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# AN INTEGRATED OPTIMIZATION MODEL FOR PRODUCT DESIGN AND PRODUCTION ALLOCATION IN A MAKE TO ORDER MANUFACTURING SYSTEM

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## ABSTRACT

A mechanical assembly consists of several components to perform an intended function. At the design stage, the intended function must be converted into critical product dimensions. After determining the dimensions, a designer must determine the assembly tolerance and allocate this tolerance to the tolerances of the corresponding components. After determining the optimal tolerances, process selection must be conducted along with production allocation to the selected process. There are three aspects in commercial competition that must be considered by a manufacturing company: cost, quality, and delivery. The aim of this research is to develop an optimization model for process selection for a make to order company to minimize manufacturing cost, quality loss, and lateness cost. The model attempts to determine optimal tolerance and production allocation, which takes into consideration the production capacity and process sequence. Hence, the model attempts to include not only the product design decision, but also to solve the process selection and allocation problems. A numerical example is provided to show the implementation of the model.

*Keywords:* Integrated optimization; Make to order; Production allocation; Product design

## 1. INTRODUCTION

A mechanical assembly consists of several components to perform an intended function. At the design stage, the intended function must be converted into critical product dimensions. After determining the dimensions, a designer must determine the assembly tolerance and allocate this tolerance to the tolerances of the corresponding components. The tolerance must be set to accommodate the interchangeability of the components and uncertainties in their manufacturing processes. There are two main methods in tolerance design: tolerance synthesis and tolerance analysis. Tolerance synthesis is a method to allocate the assembly tolerance into the tolerances of the corresponding components, while tolerance analysis is a method to predict the resulted assembly tolerance based on the component tolerance. A simulation technique, such as Monte Carlo has been widely used in tolerance analysis. The Monte Carlo simulation uses repeated random sampling to determine the properties of some phenomena. The designer will tend to set a tight tolerance to make the product work properly. In contrast to the designer, the manufacturing engineer will tend to set a loose tolerance so the components can be manufactured at a lower cost. Hence, tolerance design is important, since it will affect the functionality and manufacturing cost of a product.

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Typically, tolerance design can be modeled in two ways: continuous and discrete. By using a continuous model, manufacturing cost was constructed using a cost-tolerance relationship function with upper and lower tolerances are set as the solution space. By using a discrete model, tolerance design is constructed as a process or supplier selection problem. Tolerance design can also be modeled as a mixed model which combines the discrete process selection with the corresponding tolerance-cost function as discussed in the research of Zhang et al. (1992). Manufacturing cost and quality loss are two common objective functions used in the model. In the earlier model, manufacturing cost is the only concern of the researcher. For example, Zhang et al. (1992) and Chase et al. (1990) are two early researchers which try to determine the optimal component tolerance through process selection to minimize the manufacturing cost. Quality cost is added in the later research (Muthu et al., 2009; Rosyidi et al., 2009).

In more recent research, Sivakumar et al. (2011) developed an optimization model to determine the optimal tolerance considering the existence of some alternatives in the manufacturing processes. Rosyidi et al. (2013) developed a model to simultaneously determine the optimal component tolerance through supplier selection and to determine the allocation of such components to the selected supplier. Rosyidi et al. (2014) also developed a make or buy analysis, which can be used to help a decision maker in a manufacturing company in determining the optimal tolerance through supplier/process selection. Although the above research attempts to develop a simultaneous model for product design and production allocation decisions, the research assumed a single stage manufacturing process. In a real system, a component needs a multi-stage manufacturing process and different components will have a different routing process, like in the make to order manufacturing system. This manufacturing system has a complex problem, since different components will be processed using the same manufacturing facilities. The due date of each component will be used as an important aspect of the job assignment and therefore, lateness cost must be added to the objective function of the model.

