown in Figure 2(b). By understanding the complexity of the part, a cost estimation calculation for the assembly process can also be made easier. The amount of material removal volume shows the complexity level of the process because of the feature's dimensions, geometry, tolerance, etc. which changes accordingly with each one of the characteristics. The standard of overall applicable costs, such as raw material prices, tool prices, overhead costs of machining, labour rates and energy rates are used for calculate the total cost estimation.



(a) (b)

Figure 2 (a) Early cost estimation that considers complexity of manufacturing process; (b) the role of complexity in cost estimation

The methodology to determine complexity of a manufacturing process (that can be represented by a part machining process) is presented in Figure 3. To develop the complexity model data, information about variations in shape, geometry and tolerance of all standard features in the milling process, that include the prismatic feature and slab feature, are needed.

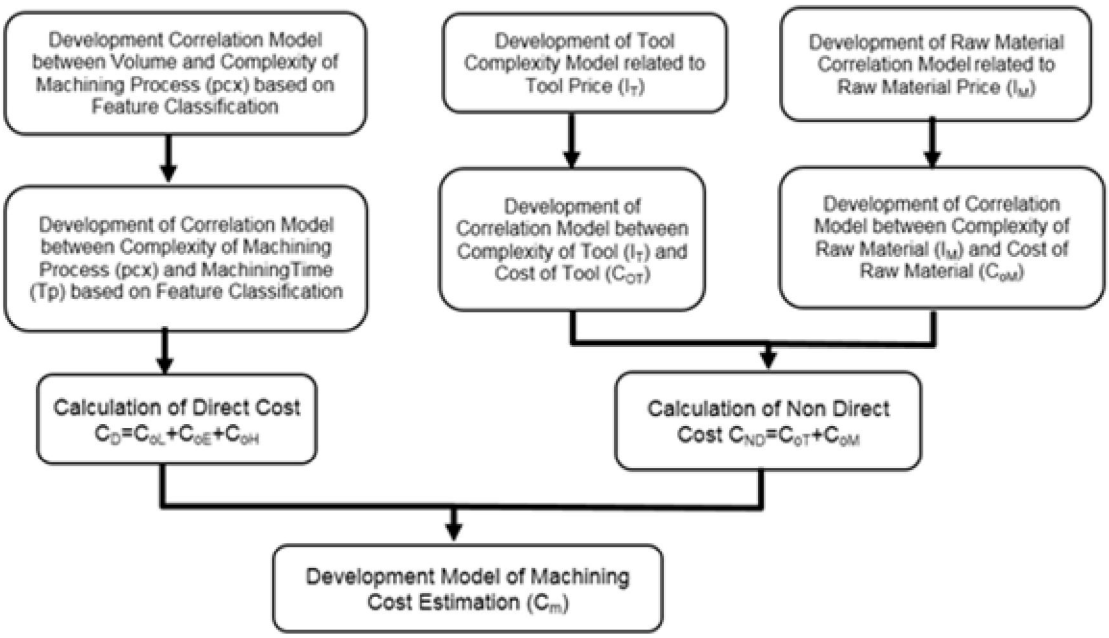


Figure 3 Methodology cost estimation model during early design phase related to complexity of the part machining process

4.1. Development of Model for Machining Process Complexity Calculation (pc_x)

Complexity of the machining process of parts (pc_x) consists of the operational complexity (p_{c-op}), the set up process complexity (p_{c-su}), and the non-operational complexity (p_{c-no}) as described below.

4.1.1. Operational Process Complexity ($p_{c\text{-}op}$)

The complexity calculation of the operational machining process ($p_{c\text{-}op}$) which is affected by many factors, such as cutting material, cutting tool geometry, cutting tool material, machining process, feature shape, feature geometry, tolerance and roughness is performed using Equation 1. DR and H are calculated after the number of fixtures, tools, gauges and machines used for each process when of all of the available features are known, while the weighting for shape and tolerance to calculate relative complexity ($c_{process,x}$) is determined using a multi-tier ranking method while material removal volume is calculated from the feature geometry using the normalization method.

