Sustainability Product Design Assessment: Case Study of a Screw Design

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Abstract. Three main criteria have been identified to evaluate the sustainability of a product at the design stage which is manufacturing cost, environmental impact and ergonomics assessment. Manufacturing cost is critical in ensuring economic sustainability. Environmental impact assessment is important as the world communities have realized the necessity to meet the present generation needs without compromising the ability of the future generations to meet their own needs. Social costs are difficult to identify since the evaluation method varies; but at the factory floor it implies ergonomics implication during manufacturing. These three criteria are considered at the early stages of product design and as such decision for the final design involves multi criteria decision making in the presence of multiple objectives. In this case, the objectives are usually conflicting and therefore, the proposed solution is highly dependent on the preferences of expert groups of decision makers and must be developed within an understanding framework and mutual compromise. This paper presents a case study of screw manufacturing to demonstrate sustainability assessment at the design stage. Several manufacturing alternatives are evaluated against the three criteria. Fuzzy Analytical Process Hierarchy (FAHP) is used to obtain the criteria weights and the alternatives are then ranked using the distance method to obtain the best solution.

Keywords: Sustainability Assessment, Product Design and Fuzzy Analytical Process Hierarchy (FAHP)

1. INTRODUCTION

A sustainable product can be defined as a product that has minimum impact on the environment at each phase of its life cycle. However a sustainable product has implication on the environmental, social and economic aspects of its design. In addition to fulfilling the technical performance and costs demanded by the client, a product designer needs to consider the various interested parties in the product. However to take into consideration the whole gamut of stakeholders as depicted by Howarth *et. al.*, 2006 is complex where it involves customer, client, user, manufacturers, local council, employers, professional institutions, material supplier, environment agency, trade associations, contractors, community, planning officer, energy and water supplier as shown in Figure 1.

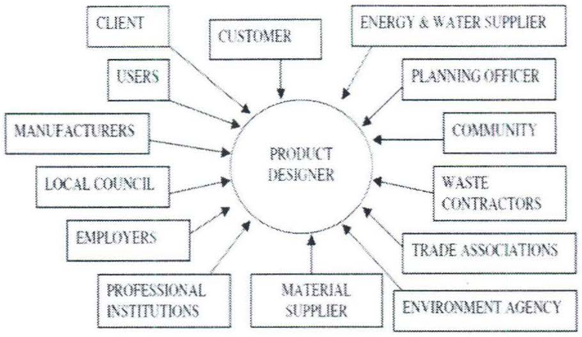

Figure 1: Typical range of stakeholders.

In this paper we proposed an approach that takes into consideration only several major stake holders interested in the economics, environmental and ergonomic aspects of the product. The client and the user can be considered as one major stake holder who is both interested in the economics aspects. The trade associations will be interested in the social aspects of the workers and in this case we have focused on the ergonomics implications as it would have a long term effect on the quality of life of the workers. The environmental aspects would be of interest to the environmental agency and the community. However making decisions taking into consideration these three aspects is still a difficult task as it involves multiple objectives.

One approach is to use Fuzzy Analytical Process Hierarchy (FAHP). In this method fuzzy weights are assigned and the distance method is used to rank the proposed solutions according to the highest value of R(A) to arrive at the best solution. In this study a screw design manufacturing process is evaluated which consists of three main criteria, seventeen sub-criteria and four proposed solutions. A group of decision makers was gathered to evaluate the criteria, sub-criteria and proposed solutions according to the fuzzy analytical hierarchy process (FAHP).