The aim of this research is to develop an optimization model for process selection in a make to order company to minimize the total cost, which is comprised of manufacturing cost, quality loss, and delivery lateness cost. The model attempts to simultaneously determine optimal tolerance and production allocation, which takes into consideration the production capacity and the process sequence. Consequently, the model attempts to include not only the product design decision, but also attempts to solve the process selection and allocation problems. Those components of the total cost appropriate with the current condition include three aspects that must be considered in commercial competition: manufacturing cost, quality cost, and delivery cost. The manufacturing companies tries not only to manufacture their product at a lower manufacturing and quality cost, but also to deliver their products on time.

## 2. LITERATURE REVIEW

Process selection is a subsequent activity after product design, in which the objective is to determine the appropriate process, resulting in the final shape and dimension of the components. Chase et al. (1990) developed an optimization model to determine the optimal tolerance allocation with an automated process selection. The binary integer model was used to minimize the manufacturing cost by taking into consideration the assembly tolerance. Zhang et al. (1992) developed a similar model by adding manufacturing tolerance and using mixed integer programming in the model. The research used a simulated annealing method to solve the model. In another context, Feng et al. (2001) developed a concurrent optimization model for simultaneously selecting optimal components tolerance and suppliers. Their model was similar to the process selection model with one exception that the process selection needs a process sequence and consequently, the intermediate tolerance is needed in the model.

Ming and Mak (2001) developed an intelligent approach to tolerance allocation and manufacturing operations selection in process planning. The model is applicable to the system in which a feature has several process sequences. The research used Genetic Algorithm (GA) to generate the optimal tolerance for each one of the manufacturing operations. The Hopfield Neural Network (HNN) is adopted to solve the manufacturing operations selection. Singh et al. (2005) developed a mixed integer model to determine the optimal tolerance with interrelated dimension chains. The objective function of the model was to minimize the manufacturing cost. Quality loss has also been added to manufacturing cost in many tolerance design research. For example, Muthu et al. (2009) have developed a model with the same objective function, using a metaheuristic algorithm to solve the model. Sivakumar et al. (2011) have developed a simultaneous optimal selection of design and manufacturing tolerances, considering the alternative manufacturing process.

The models, which use quality loss as the objective function must consider the process capability of the manufacturing facilities. Process capability provides numerical measures on whether a process meets the customer requirement or not (Kaya & Kahraman, 2011). According to Delaney and Phelan (2008), process capability data are also important for design improvement. Beside process capability, production capacity must also be considered in the tolerance design model, especially in a make to order company. In a make to order company, customers order a high variety of products with a low quantity or low volume. Unlike a make to stock company which holds finished goods in inventory as a buffer against variations in customer demand, a make to order company holds capacity in reserve to meet customer demands (Chen et al., 2009). Irianto and Rahmat (2008) developed an optimization model to select the optimal process for a make to order company considering the appraisal cost. Mustajib and Irianto (2010) developed an optimization model for process selection and quality improvement in multi-stage processes. Those research are suitable for process selection in a make to order company without taking into account the allocation problem. Hence, the machine capacity was assumed to be sufficient in meeting the customer's demands.

Several research have been developed to integrate the decisions in product design and manufacturing. Wei (2001) developed a model to concurrently determine the optimal variations, tolerances and batch sizes of an assembly product. The objective of the model was to minimize quality cost, inventory cost, and operation cost of a machine at specific work station. Kazancioglu and Saitou (2006) developed a multi-period production capacity planning for an integrated product and production system design. The model used two stages in decision making. First, tolerance allocation is performed through machine selection using Monte Carlo simulation. Second, the types and quantities of the selected production machines are determined to minimize the production cost during the entire planning horizon. Though it was an integrated model, the product design and production design are not performed simultaneously. Since different production machines must be purchased and sold in every period, the model is not efficient in a practical sense.

