Implementation of Triple Bottom Line Concept and Selection of a Product Design

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Abstract. Triple bottom line concept is based on three criteria's evaluation namely manufacturing costs, environmental integrity and social equity. Manufacturing costs is a critical element to ensure the economic sustainability of a company. Environmental integrity has become very crucial as people around the world realized the importance to meet the needs of the present generations without compromising the ability of future generations. Social equity is difficult to evaluate, but at the production floor level it could involve the production operator health. In this paper the concept is applied in the manufacturing phase of a pneumatic nipple hose taking into consideration the impact of the machining processes on manufacturing costs, environmental divided into energy consumed and carbon footprint and ergonomics effect. This study involves multi criteria decision making in the presence of multiple objectives. In this case there are four criteria which usually conflicting and therefore, the proposed solution is highly dependent on the preferences of groups of decision makers and is developed within an understanding framework and mutual compromise. This study use genetic algorithm and Fuzzy Analytical Hierarchy Process (Fuzzy AHP) at the product design stage in making decision based on the triple bottom line concept.

Keywords: Triple Bottom Line, Fuzzy AHP and Genetic Algorithm

1. INTRODUCTION

Today, manufacturing cost to produce a product is continuously increasing because of the increasing costs of raw materials, energy, coolant and lubricant and man power costs due to inflation and unfavorable exchange rates. This situation also forced the manufacturers to also consider the costs associated with environmental impact and workers wellbeing. There are several major stake holders interested in the 4 aspects of a product namely economic profitability, environmental integrity, energy integrity and ergonomic equity. Client and user is a stake holder which is interested in the economics aspects. On the other hand, the trade associations are interested in the social aspects of the workers such as long term effect of the manufacturing process on the quality of life of the workers. The environmental and energy aspects would be of interest to the environmental agency, the community and private sector since the private sector need to fulfill the environmental regulation set by the European nation and the USA if they want to compete in the global market. However taking into consideration these four aspects in making any decision on the design of product is still a difficult task as it involves optimization of criteria and multiple objectives problems.

One of the approach is to optimized is by using Genetic Algorithm (GA) and then implement Fuzzy AHP method to ranks the solutions. Here, genetic algorithm function is to optimize the possible solutions and then fuzzy weights are assigned to the each criteria using fuzzy AHP and lastly, the distance method is used to rank the solutions. This method is demonstrated with a case study of a pneumatic connector.

2. SELECTION OF A PRODUCT DESIGN

Nowadays, there are several methods developed and introduced by researchers to select the most optimum design to be implemented. Among the methods are Quality Function Deployment (QFD), Pugh Concept selection method and Fuzzy Analytic Hierarchy Process (Fuzzy AHP).

According to Kasaei et al (2004), the Quality Fun ction Deployment (QFD) approach is a structured appr oach used to define consumer needs and translating th em into specific plans and to produce products that m eet those needs. In this approach, consumer opinion is used to make product improvement. Consumer voice is captured by using discussion method, interviews, surve ys, focus groups, customer specifications, observation, warranty data and field reports. The collected data is t hen summarized in a product planning matrix also kno wn as "house of quality". These matrices are used to t ranslate higher level "what's" or needs into lower level "how's" - product requirements or technical characterist ics to satisfy these needs (Kasaei et al, 2004). The working principle of quality function deployment is based on weighting factors and available number of solutions set by a group of expert people suggested to be implemented.

Pugh concept selection method is a structured approach used to select the best concept to be implemented (Ulrich and Eppinger, 2015). In this concept selection method, all the related criteria that will be used in the evaluation need to be set first. Then, based on the pair wise comparisons with datum concept, the available concept is rated by using symbols “+” for better than datum concept or “-“ for worse than datum concept and “=” for equal with datum concept. The highest “+” results symbols will be selected as a concept that will be implemented. If the result is the same for more than one concept, the evaluation will be done again with a different set of criteria.

