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Decision Making With the Analytical Hierarchy Process (AHP) for Material Selection in Screw Manufacturing for Minimizing Environmental Impacts

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Abstract. This study is an approach to investigate the environmental impact of screw manufacturing and to choose suitable material for selected screw-making processes for the best performance with minimum environmental impact. The parameters involved were types of material and screw-making process using the environmental data available in Asia region. The two different manufacturing approaches being evaluated were machining and forging. The types of material considered were low carbon steel, stainless steel, titanium alloy and aluminium alloy. As for machining process, the materials being considered in screw manufacturing were low carbon steel, stainless steel, titanium alloy, aluminium alloy, magnesium alloy and cast iron. The information of environmental impact are generated by *SolidWorks*. Sustainability tool was used in the formation of pair-wise comparison matrices for Analytic Hierarchy Process (AHP). Then, the ranking of global priorities had enabled the determination of appropriate material to be used for those selected screw manufacturing process. As a result, aluminium alloy was found to give minimum environmental impact for forging process whereas cast iron was found to excel in machining process. At the same time, titanium alloy was not suggested to be used in either process.

Introduction

Nowadays, due to the dramatic increase of manufacturing industries, the global community is confronted with overconsumption of natural resources and also overproduction problems that consequently results in critical environmental degradation. The exhaustion of natural resources and extinction of biological species may occur if no appropriate strategy or regulation being implemented to control it. Feng & Joung [1] pointed out that manufacturing itself is the ultimate source of natural resources consumption with the toxic by-products and waste generated being detrimental to the environment. The product designers are often asked to consider the environmental impacts when dealing with the products they design. The prerequisite for manufacturers to survive in the competitive market is the ability to cope with the needs of sustainable development. Brundtland report in 1987 had declared that the development which meets the needs of the present without compromising the ability of future generations to meet their own need is known as sustainable development [2]. Anyhow, being a responsible manufacturer towards environmental protection is paramount. Recently, the public awareness of environmental issues is found to increase as well. Citizens in almost all countries start to realize that quality of the environment is essential to their well being and also common good. Therefore, in today's market place, the 'greener' products are highly demanded by customer. There are two relative important approaches of decision making method in the manufacturing environment, namely (i) graph theory and matrix method and; (ii) fuzzy multiple attribute decision making method. The role of a decision maker is to determine the best alternative and to rank the entire set of alternatives. AHP is recognized as one of the most popular analytical technique which is often used in complex decision making tasks [3]. Besides decision making application, AHP is also used in evaluation, benefit-cost analysis, resources allocation, planning and development, resolving conflict, etc. [4]. In fact, it is easy to perform and it does not need advanced technical knowledge as the judgement is made based on people's feelings and emotions as well as thoughts. This report is involves the study that investigates the environmental impacts of screw manufacturing with respect to alternate material over two manufacturing processes namely machining and forging. Then, the final decision is made based on the ranking from the analytic hierarchy process (AHP).

Methodology

The study starts with the determination of screw type and size. Then, the CAD modelling of M5 hexagonal machine screw was performed. After the parameters were decided, the sustainability analysis concerning environmental impacts was carried out using *SolidWorks Sustainability tools*. Next, the data of environmental impacts were applied in AHP, so that the selection of suitable material with minimum environmental impact to both manufacturing methods in screw manufacturing can be done.

***SolidWorks* Sustainability Tool.** The *SolidWorks* Sustainability software is a kind of powerful sustainability tool that is integrated in *SolidWorks* software. It can be used in sustainability analysis to evaluate the four environmental impacts throughout the life cycle of a product and incorporate sustainability into the design process. These impacts are examined by the science of Life Cycle Assessment (LCA) through a partnership with LCA pioneer PE International [5]. Moreover, this tool can also be used as material selection tool. It enables a designer to determine the suitable material effectively after considering the environmental impact as well as standard engineering properties for particular product. In this study, this tool has been adopted for environmental impact analysis for two selected manufacturing processes with alternate material change.