## 3. PROBLEM STATEMENT

A class of production systems, similar to the research of Kazancioglu and Saitou (2006) is considered in this research. The company received orders from its customers in the form of assembly products in which each assembly consists of several components. The components are produced by the company using its own production facilities. The company has several shops to manufacture the needed components. Each shop in the production system has $K$ machines to manufacture the components. Each machine in a shop erforms the same manufacturing process. Each component will have different manufacturing process sequence. Figure 1 depicts the system under consideration in which the company will produce *i* components in a production system with 3 shops. For example, the process sequence of Component 1 starts with Shop 1, Shop 2, and then Shop 3. Component 2 has different sequence in which it must be manufactured in Shop 1, Shop 3 and then Shop 2. Component *i* will be firstly manufactured in Shop 3, then Shop 2, and Shop 1. After completing the manufacturing processes, the components will be assembled into a final product. It is assumed that every machine in each shop has its own process capability and production capacity. Hence, there are two problems which are being attempted to solve in this research. First, how to select the optimal tolerances through process selection. Second, how to allocate the components to the selected machine in each shop to minimize a total cost comprised of manufacturing cost, quality loss, and lateness cost.

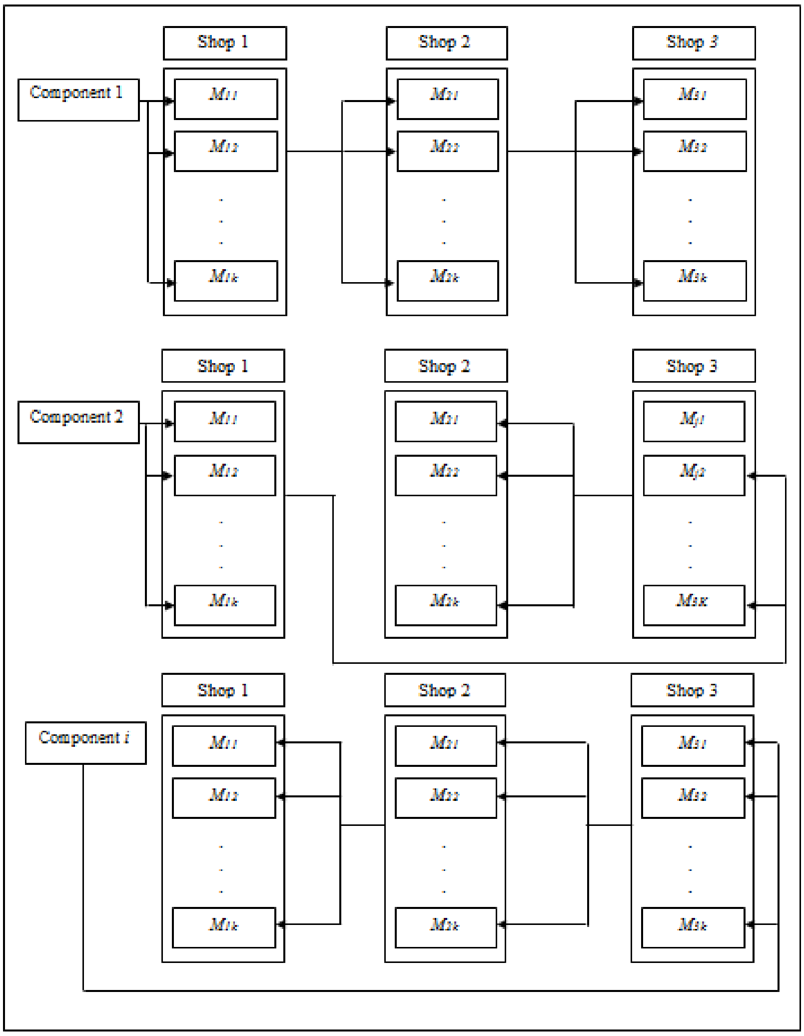


Figure 1 System under consideration

# 4. MODEL DEVELOPMENT

## 4.1. The Objective Function

The objective function of this research is to minimize a total cost which is comprised of manufacturing cost, quality loss, and lateness cost. The manufacturing cost can be expressed as in Equation 1. In this equation, $b_{ijk}$ denotes the binary variable which represents the process selection, while $c_{ijk}$ denotes the cost to manufacture component $i$ in shop $j$ using machine $k$.