Fuzzy Analytic Hierarchy Process is an evaluation process used by researchers to solve multi-criteria decision making (MCDM) problems. Generally, in MCDM problems, there is more than one objective involved in the evaluation and each of the criteria is conflicting with one another. Each criteria output is not necessary in the same units but usually is in different units. Hence Analytic Hierarchy Process (AHP) evaluation method will convert the different units into one common language. The used of fuzzy element allows the evaluation method to mimic the human thinking hence it is hard to predict the results as at the early stages of the evaluation. The highest ranked is the most optimum hence will be selected as the implemented solution.

3. PROJECT METHODOLOGY

The triple bottom line concept was introduced by John Elkington which encompasses a new framework to measure performance in corporate companies in the United States of America (USA). The proposed concept went beyond the traditional measures of profits, return on investment, and shareholder value used by company more than 10 years ago. These concepts include environmental and social dimensions in the assessment. By focusing on financial profitability, social equity and the environmental integrity, triple bottom line reporting can be an important tool to support sustainability goals.

Financial profitability includes the costs of pollutio n, worker displacement, and other factors in its profit calculations; while environmental integrity is a commit ment by the company to reduce its environmental foot prints by reducing waste, conserving more energy, and maintaining environmentally safe manufacturing process

There is no universal indicator that can be used to measure triple bottom line (Slaper and Hall, 2011). Among the indicators that can be used to assess financial profitability are personal income, cost of underemployment, job growth and revenue by sector contributing to gross state product. On the other hand, Environmental integrity represents measurement of environmental impact when manufacturing products. It could incorporate the surrounding air and water quality, energy consume during producing products, natural resources; disposal of solid and toxic waste and land use / land cover. Lastly for social equity, it represents the measurement of human well being such as unemployment rate, median household income, relative poverty, and violent crime per capita.

In this paper the triple bottom line approach is proposed to select the most optimum design solutions of a product namely pneumatic connector. The pneumatic connector as shown in Figure 1 was used as a case study because the demand of the product is high since it is used in many industries.

Figure 1: Pneumatic Connector

For financial profitability, the total manufacturing cost approach is adopted because it represents the production cost needed to produce the part.. the total manufacturing cost equation is adopted from Hao (2012) by Zahari Taha et al., 2015 and is as shown in Equation (1).

Total manufacturing cost = Material cost + Tool cost + coolant and lubricant cost + Energy cost + Labor cost (1)

Where:

Material Cost = Standard size price (RM/Vol) x Required size (2)

Tool cost = (Number of cutting tool (n) x tool cost / unit (RM)) / number of product produced (3)

Energy cost = Energy used to fabricate a product (kWh) x electrical tariff (RM/kWh) (4)

Labor cost = Salary (RM/month) / output per month (5)

If the machining process involves more than one type of cutting tool, each type of cutting tool cost must be considered.

Coolant or Lubricant Cost = Coolant or lubricant volume x Coolant or lubricant cost rate (6)

For Coolant or Lubricant Volume and Makeup volume, the detail calculation is given by

Coolant or lubricant volume = (tank capacity + makeup volume) / (month used x actual output) (7)

Makeup volume = (tank capacity x coolant or lubricant loss rate) / (1 – coolant or lubricant loss rate) (8)

In this study, the coolant cost is not take into account since the machining process did not used any coolant. Besides that, the tool cost is also not taken into account since the contribution is too small compared to the whole manufacturing costs.

Based on literature survey, the evaluation of environmental integrity assessment in a production line consists of chip recycling impact, coolant and lubrication impact and energy impact (Narita et al., 2012). In this study, energy cost is considered separately since it contributes more than 50% to the environmental cost such that other factors will lose its impact. The chip recycling impact, coolant and lubrication impact is assessed from Narita *et. al.* (2012) which consider the amount of carbon weight released into the air by the scrap material produced from the fabrication process, amount of coolant used in the fabrication process and amount of lubricant used to fabricate the product. The following equations are used to calculate these three elements.

$$C_e = (CUT/CL) \times \{(CPe + CDe) \times (CC + AC) + WA_e \times (WAQ + AWAQ)\} \quad (9)$$