Figure 4 shows the relationship between the volume and the Operational Process Complexity $p_{c\text{-}op}$ for several types of features involved in this study. The complexity of the process for all features increases with the increasing volume of material being cut in the roughing process.

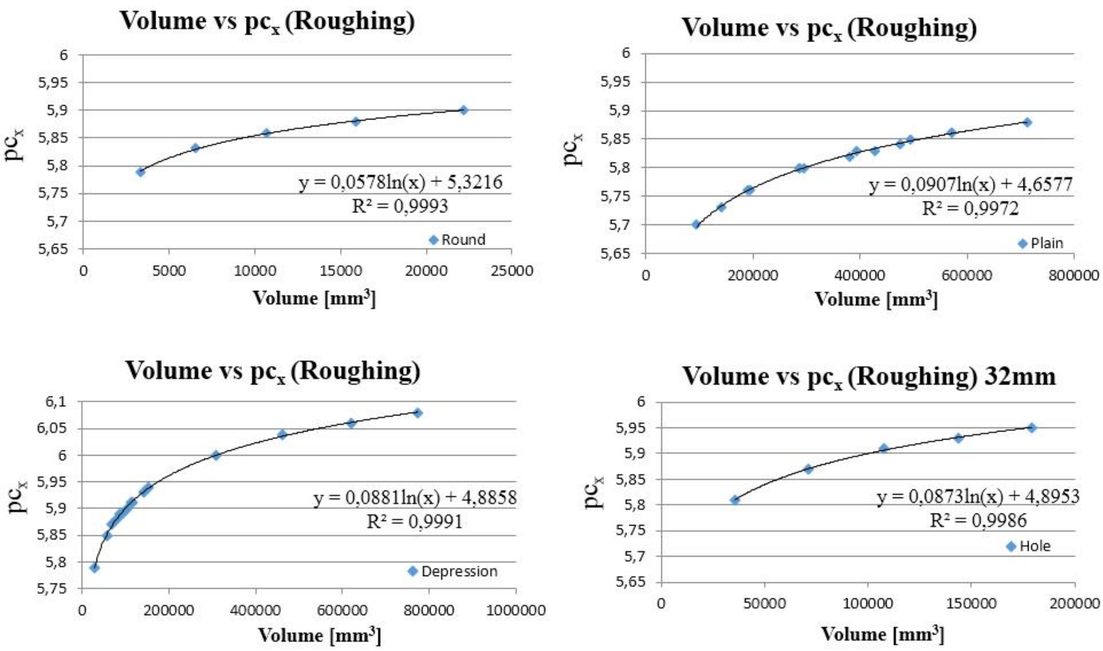


Figure 4 Relationship between volume and $p_{c\text{-}op}$

4.1.2. Set-up Process Complexity ($p_{c\text{-}su}$)

Set-up time is calculated as shown in Equation 8, where the set-up time (T_{su}) is the set-up time standard (T_{std}) which is in the Standard Handbook MTI times the coefficient of plane complexity ($p_{c\text{-}su}$) shown in Table 1 below.

$$T_{su} = T_{std} \times p_{c-su} \tag{8}$$

Table 1 Coefficient of Plane Complexity

Number of Plane	1	2	3	4	5	6
Coefficient of Plane	0,2	0,3	0,5	0,7	0,8	1

4.2. Development of Model Correlating pc_x and T_p

Machining time related with the amount of material removal volume, which is dependent on the geometrical information, process planning, and machine characteristics, must be calculated (Liu et al., 2013). Roughing machining time is calculated with Equation 9, that is

$$t_r = \frac{V_r}{MRR} \tag{9}$$

where;

t_r : rough cutting time (min)

V_r : material volume removed (in^3)

MRR : material removal rate (in^3/min) which depends on the cutting material, cutting geometry, cutting tool tool material and the machining process