The binary variable $b_{ijk}$ will have the value of 1 if machine $k$ in shop $j$ was selected to manufacture component $i$, and 0 otherwise. Equation 2 expresses the binary variable. The number of allocated component $i$ to shop $j$ using machine $k$ is denoted by $m_{ijk}$.

$$MC = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} b_{ijk} m_{ijk} c_{ijk} \tag{1}$$

$$b_{ijk} = \begin{cases} 1, \text{ if component } i \text{ is manufactured in shop } j \text{ using machine } k \\ 0, \text{ otherwise} \end{cases} \tag{2}$$

In this research, the Taguchi loss function details the implications involved with poor quality and is used to measure the quality cost in order to focus on continuous improvement. Assuming that the process mean is equal to the nominal value and the quality loss is symmetric, then the quality cost per unit component can be written as in Equation 3. The second cost component of the model is found from the product of the binary variable, the number of components, and the variance per component as seen in Equation 4. In this equation, $\sigma_{ijk}$ denotes the standard deviation of component $i$ which is manufactured in shop $j$ using machine $k$. The standard deviation will depend on the process capability index of machine $k$ in shop $j$. Equation 5 shows the relationship between the standard deviation and the process capability index. In this equation, $t_{ijk}$ denotes the tolerance of component $i$ which is manufactured in shop $j$ using machine $k$ and $Cp_{jk}$ is the capability index of machine $k$ in shop $j$. The capability index is a value that is related to the design and manufacturing process. This equation is needed to determine the standard deviation of component $i$ in which the results will be used to determine the quality cost in Equation 4.

$$Q_I = E[L(x_1, x_2, .., x_i)] = E\left[\sum_{i=1}^{I} a\left(x-\mu\right)^2\right] = \sum_{i=1}^{I} a_i \sigma_i^{\,2} \tag{3}$$

$$QC = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} b_{ijk}\sigma_{ijk}^2 m_{ijk} \tag{4}$$

$$\sigma_{ijk} = \frac{t_{ijk}}{3Cp_{jk}} \tag{5}$$

The third component of the total cost is the lateness cost. Equation 6 determines the actual time it takes to manufacture the components, which is defined as the longest time in the manufacturing process. In this equation, $w_{ijk}$ denotes the time needed to manufacture component $i$ in shop $j$ using machine $k$.

$$w_{max} = max\{\sum_{i=1}^{I}\sum_{j=1}^{J} w_{ijk} m_{ijk} b_{ijk}\},\ \forall k \tag{6}$$

The lateness cost is expressed in Equation 7, where $l$ denotes the lateness cost per unit time, $W$ denotes total time to manufacture and assemble the components into a final product, and $w_T$ denotes the order due date. The lateness of an order is defined as the difference between $W$ and $w_T$ which can be expressed in Equation 8.

$$LC = l(W - w_T) \tag{7}$$

$$w_T = \begin{cases} W - w_T, \ if\ W > w_T \\ 0,\ if\ W \le w_T \end{cases} \tag{8}$$

### 4.2. The Constraints

In this research, five constraints are considered: assembly tolerance, production capacity of the machines, total number of components to be manufactured, the minimum number of selected machines for each component, and the manufacturing process sequence.

*4.2.1. Assembly tolerance constraint*

The assembly tolerance is a result of the tolerance accumulation of its constituent components. Equation 9 shows the constraint in which the accumulation of the overall components tolerance may not exceed the assembly tolerance set by the designer.