2. FUZZY ANALYTIC HIERARCHY PROCESS (FAHP)

FAHP is an extension of the AHP method. Analytical Hierarchy Process (AHP) was first developed by Thomas L. Saaty in the year 1970's as 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). Although this method is commonly used, it also has disadvantages such as the inconsistency being large; which have been criticize by many researchers where the AHP method uses a rating scale range between 1-9 and cannot handle uncertainty in judgments (Srdjevic, 2005). To overcome this shortcoming, many researchers have developed new techniques and methods to replace the eigenvector prioritization method in AHP (Srdjevic, 2005) such as triangular fuzzy numbers (TFN), α-cut, trapezoidal fuzzy numbers and synthetic extend analysis (Mikhailov, 2003). FAHP mimics human thinking as it sometimes uses misleading information and ambiguity to generate decision (Noor *et. al.*, 2012). Classical decision making method works only with exact and ordinary data such as evaluating a car speed by using linguistic terms like "very slow", "slow", "fast", "very fast" can be used. Here, fuzzy method can be used for vague and qualitative assessment of human beings (Ali *et. al.*, 2012). The theory of fuzzy sets has extended traditional mathematical decision theories so that it can cope with any vagueness problems. The assessment of different criteria is done using fuzzy number in FAHP compared to AHP which uses crisp numbers. According to Rouyendegh and Erkan (2012), Fuzzy AHP have been applied in many applications such as in staff selection and economics of government size (Mirsepassi and Mehrara, 2012), weapon selection (Dag˘deviren *et. al.*, 2009) and sustainability assessment (Damghani and Nezhad, 2013). According to Chan *et. al.*, (2000), there are 8 steps to be taken in conducting FAHP. The first step is to form a group of expert people to describe in detail the problem and knowledge required for ease of solving the problem and also detailing the criteria and possible alternatives. Then, a proper linguistic scale is chosen such as shown in Table 1 and the experts 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)

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The third step is to establish an independent hierarchical structure such as shown in Figure 2 to show the correlation of the case study.

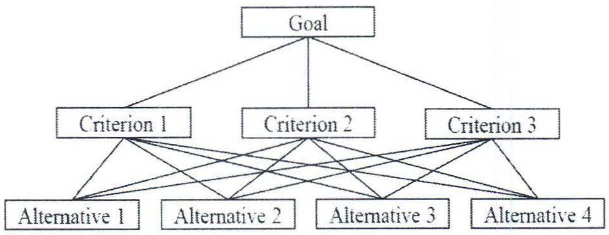

Figure 2: A three level AHP decision making problem.

The next step is to convert the linguistic variables into fuzzy number triangle and the fifth step is to 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 (1) and then normalized it by using equation (2).

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

$$W_k = r_i \oslash (r_1 \oplus r_2 \oplus r_3 \oplus \ldots \oplus r_k), i = 1, 2, \ldots, k \qquad (2)$$

The sixth step is to calculate the fuzzy appropriate index (FAI_m) by using the standard arithmetic method as shown in equation (3) 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.

$$FAI_m = \left(\frac{1}{k}\right) \otimes [(S_{m1} \otimes W_1) \oplus (S_{m2} \otimes W_2) \oplus \cdots \oplus (S_{mk} \otimes W_k)] \qquad (3)$$

According to Rao and Shankar (2011), ranking procedures associated with fuzzy numbers has been developed since 1976 when the first fuzzy set theory was introduced by Zadeh and since then, many researchers have developed fuzzy ranking methods as shown in Table 2.

Table 2: Summary of Ranking Fuzzy Numbers Methods.

Author(s)	Fuzzy Numbers Ranking Methods
Dubois and Prade	The mean value of a fuzzy number
Kim and Park	Ranking fuzzy numbers with index of optimism
Saade and Schwarzlander	Ordering fuzzy set over the real line
Liou and wang	Ranking fuzzy numbers with integral value
Choobineh and Li	Index for ordering fuzzy numbers

Other ranking fuzzy numbers methods that have been proposed include area compensation, distance method, (Rao and Shankar, 2011); left and right dominance, fuzzy distance measure, area between centroid point and original point distance minimization and fuzzy risk analysis based on the ranking of generalized trapezoidal fuzzy numbers (Hajjari, 2012). Distance method using circumcenter and an index of modality is another ranking fuzzy numbers method that 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

$$S_{\tilde{A}}(\overline{x_0}, \overline{y_0}) = \left(\frac{a+2b+2c+d}{6}, \frac{(2a+b-3c)(2d+c-3b)+5w^2}{12w}\right) \qquad (4)$$