Where C_e is coolant impact consumption; CUT is coolant usage time in an NC program (s); CL is mean interval of coolant update (s); CPe is environmental burden of cutting fluid production (kg-CO2/L); CDe is environmental burden of cutting fluid disposal (kg-CO2/L); CC is initial coolant quantity (L); AC is additional supplement quantity of coolant (L); WAe is environmental burden of water distribution (kg-CO2/L); WAQ is initial quantity of water (L) and AWAQ is additional supplement quantity of water (L).

$$LO_e = (SRT/SI) \times SV \times (SPe + SDe) + (LUT/LI) \times LV \times (LPe + LDe) \quad (10)$$

Where LO_e is lubricant oil impact consumption; SRT is spindle runtime in an NC program (s); SV is discharge rate of spindle lubricant oil (L); SI is mean interval between discharges; SPe is environmental burden of spindle lubricant oil production (kg-CO2/L); SDe is mean interval between discharges; SPe is environmental burden of spindle lubricant oil disposal (kg-CO2/L); LUT Slide way runtime in an NC program (s); LI is mean interval between supplies (s); *LV*: Lubricant oil quantity supplied to slide way [L]; LPe is Environmental burden of slide way lubricant oil production [kg-CO2/L] and *LDe*: Environmental burden of slide way lubricant oil disposal [kg-CO2/L]

$$Ch_e = \left(WpV - pV \times d \times LCI(M)\right) \quad (11)$$

Where Ch_e is chip recycling impact; WpV is workpiece volume; pV is product volume; d is material density; LCI (M) is metal chip recycling emission intensity. The energy cost for CNC turning process is given by:

$$E_e = k \ (SME + SPE + SCE + CME + CPE + TCE1 + TCE2 + ATCE + MGE + OAE + COE + CUE + SBE)$$

Where E_e is machine power consumption impact; k: CO2 emission intensity of electricity (kg-CO2/kWh); *SME*: Electricity consumption of servo motors (kWh); *SPE*:

Electricity consumption of a spindle motor (kWh); *NCE*: Electricity consumption of an NC controller (kWh); *SCE*: Electricity consumption of a cooling system of spindle (kWh); *CME*: Electricity consumption of a compressor (kWh); *CPE*: Electricity consumption of a coolant pump (kWh); *TCE1*: Electricity consumption of a lift up chip conveyor (kWh); *TCE2*: Electricity consumption of a chip conveyor in machine tool (kWh); *ATCE*: Electricity consumption of an auto tool changer (ATC) (kWh); *MGE*: Electricity consumption of a tool magazine motor (kWh); *OAE*: Electricity consumption of an oil air compressor (kWh); *COE*: Electricity consumption of an oil mist compressor (kWh); *CUE*: Electricity consumption of a chip air blow compressor (kWh); *SBE*: Stand-by energy of a machine tool (kWh).

Generally, social equity is related to the human happiness in living. In this study, ergonomic assessment is considered since ergonomics assessment is related to human machine interaction especially in the production line. The main reason for choosing ergonomic assessment is because it reflects the immediate impact on labor on the machining production floor (Zahari Taha et al., 2015). The assessment is based on the revised Lifting Equation, where the evaluation method is based on scale Equation (13) and (14).

$$LI = Load\ Weight / Recommanded\ Weight\ Limit = L/RWL \quad (13)$$

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \quad (14)$$

Where LC is load constant = 23kg; HM is Horizontal Multiplier; VM is Vertical Multiplier; DM is Distance Multiplier; AM is Asymmetric Multiplier; FM is Frequency Multiplier, and CM is Coupling Multiplier. The value for each multiplier can be referred in tables provided by the developer.