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\left(\left(\frac{\delta f}{\delta x_i}\right)^2 \sigma_{ijk}{}^2 b_{ijk}\right) \leq \sigma_A{}^2 \tag{9}$$

Substituting Equation 5 into Equation 9 results in the following:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\left(\left(\frac{\partial f}{\partial x_i}\right)^2 \left(\frac{t_{ijk}}{Cp_{jk}}\right)^2 b_{ijk}\right) \leq \left(\frac{T_A}{Cp_{jk}}\right)^2 \tag{10}$$

where:

$\left(\frac{\delta f}{\delta x_i}\right)^2$ : partial derivative of functional dimension of component *i*

$t_{ijk}$ : tolerance of component i which is manufactured in shop *j* using machine *k*

$Cp_{jk}$ : capability index of machine *k* in shop *j*

$T_A$ : assembly tolerance

A component tolerance results from a series of manufacturing processes. Furthermore, the manufacturing tolerance constraint must be imposed on the model to keep the resulted components tolerance within the specified tolerance. Equation 11 shows the constraint. In this equation, $\delta_{ijk}^{a}$ denotes the resultant variance of component *i* in shop *j* using machine *k* at *a*-th process in the sequence, while $\delta_{ijk}^{a-1}$ denotes the process prior to *a*-th process in the respective sequence.

$$\left(\frac{\delta_{ijk}^{a-1}}{3Cp_{jk}}\right)^2 + \left(\frac{\delta_{ijk}^{a}}{3Cp_{jk}}\right)^2 \leq \sigma_i{}^2 \tag{11}$$

*4.2.2. Production capacity of the machine*

This constraint ensures that the number of components *i* which is manufactured in shop *j* using machine *k* must be equal to the components needed for assembly. The constraint shows in Equation 12, in which $n_i$ and *D* denote the number of component *i* in the final assembly and total demand, respectively.

$$\sum_{k=1}^{K} m_{ijk} = n_i D \qquad \forall i,j \tag{12}$$

*4.2.3. The minimum number of selected machines for each component*

This constraint is needed to ensure the number of selected machines is enough to manufacture the components. Equation 13 shows the constraint in which $N_{jk}$ denotes the minimum number of machines *k* in shop *j* to be selected in manufacturing of component *i*.

$$\sum_{j=1}^{J}\sum_{k=1}^{K} b_{ijk} \geq N_{jk} \tag{13}$$

*4.2.4. Manufacturing sequence*

The manufacturing sequence is assumed to be known in advance. This constraint is used to ensure the component has the right sequence in the manufacturing process. According to Pinedo (2008), two constraints must be imposed as in Equations 14 and 15. Equation 14 is used to ensure the successor manufacturing process cannot be started before the current process, while

Equation 15 ensures that the manufacturing process time does not exceed the longest time to manufacture a component in the sequence.

$$s_{ijk}^{b} - s_{ijk}^{a} \geq p_{ijk}^{a} \tag{14}$$

$$w_{max} - s_{ijk}^{a} \geq p_{ijk}^{a} \tag{15}$$

Where;

$s_{ijk}^{a}$ : the starting time of component *i* in shop *j* using machine *k* at *a*-th sequence

$s_{ijk}^{b}$ : the starting time of component *i* in shop *j* using machine *k* at *b*-th sequence

$p_{ijk}^{a}$ : processing time of component *i* in shop *j* using machine *k* at *a*-th sequence

$w_{max}$ : the longest time in the manufacturing process in the sequence

## 5. NUMERICAL EXAMPLE AND ANALYSIS

A simple asssembly from Cao et al. (2009) is used for the numerical example. The assembly was used commonly for tools and consists of three components, namely the revolution axis (RA), the end shield nut (ESN), and the sleeve (S). Gap ($x_0$) between the sleeve and revolution axis is the key characteristic of the assembly. The dimensions of key characteristics of the revolution axis ($x_1$), the end shield nut ($x_2$), and the sleeve ($x_3$) are 38, 42, and 80 mm, respectively. The tolerance of the gap is 0.25 mm. The dimension chain of the assembly is shown in Figure 1, while the dimension function and its variance function are expressed in Equations 16 and 17, respectively. Equation 17 is then used to derive the constraint in Equations 9 and 10. The company received an order of 45 units of final product. Since each assembly needs one component, then the company must produce 45 units for each component.