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

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

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

$$R(\tilde{A}) = \sqrt{\bar{x}_0^2 + \bar{y}_0^2} \qquad (6)$$

$$R(\tilde{A})_{TS1} = R(\tilde{A})_{C1S1} + R(\tilde{A})_{C2S1} + R(\tilde{A})_{C3S1} \qquad (7)$$

which is the Euclidean distance from the circumcenter of the centroids. Using the above definitions, the ranking

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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

$$I_{\alpha,\beta}(\tilde{A}) = \beta\frac{(\overline{x}_0+\overline{y}_0)}{2} + (1-\beta)I(\tilde{A}) where\ \beta \in [0,1] \quad (8)$$

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

$$I_\alpha(\tilde{A}) = \alpha\overline{y}_0 + (1-\alpha)\overline{x}_0 where\ \alpha \in [0,1] \quad (9)$$

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 $\tilde{A}_i < \tilde{A}_j$

3. PROPOSED METHODOLOGY

The product involve in this study is a screw as shown in Figure 3 below In this case study the proposed solutions consider only the different possible manufacturing processes as shown in Table 3.

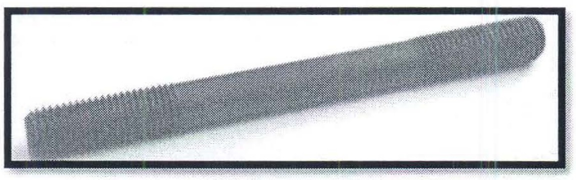

Figure 3: Screw Design.

Table 3: Summary of manufacturing process solutions.

Solution	Manufacturing Process Decription
1	Cooling Method: Ambient air; Cutting Speed: 100m/min; Feedrate: 0.18rev/mm Depth of Cut: 2mm x 2, 1mm x 1
2	Cooling Method: Ambient air; Cutting Speed: 100m/min; Feedrate: 0.18rev/mm Depth of Cut: 3mm x 1, 1mm x 1
3	Cooling Method: Vortex Cooling; Cutting Speed: 100m/min; Feedrate: 0.18rev/mm Depth of Cut: 2mm x 2, 1mm x 1
4	Cooling Method: Vortex Cooling; Cutting Speed: 100m/min; Feedrate: 0.18rev/mm Depth of Cut: 3mm x 1, 1mm x 1

Manufacturing process of the screw involve turning process using two different dry cooling methods known as ambient air and vortex cooling. In ambient air cooling method, the machining process uses the surrounding environmental air to cool down the cutting area while in vortex cooling, the cutting area is supplied with high compressed air at low temperature to cool down the cutting area using Exair vortex cooling tube as shown in Figure 4 below. The Vortex cooling tube consists of a hollow cylinder, hot and cold air exit nozzle, an input air inlet and a control valve.

Figure 4: Exair Vortex Cooling Tube.

According to Salaam *et. al*, (2012), high compressed air pressure is supplied into the vortex tube tangentially through an internal counter bore which set the air in a vortex motion. This air stream turns 90° and passes down the hot tube in the form of a spinning motion similar to a tornado. The control valve at one end allows some of the warmed air to escape and the rest heads back down the tube as a second vortex flow inside the low pressure area. This inner vortex loses heat and exhausts as cold air through the cold air exit.

Both inner and outer streams rotate in the same direction at the same angular velocity. Here, particles in the inner stream complete one rotation at the same amount of time as particles at the outer stream. However, because of the conservation of angular momentum principle, the rotational speed of the smaller vortex might be increased. But in the vortex tube case, the speed of the inner vortex remains the same while the angular momentum is lost from the inner vortex. The energy that is lost shows up as heat in the outer vortex. Thus the outer vortex becomes warm, and the inner vortex is cooled

Theoretically when using dry machining, the environmental impact and the manufacturing cost will be reduced since there is no need to buy coolant and to dispose it. But in this case, we want to see the performance of the manufacturing process of a screw design when using different cooling methods in terms of sustainability.