To simplify the calculation, machining time of milling for all features is calculated using Unigraphics NX-8. This research focuses on the machining process of standard features so the effect of $p_{c\text{-}su}$ and $p_{c\text{-}no}$ are not yet taken into account and it can be stated that $p_{c\text{-}op}$ is p_{cx}. The relationship between pc_x and the machining time (T_P) is shown in Figure 5 below. The rate of increase in the complexity process (p_{cx}) for all the features affects the increase in duration of the machining process (T_p)

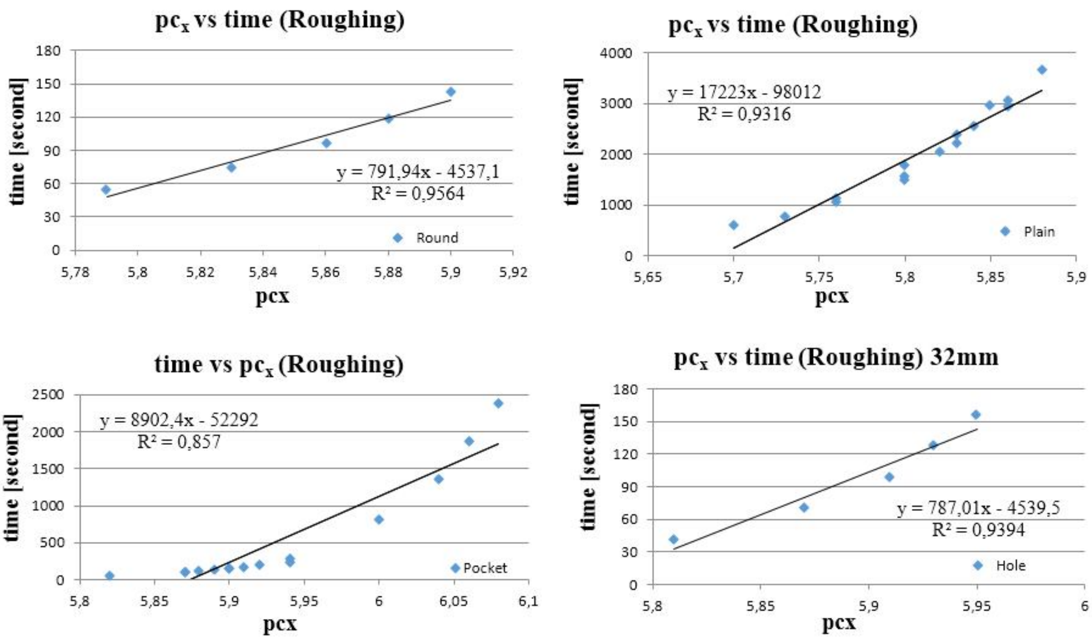


Figure 5 Relationships between pc_x *vs* T_p

The relationship between V and pc_x and also the relationship between pc_x and T_p as shown in Figures 4 and 5 above can be further stated as the general equation to calculate the machining time (y_{time}) as shown in the Equations 10–13. This model is the calculation model of the machining time of a particular feature (y_{time}) which considers the complexity of the machining process (y_{pcx}), the feature and the material removal volume (x_{vol}). The constant values a, b, c, and d are dependent on the feature type, considering Figures 4 and 5.

$$y_{pcx} = a \times \ln(x_{vol}) + b \tag{10}$$

$$y_{time} = c \times x + d \tag{11}$$

$$y_{time} = c \times y_{pcx} + d \tag{12}$$

$$\therefore y_{time} = c \times \left\{ a \times \ln\left(x_{vol}\right) + b \right\} + d \tag{13}$$

4.3. Direct Cost (C_D) and Non-Direct Cost (C_{ND})

4.3.1. Direct Cost (C_D)

Direct Cost (C_D) is the addition of Overhead Cost (C_{OH}), the Cost of Energy (C_{oE}), and the Labor Cost (C_{oL}) based on machining time (T_p). To calculate the Non-Direct Cost (C_{ND}) Equations 14-16 are used, associated with the standard local cost; L_r is the local operator's rate per hour, Er is the local machine's rate per hour, Inv is the machine price, Ey is life time of the machine, and Hy is the total number of work days in a year.