When all the data collected have been summarized according to the 4 criteria's; the next steps is to optimize them. In this study, genetic algorithm (GA) is used to determine which criterion gives the most significant impact by using Microsoft Excel or Matlab Software. According to Hasan et. al., 2012, the advantages of using GA is its implicit parallelism where solution space is explored in multiple directions. Besides that, it also can handle nonlinear problems where large solution space and it on complex landscape (discontinuous, noisy, and changing with time). Many researchers have used genetic algorithm in their research such as in aeronautics (Hasan et al., 2012), product design (Sun et al., 2007); (Poirson et la., 2006), electromagnetic engineering (Merino et la., 2005), transportation (Tortensfelt and Klarbring, 2007) and sustainable product development area (Heintz et al., 2014). The mathematical function that will be used as follow:

$$Min\, f(x) = \begin{cases} Manufacturing\ cost = Raw\ Material\ cost + Energy\ Cost + Man\ Power\ Cost + Tool\ Cost \\ Environmental\ Impact = Chip\ recycling\ impact + Coolant\ recycling\ impact + Lubrication\ Impact \\ Energy\ Impact = Energy\ used \times 0.7488\ kgCO_2 \\ Lifting\ Index, LI = \frac{Load}{8.002} \end{cases} \quad (15)$$

Where manufacturing costs, environmental impact, energy impact and lifting Index (Ergonomic) need to be minimized.

Different assessment method usually gives different units answer, thus there is a need to find a solution or method which will be able to communicate with each others. To solve this problem, we adopt Fuzzy AHP method because this is where the company can give their input on the weight of each criterion; where the weight for each criteria can be equal or different.

Fuzzy AHP is an extension of the AHP method developed by Thomas L. Saaty in the year 1970's. It is a flexible quantitative method used for selecting decision among alternatives based on criteria performance with respect to one or more criteria (Rouyendegh and Erkan, 2012). According to Chan *et. al.*, 2000, there are 8 steps need to be taken in using Fuzzy AHP method. Firstly, a group of expert people are formed to describe in detail the problem and knowledge required for ease of solving the problem and also detailing the criteria and possible alternatives. Next, a proper linguistic scale is chosen such as shown in Table 1 and the all expert members are asked to give their judgment by either directly assigning weight according to the linguistic scale or in triangular fuzzy number form.

Table 1: Fuzzy AHP conversion scale (Chan *et. al.*, 2000)

	Linguistic Scale	Triangular Fuzzy Number
Very High	VH	(3,5,5)
High	H	(1,3,5)
Medium	M	(1/3,1,3)
Exactly Equal	EQ	(1,1,1)
Low	L	(1/5,1/3,1)
Very Low	VL	(1/3,1/5,1/5)

Then, this followed by an establishment of an independent hierarchical structure such as shown in Figure 2 to show the correlation of the case study.

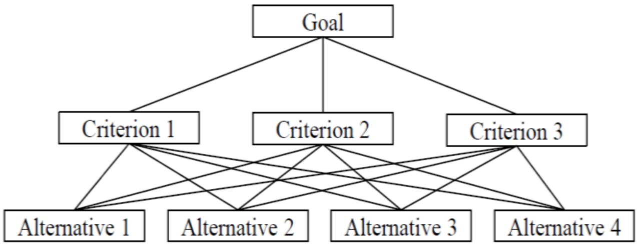

Figure 2: A three level AHP decision making problem.

The next step is to convert the linguistic variables into fuzzy number triangle and then construct a fuzzy reciprocal matrix of various criteria, sub-criteria as well as the proposed solutions. The geometric row means of each fuzzy reciprocal matrix is calculated by using Equation (16) and then normalized by using Equation (17).

$$Geometric\ row\ mean, r_i = (a_{i1} \otimes a_{i2} \otimes a_{i3} \otimes \dots \otimes l_{ik})^{\frac{1}{k}}, \quad i = 1, 2, \dots, k \quad (16)$$

$$W_k = r_i \oslash (r_1 \oplus r_2 \oplus r_3 \oplus \dots \oplus r_k), i = 1, 2, \dots, k \quad (17)$$

The next step is to calculate the fuzzy appropriate index (FAI_m) by using the standard arithmetic method as shown in Equation (17) where the S_{mk} represents the weight of solutions versus criterion C_k and W_k is the weight criterion C_k and a_{ij} be the element of fuzzy reciprocal matrix. Lastly, the fuzzy ranking numbers is ranked to obtain the best solution for the problem.