This study follows the methodologies proposed by Hao (2012) for the identification of sustainability criteria at a

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factory level; Chan *et. al.*, (2000) for determining the weight of each involved criteria using FAHP method; and Rao and Shankar (2011) to rank the resulting fuzzy numbers. Firstly, the unstructured problem is described in detail for a better understanding. Then, the criterion, sub-criterion and possible solutions are listed in the hierarchy structure as shown in Figure 5 below which consists of three main criteria, seventeen sub-criteria and four solutions for each sub-criterion.

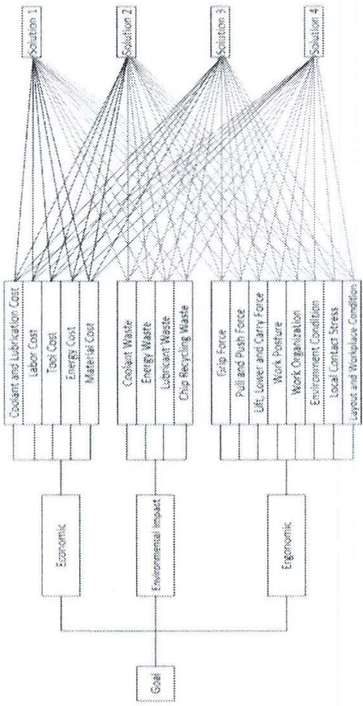

Figure 5: Proposed four levels Fuzzy Analytic Hierarchy Process.

For the economic criteria, the total manufacturing cost is considered and the equation is given by:

Total manufacturing cost = Material cost + Tool cost + coolant and lubricant cost + Energy cost + Labor cost (10)

Where:
Material cost = Standard size price (RM/Vol) x Required size (11)

Tool cost = (Number of cutting tool (n) x tool cost / unit (RM)) / number of product produced (12)

Energy cost = Energy used to fabricate a product (kWh) x electrical tariff (RM/kWh) (13)
Labor cost = time to produce a product (hr) x salary (RM/hour) (14)

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 (15)

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) (16)

Makeup volume = (tank capacity x coolant or lubricant loss rate) / (1 – coolant or lubricant loss rate) (17)

The environmental impact assessment used in this study follows Narita *et. al.* (2006) which consider the amount of carbon weight released into the air by the electrical energy used during the fabrication process, 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 four elements are given by:

$$C_e = \left[\left(LCI(cp)\right) + LCI(cd) \times Tc + LCI(w) \times Tw\right] \times [Mt/MTTR] \quad (18)$$

Where C_e is coolant impact consumption; LCI(cp) is coolant production emission intensity; LCI(cd) is coolant disposal emission intensity; Tc is total coolant amount; LCI(w) is water distribution emission intensity; Tw is total water amount; Mt is machining time and MTTR is Mean time to replenish coolant.

$$LO_e = [Mt/MTTD] \times Ld \times \left(LCI(lp) + LCI(LD)\right) \quad (19)$$

Where LO_e is lubricant oil impact consumption; Mt is moving parts running time; MTTD is mean time to discharge lubricant; Ld is amount of lubricant discharge; LCI(lp) is lubricant production emission intensity; LCI(LD) is lubricant disposal emission intensity.

$$E_e = LCI(e) \times (PSm + PFM + \Sigma PP) \quad (20)$$

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Where E_e is machine power consumption impact; LCI (e) is electricity emission intensity; PSm is spindle motor power consumption; PFM is feed motor power consumption; ΣPP is peripheral device power consumption.

$$Ch_e = \left(WpV - pV \times d \times LCI(M)\right) \quad (21)$$

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 ergonomic assessment is based on Musculoskeletal Injury Risk Assessment proposed by School district 53 (2007) which consist of eight detail assessments such as force required to grip force, force required to lift, lower or carries objects, force required to pull and push objects, work posture, aspect of the layout and workplace condition, local stress, environmental conditions and work organization.