$$C_{oL} = T_p \times L_r \tag{14}$$

$$C_{oE} = T_p \times E_r \tag{15}$$

$$C_{oH} = \frac{Inv}{\left(E_y \times H_y \times 3600\right)} \times T_p \tag{16}$$

4.3.2. Non-Direct Cost (C_{ND})

Non-Direct Cost (C_{ND}) consists of the cost of tools (C_{oT}) and the cost of materials (C_{oM}) which are obtained by multiplying the complexity index of the tools (I_T) and the raw materials (I_M) by the price of Tools and Raw Materials respectively. The Gold Price Index is used as the reference to calculate the Raw Material Complexity Index as shown in Equation 17 where V is the Volume of raw material, Mp is the Material price, and Gp is the Gold price. The Complexity Index of the tools (I_T) is calculated using Equation 18 with the I_T IS index to indicate the complexity of the tool price, where T_o is time tool used during machining process, and T_{life} is life time of tool used:

$$I_M = V \times \frac{M_P}{G_P} \tag{17}$$

$$I_T = \frac{T_o}{T_{life}} \tag{18}$$

5. IMPLEMENTATION AND DISCUSSION

The implementation model is used to calculate the machining time of the SPMF product to determine if the estimation cost model is applicable. The Single Product Multi-Features (SPMF) is a product which has four features, which are: stair, depression, pocket, and slot as shown in Figure 6. The raw material used is a SS 400 type and the machining process uses carbide tools with different diameter tools. The 25 mm diameter tool for the machining feature is related to the stair and slot feature and 32 mm diameter tool is for the feature related to depression and pocket. The machining parameters used for this roughing process are a spindle speed of 900 rpm, a feed rate of 1500 mm/min and depth of cut dimension of 1 mm.

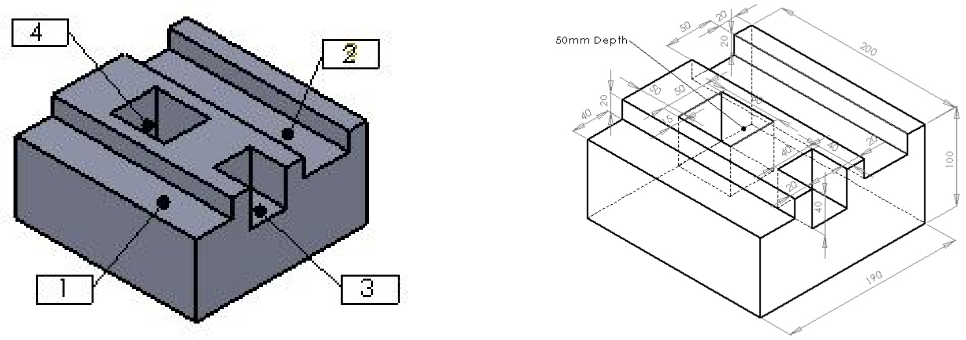


Figure 6 SPMF Product

The machining complexity (p_{cx}), and the machining time (T_p) of the roughing process is calculated based on the volume of materials discarded during the roughing process and is calculated by using Equations 10 and 13 as shown in Table 2 below

Table 2 Result of SPMF product calculation

No	Feature Type	Tool Diameter (mm)	Dimension (mm)			Volume Roughing (mm^3)	Machining Time (minute)
			Length (P)	Width (L)	Depth (T)		
1	Stair	25	200	40	20	154,050	9.4
2	Slot	25	200	50	20	191,100	8.6
3	Depression	32	60	40	40	91,660	4.0
4	Pocket	32	60	50	50	143,105	6.9
	Total of machining time of SPMF Product						28.9

Based on the machining time (T_p), which can be calculated as the total cost of the Direct Cost (C_D) which is in addition to the Cost of Energy (C_{oE} = IDR 6.629), the cost of overheads (C_{oH}=idr 1.372) and the Cost of Labour (C_{oL}=IDR 14.038). The Non-Direct Cost (C_{ND}= IDR 641.609) can be derived from addition of the Cost of Tools (C_{oT}= IDR 137.904) and the Cost of Materials (C_{oM}= IDR 503.705). The total cost of the machining process C_m for the SPMF product is the addition of (C_D) and (C_{ND}) = IDR 663.648 or US$55.3.