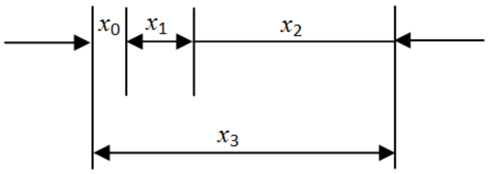


Figure 2 The dimension chain of the assembly

$$x_0 = x_3 - x_2 - x_1 \tag{16}$$

$$\sigma_0^2 = \left(\frac{\delta x_0}{\delta x_1}\right)^2 \sigma_1^2 + \left(\frac{\delta x_0}{\delta x_2}\right)^2 \sigma_2^2 + \left(\frac{\delta x_0}{\delta x_3}\right)^2 \sigma_3^2 \tag{17}$$

The process sequence for each component is shown in Table 1. In that table we can see that Component RA has a process sequence of Shop 1, Shop 2, and Shop 3. Component ESN has a process sequence of Shop 2, Shop1, and Shop 3, while Component S has a sequence of Shop 3, Shop 1, and Shop 2. Each Shop in the manufacturing system has 2 machines in which the corresponding manufacturing cost at each machine is shown in Table 2. Tables 3, 4, and 5 show the tolerance, processing time, and production capacity of each machine in each shop for the purpose of manufacturing the components. In the manufacturing process, tighter tolerance requires higher cost and longer processing time. For example, using Machine 1 and Machine 2, the tolerance of component ESN in shop 1 are 0.07 and 0.09 mm, respectively. The manufacturing cost and processing time of such a component in Machine 1 is higher than that in Machine 2. It is assumed that each machine has the same process capability $C_p$ = 1.25. The quality loss and lateness cost are assumed to be the same, which are IDR 100,000 and IDR 20/min, respectively.

Table 1 The manufacturing sequence for each component

| Component | Manufacturing Sequence | | | | |
|---|---|---|---|---|---|
| RA | Shop 1 | → | Shop 2 | → | Shop 3 |
| ESN | Shop 2 | → | Shop 1 | → | Shop 3 |
| S | Shop 3 | → | Shop 1 | → | Shop 2 |

Table 2 Manufacturing cost for each component

| Component | Shop 1 (IDR) | | Shop 2 (IDR) | | Shop 3 (IDR) | |
|---|---|---|---|---|---|---|
| | $M_1$ | $M_2$ | $M_1$ | $M_2$ | $M_1$ | $M_2$ |
| RA | 7,500 | 8,500 | 6,200 | 8,500 | 7,900 | 6,500 |
| ESN | 7,000 | 6,500 | 7,600 | 8,700 | 6,000 | 8,900 |
| S | 6,200 | 8,700 | 8,000 | 6,700 | 7,600 | 8,800 |

Table 3 Tolerance data for each component

| Component | Shop 1 (mm) | | Shop 2 (mm) | | Shop 3 (mm) | |
|---|---|---|---|---|---|---|
| | $M_1$ | $M_2$ | $M_1$ | $M_2$ | $M_1$ | $M_2$ |
| RA | 0.08 | 0.05 | 0.10 | 0.05 | 0.07 | 0.09 |
| ESN | 0.07 | 0.09 | 0.08 | 0.05 | 0.10 | 0.05 |
| S | 0.10 | 0.05 | 0.07 | 0.09 | 0.08 | 0.05 |

Table 4 Processing time data for each component

| Component | Shop 1 (min) | | Shop 2 (min) | | Shop 3 (min) | |
|---|---|---|---|---|---|---|
| | $M_1$ | $M_2$ | $M_1$ | $M_2$ | $M_1$ | $M_2$ |
| RA | 9 | 12 | 9 | 15 | 12 | 9 |
| ESN | 10 | 8 | 11 | 14 | 8 | 14 |
| S | 8 | 14 | 10 | 8 | 11 | 15 |

Table 5 Production capacity in each machine (unit)

| Shop 1 | | Shop 2 | | Shop 3 | |
|---|---|---|---|---|---|
| $M_1$ | $M_2$ | $M_1$ | $M_2$ | $M_1$ | $M_2$ |
| 95 | 65 | 105 | 75 | 80 | 120 |

Table 6 shows the results of optimal process selection and component allocation to the selected process. The total cost to manufacture 45 units of assembly product is IDR 3,107,766 which consists of IDR 3,070,500 of manufacturing cost, IDR 27,266 of quality cost, and IDR 10,000 of lateness cost.