$$FAI_m = \left(\frac{1}{k}\right) \otimes [(S_{m1} \otimes W_1) \oplus (S_{m2} \otimes W_2) \oplus \cdots \oplus (S_{mk} \otimes W_k)] \quad (18)$$

According to Rao and Shankar (2011), the distance method using circumcenter and an index of modality can be used for ranking fuzzy numbers. This method can discriminate fuzzy numbers, mimic the way of human thinking and it can rank crisp numbers especially in fuzzy numbers (Rao and Shankar, 2011). The first step is to determine the generalized trapezoidal fuzzy number $\tilde{A} = (a, b, c, d; w)$ with Circumcenter of Centroid $S_{\tilde{A}}(\overline{x_0}, \overline{y_0})$ defined as

$$S_{\tilde{A}}(\overline{x_0}, \overline{y_0}) = \left(\frac{a+2b+2c+d}{6}, \frac{(2a+b-3c)(2d+c-3b)+5w^2}{12w}\right) \quad (19)$$

Trapezoidal fuzzy numbers will be triangular fuzzy numbers when c=b and the Circumcenter of Centroid is given by:

$$S_{\tilde{A}}(\overline{x_0}, \overline{y_0}) = \left(\frac{4a+4b+d}{6}, \frac{4(a-b)(d-b)+5w^2}{12w}\right) \quad (20)$$

Next, the second step is to determine the ranking function of the trapezoidal fuzzy number $\tilde{A} = (a, b, c, d; w)$ which maps the set of all fuzzy numbers to a set of real numbers defined as

$$R(\tilde{A}) = \sqrt{\bar{x}_0^2 + \bar{y}_0^2} \quad (21)$$

$$R(\tilde{A})_{TS1} = R(\tilde{A})_{C1S1} + R(\tilde{A})_{C2S1} + R(\tilde{A})_{C3S1} \quad (22)$$

which is the Euclidean distance from the circumcenter of the centroids. Using the above definitions, the ranking between fuzzy numbers is defined as follows:

Let $\tilde{A}_i$ and $\tilde{A}_j$ be two different fuzzy numbers, then

I. If $R(\tilde{A}_i) > R(\tilde{A}_j)$, then $\tilde{A}_i > \tilde{A}_j$
II. If $R(\tilde{A}_i) < R(\tilde{A}_j)$, then $\tilde{A}_i < \tilde{A}_j$
III. If $R(\tilde{A}_i) = R(\tilde{A}_j)$, the discrimination of fuzzy numbers is not possible. Hence index of optimism formula

$$I_{\alpha,\beta}(\tilde{A}) = \beta \frac{(\overline{x_0} + \overline{y_0})}{2} + (1-\beta) I(\tilde{A}) \quad (23)$$

$$where\ \beta \in [0, 1]$$

will be used with pessimistic ($\alpha = 0$), optimistic $\alpha = 1$) or neutral ($\alpha = 0.5$);

$$I_\alpha(\tilde{A}) = \alpha \bar{y}_0 + (1-\alpha)\bar{x}_0 where\ \alpha \in [0, 1]$$

(24) and

If $I_{\alpha,\beta}(\tilde{A}_i) > I_{\alpha,\beta}(\tilde{A}_j)$ then $\tilde{A}_i > \tilde{A}_j$ and

If $I_{\alpha,\beta}(\tilde{A}_i) < I_{\alpha,\beta}(\tilde{A}_j)$ then $\tilde{A}_i < \tilde{A}_j$

4. RESULTS AND DISCUSSIONS

There are two types of materials involved in this study namely Aluminum 6061 steel and Brass C3604 as they are commonly used by manufacturers. The machining process involved are facing, rough cutting, drilling and thread cutting using CNC lathe machine. Machining parameters for all machining processes follows Kalpakjian and Schmid, 2010 and also recommendation by the tool manufacturers as shown in Table 2.

Table 2: Machining parameters used.