Each shape produces the level of complexity for the different machining processes. The increasing complexity of the machining process proved to be influential to the increase in the cost of the manufacturing process. The resulting models can be used to estimate the cost of the manufacturing process at the early stages of the design process, even though this procedure is only limited to the case in accordance with the range of dimensions in this study. This model needs to be developed further so that more research can be undertaken and then implemented in the manufacturing industry

Some local average standards used are:

1. Standard price for machine operators per hour is IDR 29.255
2. Standard price of machine use per hour is IDR 41.105
3. Large machinery investment is IDR 800 million
4. Engine service life is 10 years
5. Operation of the machine in 1 day is 2 shifts = 16 hours
6. Cost of 1 kWh is IDR 1.380
7. Power of milling machine is 10 kW

8. Total number of workdays in a year is assumed to be 265 days
9. 1US$ ≈ IDR 12.000

6. CONCLUSION

The model for cost estimation during the early design phase is based on the process complexity approach which has been developed and implemented in order to estimate the machining cost for the SPMF Product. The model developed has an accuracy rate of 9% when compared with the calculation of the actual cost of the manufacturing industry. To improve on the accuracy of the cost estimation model, it is necessary to develop a more detailed calculation complexity with consideration of aspects such as the step over of the tool diameter in calculation of the coefficient of relative complexity ($c_{proses-x}$). This research is aimed to support a method for the development of an expert system that can directly estimate the product cost with a high degree of accuracy based on 3D CAD models.

7. ACKNOWLEDGEMENT

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8. REFERENCES

Adnan Niazi, et al. 2006. Product Cost Estimation: Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering*, Volume 128, pp. 563–575

Asiedu, Y., Gu, P., 2010. Product Life Cycle Cost Analysis: State of the Art Review. *International Journal of Production Research*

Boothroyd. 2011. *Product Design for Manufacture and Assembly*. 3rd Edition. Boothroyd Dewhurst Inc. and the University of Rhode Island, USA

Changqing Liu et al, 2013, *A feature-based method for NC machining time estimation*, Robotics and Computer-Integrated Manufacturing 29 (2013) 8–14

Dewhurst, P., Boothroyd, G., 1988. Early Cost Estimating in Product Design. *Journal of Manufacturing Systems*, Volume 7(3)

Duverli, P., Castelain, J.M., 1999. Cost Estimation Design Step: Parametric Method Versus Case Based Reasoning Method, *International Jurnal Advance Manufacturing Technology*

El Maraghy, W.H., Urbanic, R., Jill, 2003. *Modelling of Manufacturing Systems Complexity*. Intelligent Manufacturing Systems (IMS) Centre. Faculty of Engineering University of Windsor, Windsor, Ontario, Canada

Jung, Jong–Yun., 2002. Manufacturing Cost Estimation for Machined Parts Based on Manufacturing Features. *Journal intelligent Manufacturing*

MTI System, 2010. *Costimator Standard Handbook* 3rd edition

Nasr, E.S.A., Kamrani, A.K., 2006. A New Methodology for Extracting Manufacturing Features From CAD system. *Computers & Industrial Engineering*, Volume 51, pp. 389–415

Ou-Yang, C., Lin, T.S., 1997. Developing an Integrated Framework for Feature-based Early Manufacturing Cost Estimation. *International Journal Advanced Manufacturing Technology*. Springer-Verlag London Limited

Roy, R., Souchoroukov, P., Shehab, E., 2011. Detailed Cost Estimation in the Automotive Industry: Data and Information Requirements. *Int. J. Production Economics*, Volume 133, pp. 694–707

Shehab, E.M., Abdalla, H.S., 2001. *Manufacturing Cost Modelling for Concurrent Product Development*, Robotics and Computer Integrated Manufacturing. Pergamon