Table 6 The results of optimization

| Component | Shop 1 | | Shop 2 | | Shop 3 | |
|---|---|---|---|---|---|---|
| | $M_1$ | $M_2$ | $M_1$ | $M_2$ | $M_1$ | $M_2$ |
| RA | 45 | - | 45 | - | 45 | - |
| ESN | 45 | - | 45 | - | - | 45 |
| S | 5 | 40 | 5 | 40 | 35 | 10 |

A sensitivity analysis is performed to study the effect of model parameters on the decision variables and the objective function of the model. The effects of the changes in quality loss coefficient, tolerances, manufacturing cost, and manufacturing process time are studied. The quality loss coefficient will be changed by 0.5, 2, 10, and 20 times from the initial value of the parameters in the numerical example. Varying the value of quality loss coefficient is needed, since the coefficient is one of the important parameters that is affecting the total cost. Feng and Balusu (1999) explained that the quality loss coefficient has a relationship with the manufacturing cost of the entire assembly. Hence, in manufacturing practice, it explains the effect of the selected machine in each shop, i.e. the manufacturing cost of the entire assembly to the resultant total cost. Furthermore, Feng and Balusu (1999) explained that, according to Cali (1993), varying the coefficient to 10-times of its original value is based on the GE 10-times rule which when simply stated says: if a defective part is skipped and passed to the next process, the cost of detecting and fixing the same defect would be 10 times the cost, if it were detected in the previous process.

In the sensitivity analysis, four scenarios are developed in this research. The first scenario is developed to study the effect of loosening the component tolerance to the model. As a consequence, in the first scenario, the tolerance of RA in each shop at Machine 1 is twice that given in the numerical example and the manufacturing cost is also decreased by a half. The manufacturing process time is assumed not to be affected by the loosening of the tolerance. In the second scenario, the manufacturing cost in each shop at Machine 1 is half that given in the numerical example with the same tolerances and manufacturing process time. With this scenario, we study the effect of changes in manufacturing cost to the model. In the third scenario, the tolerance of the component in each shop at Machine 2 is made tighter than that in the numerical example. The manufacturing process time in each shop at Machine 2 is twice that given in the numerical example with the same manufacturing cost. Hence, we study the effect of tightening the tolerance, which will take longer in terms of manufacturing process time than the model. In the last scenario, the tolerances of ESN and S in each shop are tightened. The manufacturing process time is twice that given from the one in the numerical example with the same manufacturing cost. This scenario is developed to study the effect of changing two parameters of two components simultaneously.

The results of the sensitivity analysis are shown in Table 7. For Scenario 1, when the quality loss coefficient is twice that given in the initial value, all machines are selected for S. It indicates that the model tends to select the machine with a looser tolerance to result in a lower manufacturing cost. When the quality loss coefficient is made 10 and 20 times from the initial value, the model tends to select the process with tighter tolerance, since the reduction in manufacturing cost will not justify the increase of quality loss. For Scenario 2, due to the decrease in the manufacturing cost of Machine 1 at each shop, some of the components will be allocated to Machine 1. When the reduction of manufacturing cost is not justified by the increase of quality loss, then Machine 1 is not selected to manufacture the components. In Scenario 3, the model tends to select the machine with a tighter tolerance, since there are no changes in the manufacturing. It means that the increase of the resulted total cost comes from the lateness cost due to the longer processing time. In Scenario 4, due to tighter tolerance resulting from each machine for ESN and S, the selected machine was changed to a machine with lower lateness cost.