SET	Description
1	Cutting Speed: 1000m/min; Feedrate: 0.1mm/rev; Depth of Cut: 0.5, 0.25mm;
2	Cutting Speed: 1000m/min; Feedrate: 0.3 mm/rev; Depth of Cut: 1.50, 0.25mm

3	Cutting Speed: 1500m/min; Feedrate: 0.1mm/rev; Depth of Cut: 0.5, 0.25mm
4	Cutting Speed: 1500m/min; Feedrate: 0.3 mm/rev; Depth of Cut: 1.50, 0.25mm

For drilling, the tool used is the center drill, diameters 13 and 14.5 mm with feed rate of 0.4 mm/rev and cutting speed of 100m/min for Aluminum 6061 and feed rate of 0.3 mm/rev and cutting speed of 100m/min. Lastly for thread cutting, the cutting depth is 0.75mm; same with thread depth while the cutting speed is 100m/min for Aluminum 6061 and 75m/min for Brass C3604. All of these cutting parameters are based on recommendation by the supplier in their catalogue.

Before machining, both materials were sent to the laboratory to confirm the material grades.. Table 3 below shows the summary results for the 4 criteria namely Manufacturing Cost, Environmental Impact, Energy Impact and Ergonomics; where A stands for Aluminum and B stands for Brass.

Table 3: Summary results for each criteria before optimization.

	Manufacturing Cost (RM)	Environmental Impact (kgCO2)	Energy Impact (kgCO2)	Ergonomic
A1	11.6276	0.36	3.319805	0.6944
A2	15.8257	0.36	6.463342	0.6944
A3	14.9057	0.36	5.774446	0.6944
A4	23.2397	0.36	12.01495	0.6944
B1	22.3519	0.583	2.917924	0.8333
B2	30.6926	0.583	5.1522	0.8333
B3	25.3343	0.583	9.1634	0.8333
B4	41.8642	0.583	17.52873	0.8333

When looking at Table 3, the manufacturing costs and the energy impact differ for each material and machining parameters but the environmental and ergonomic is the samethe same for both materials. This is because, when using the mathematical formulas to calculate the value for each criterion, the chip recycling impact, coolant and lubrication impact under environmental impact is the same. For ergonomic criteria, the results are expected to be the same since the location of the pallet is the same all the time. After each value of the criteria is evaluated, then all the data is optimized using genetic algorithm. The results are shown in Table 4.

Table 4: Optimization Results

	Manufacturing Cost (RM)	Environmental Impact (kgCO2)	Energy Impact (kgCO2)	Ergonomic
A	16.375	0.362	4.5199	0.6949
B	25.0607	0.585	6.7243	0.8350

Where, the machining parameters results for Aluminum 6061 (A) and Brass (B) are shown in Table 5 below.

Table 5: Optimum Machining Parameters

Material	Description
Aluminum (A)	Cutting Speed: 1200m/min; Feedrate: 0.17mm/rev; Depth of Cut: 0.5, 0.25mm;
Brass (B)	Cutting Speed: 900m/min; Feedrate: 0.20 mm/rev; Depth of Cut: 1.50, 0.25mm

It is observed that if we optimized the values first, we can reduce the number of option that we have, hence it will narrow down our search. Then, the next thing to do is to calculate the fuzzy AHP weight. To simplify this study, 2 sets of weight was assigned to each of the criteria as shown in Table 6; while Table 7 shows the summary of the ranking.

Table 6: Summary of Fuzzy AHP weight assign to each criteria.

Set	Manufacturing Cost	Environmental Impact	Energy Impact	Ergonomic
a	0.25	0.25	0.25	0.25
b	0.50	0.10	0.30	0.10

Table 7: Summary of the rank evaluation results.

	Rank results, R(A)
Aa*	102.5084
Ba*	218.2469
Ab*	340.5691
Bb*	531.4651

The highest rank is the smallest value. Therefore for both set a and set b weightage, the optimum rank is machining using Aluminum material.

CONCLUSIONS

It can be concluded that the triple bottom line concept can be implemented at the design stage of a product to evaluate its impact on the environment, economics and social dimension. GA and fuzzy AHP is used to optimize the machining parameters and material for the product based on weightage of the three dimensions. The optimum results for both set of Fuzzy AHP weightage is machining by using Aluminum.

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