The group of experts were asked to make pair wise comparisons for the main criteria, sub-criteria and solutions decision elements. The fuzzy preferences scale used for pairwise comparison is adopted from Chan *et. al.*, (2000). Next the FAHP weight is calculated using equations (3) – (9). In this study, all the real numbers is converted into fuzzy numbers by giving a tolerance of 10 percent. Lastly, by using equations (10) – (15) the fuzzy numbers were ranked to obtain the final results.

4. RESULTS

Based on the proposed methodology, the pairwise comparison results for all main criteria, sub-criterion, and solutions weight each under each sub criterion are calculated and the summary is shown in figures 6 to figure 11 below.

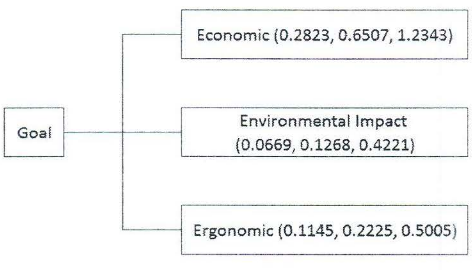

Figure 6: Summary of the main criteria weight.

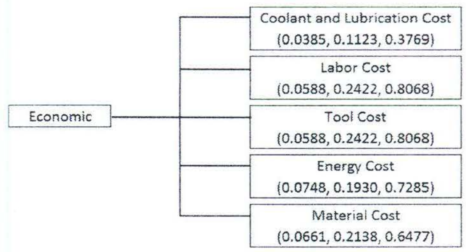

Figure 6: Summary of economic sub-criteria weight.

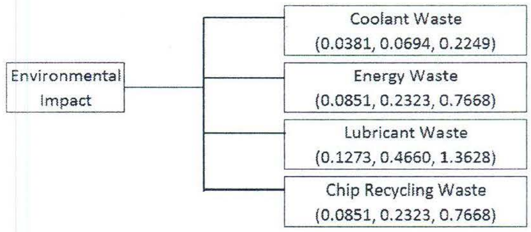

Figure 7: Summary of environmental impact sub-criteria weight.

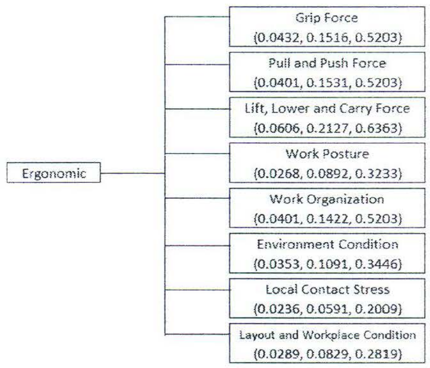

Figure 8: Summary of ergonomic sub-criteria weight.

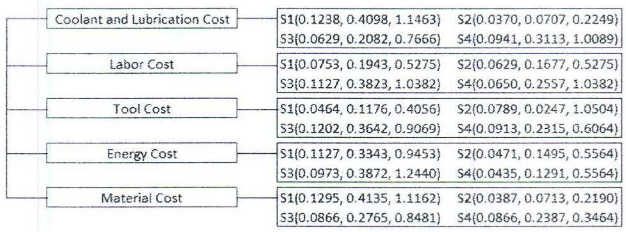

Figure 9: Summary of fuzzy weight for four solutions under economic sub-criterion.

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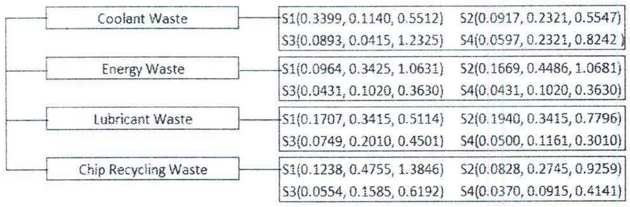

Figure 10: Summary of fuzzy weight for four solutions under environmental impact sub-criterion.