Table 7 The results of the sensitivity analysis

| Scenario | Quality Loss Coefficient | Production Allocation | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RA | | | | | | ESN | | | | | | S | | | | | |
| | | $M_{11}$ | $M_{12}$ | $M_{21}$ | $M_{22}$ | $M_{31}$ | $M_{32}$ | $M_{11}$ | $M_{12}$ | $M_{21}$ | $M_{22}$ | $M_{31}$ | $M_{32}$ | $M_{11}$ | $M_{12}$ | $M_{21}$ | $M_{22}$ | $M_{31}$ | $M_{32}$ |
| 1 | 0.5 | 45 | - | 45 | - | - | 45 | 45 | - | 45 | - | 45 | - | - | 45 | - | 45 | 35 | 10 |
| | 2 | 45 | - | 45 | - | - | 45 | 45 | - | 45 | - | 45 | - | 5 | 40 | 5 | 40 | 35 | 10 |
| | 10 | 45 | - | 45 | - | - | 45 | 45 | - | 45 | - | 45 | - | - | 45 | - | 45 | 35 | 10 |
| | 20 | 45 | - | 45 | - | - | 45 | 45 | - | 45 | - | 45 | - | - | 45 | - | 45 | 35 | 10 |
| 2 | 0.5 | 45 | - | 45 | - | 35 | 10 | 45 | - | 45 | - | 45 | - | - | 45 | - | 45 | - | 45 |
| | 2 | 45 | - | 45 | - | 45 | - | 45 | - | 45 | - | - | 45 | 5 | 40 | 5 | 40 | 35 | 10 |
| | 10 | 45 | - | 45 | - | 45 | - | 45 | - | 45 | - | - | 45 | 5 | 40 | 5 | 40 | 35 | 10 |
| | 20 | 45 | - | 45 | - | 45 | - | 45 | - | 45 | - | - | 45 | - | 45 | - | 45 | 35 | 10 |
| 3 | 0.5 | - | 45 | 30 | 15 | - | 45 | 45 | - | 30 | 15 | 45 | - | 45 | - | 45 | - | - | 45 |
| | 2 | 45 | - | 30 | 15 | - | 45 | - | 45 | 30 | 15 | 35 | 10 | 45 | - | 45 | - | 45 | - |
| | 10 | - | 45 | 30 | 15 | - | 45 | 45 | - | 30 | 15 | 45 | - | 45 | - | 45 | - | - | 45 |
| | 20 | 45 | - | 30 | 15 | - | 45 | - | 45 | 30 | 15 | 45 | - | 45 | - | 45 | - | - | 45 |
| 4 | 0.5 | 45 | | 30 | 15 | - | 45 | - | 45 | 30 | 15 | 45 | - | 45 | - | 45 | - | 35 | 10 |
| | 2 | 45 | - | 30 | 15 | - | 45 | - | 45 | 30 | 15 | 45 | - | 45 | - | 45 | - | - | 45 |
| | 10 | 45 | - | 40 | 5 | 45 | - | - | 45 | 40 | 5 | 35 | 10 | 25 | 20 | 25 | 20 | - | 45 |
| | 20 | 45 | - | 30 | - | 45 | - | 45 | - | 45 | - | 35 | 10 | - | 45 | - | 45 | - | 45 |

## 6. CONCLUSION

In this research, an integrated optimization model to determine the optimal components tolerance and production allocation through process selection was developed. The objective function of the model was to minimize a total cost which is comprised of manufacturing cost, quality loss, and lateness cost. In practicality, this paper contributed to a way of solving problems, i.e., concerning the tolerance allocation, supplier selection, and order allocation to the selected suppliers where each manufactured component has a different routing sequence. Hence, the model is applicable in a make to order company. For future research, the model can be extended by incorporating fuzziness in the manufacturing cost and quality loss to accommodate the uncertainties in the manufacturing process. Another direction of the future research is to develop an optimization model for make or buy decision making problems.

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