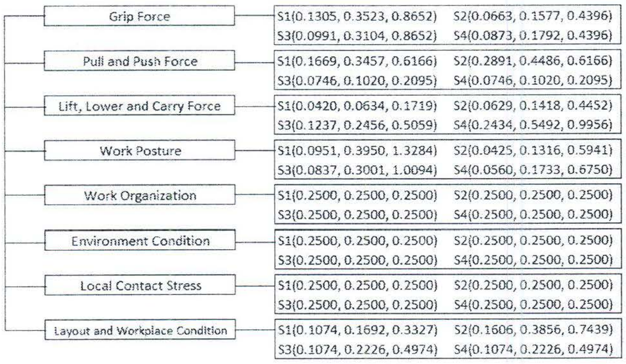

Figure 11: Summary of fuzzy weight for four solutions under ergonomic sub-criterion.

Next by using equation (3), the fuzzy appropriate index (FAI) is calculated and Table 4 shows a summary of the fuzzy appropriate indexes for all four solutions.

Table 4: Summary of fuzzy appropriate index (FAI) for all four solutions.

S1	(0.005230, 0.096600, 1.485973)
S2	(0.004522, 0.064569, 1.388343)
S3	(0.004841, 0.096205, 1.951196)
S4	(0.004330, 0.075183, 1.562174)

Since this case study involves exact data, the next step is to convert it into fuzzy number. In this case, the assumption used is a 10% tolerance for all data to see how the system reacts. Let's take the material cost as an example. Based on calculation and information provided by the material supplier, the material cost is RM 3.4375 for all four solutions since it is of the same size. When adopting the tolerance of 10%, the fuzzy numbers for material cost is (3.0938, 3.4375, 3.7813).

Lastly, the fuzzy ranking index of each solution is calculated by using equations (10) – (15). An example of solution 1 FAI calculation is (0.015431, 0.101066, 0.666849) and the summary of fuzzy ranking index is shown in Table 5.

Table 5: Summary of fuzzy ranking index value for all solutions.

	$R(\tilde{A})_{Total}$
S1	76.89985
S2	80.36622
S3	75.97820
S4	78.24222

Based on the concept proposed by Rao and Shankar 2011 to rank the Fuzzy number index using Equation (4) - (9), the highest value is at the top of the rank. Hence for this study, the rank is S2 > S4 > S1 > S3; where the production of a screw using ambient air as a cooling method with cutting speed of 100m/min; feed rate of 0.18rev/mm and depth of cut combination of 3.00 mm and 1.00 mm is ranked highest.

The best person to evaluate the pairwise comparisons in the proposed study method is a group of expert people who work in the company itself. This is because they are the one who knows the exact information needed to be provided in this evaluation and some of the information needed in this study is confidential information which cannot be disclose to anybody.

The pairwise comparisons need to be done separately to make it reliable and the pairwise comparison done by a group of expert is not bias. According to Hao (2012), if the sub-criteria in a certain case is not applicable; these sub-criteria can be removed. By doing this, this evaluation method gives the designer more flexibility to do the evaluation.

The proposed method is very useful for top management. This is because this evaluation can be used as a guide for them in making critical decision especially in expanding and monitoring the manufacturing cost. Besides that, the financial department manager, manufacturing department manager and safety officer in the company can used the data under each criterion to lower the manufacturing cost and improve the working condition in the production line.

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5. CONCLUSIONS

As a conclusion, this paper has presented a holistic approach to product sustainability based on economics, environmental and ergonomics of a screw manufacturing process. The proposed methodology not only allows the designer but also the company top management flexibility to perform sustainability evaluation and making critical decisions on the manufacturing process. The financial manager, manufacturing manager and safety officer can used the results to reduce the manufacturing cost and improve working conditions in the production line. Next, the proposed method will be evaluated against other established method.

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