Analytic Hierarchy Process (AHP). Initially, the problem was structured by identifying those possible attributes that contribute to the solution. At the same time, the goal was determined and related data was collected. After that, the hierarchical structure that contained multi-level structure was organized: the goal of the decision at the top level followed by criteria at the middle level and alternatives were located at the bottom level. As the hierarchy was well constructed, the matrices of pair-wise comparisons were formed for each criterion and alternative. These comparisons were used to obtain the weightage of importance of the decision criteria and the relative performance measures of the alternatives in terms of each individual decision criterion. Next, the maximum Eigen value (λ_{max}), Consistency Index *(CI)* and Random Index *(RI)* were found so that Consistency Ratio *(CR)* can be determined. The maximum Eigen value, λ_{max} was achieved from the multiplication of the vector of column summation in the vector of local priority. On the other hand, *CI* was calculated by using equation (1) below while *CR* was calculated when *CI* was divided by *RI* (Eq.2). *RI* was generated from a random matrix of order n (Table 1).

$$CI = (\lambda_{max} - n) / (n - 1) \quad (1)$$

$$CR = CI / RI \quad (2)$$

Table 1: RI values of different value of n

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The next stage was checking the consistency based on the obtained *CR* value. If the value of *CR* is less than or equal to 0.1, it should be maintained in order for the matrix to be consistent. On the contrary, if the *CR* is much in access of 0.1, the judgement is untrustworthy because of randomness.

Thus, the comparisons must be repeated in order to resolve the inconsistencies of the pair-wise comparisons. As the consistency checking was accomplished, a set of global weightage for the alternative was found. Based on the ranking, the best decision that fulfils the goal was selected.

Results and Discussion

Theoretically, although sustainability consists of three main dimensions, which are economic aspect, environmental aspect as well as social aspect, but, this study was merely concentrated on the environmental aspect. This is because based on the concentric circle [6] (Fig. 1) that denotes as 'deep green' ecological sustainability model [7], it implicates environment as the most vital field as it comprises economy and social components.

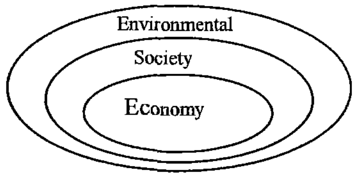

Figure 1: Graphical representation of sustainability using concentric circle [6]

Table 2: Data of environment impacts for M5 hexagonal screw under forging and machining operation

Process	Forging process				Machining Process			
Env. Impact / Material	Carbon footprint Kg CO_2	Total energy consumed MJ	Air acidification kg SO2	Water eutropication Kg PO_4	Carbon footprint Kg CO_2	Total energy consumed MJ	Air acidification kg SO2	Water eutropication Kg PO_4
Low carbon steel	0.30	3.05	$3.851x10^{-3}$	$1.630x10^{-4}$	0.01	0.19	$1.056x10^{-4}$	$6.200x10^{-6}$
Stainless steel	0.31	3.16	$3.891x10^{-3}$	$2.415x10^{-4}$	0.05	0.35	$1.740x10^{-4}$	$1.179x10^{-4}$
Aluminium alloy	0.02	0.22	$1.220x10^{-4}$	$4.500x10^{-6}$	0.02	0.32	$1.690x10^{-4}$	$6.160x10^{-6}$
Titanium alloy	0.43	4.42	$4.333x10^{-3}$	$2.052x10^{-4}$	0.21	2.20	$8.080x10^{-4}$	$6.600x10^{-5}$
Magnesium alloy	-	-	-	-	0.05	0.67	$6.460x10^{-4}$	$2.770x10^{-5}$
Cast Iron	-	-	-	-	0.01	0.13	$7.680x10^{-5}$	$9.280x10^{-6}$

During the sustainability analysis, the inputs include material, manufacturing process, location of manufacture and distribution. The material and manufacturing process were the variables while the location of manufacture and distribution is assumed Asia region. Subsequently, regarding to the environmental impact, they are measured in terms of carbon dioxide (CO_2), sulphur dioxide (SO_2), phosphate (PO_4) and energy. These impacts were specifically referred to a single unit of screw. If the screws are manufactured in a big volume, consequently, these impacts are definitely astonishing. All in all, different types of material with different manufacturing process had given different results in environmental impacts. Since these impacts were directly proportional to the dimension of screw mainly the screw size, therefore, this study was using M5 hexagonal screw as the only example. Table 2 represented the data of environmental impacts obtained from the sustainability analysis for one piece of screw with forging operation and machining operation respectively. When looking at the details of hexagonal head screw production, there are several stages required to get the final product. To make the shape/of the body and head of hexagonal screw, both forging and machining processes have different kind of approach, but they are similar for some stages like cutting the thread, heat treatment and also coating. Thus, these similar stages were neglected in this study. For forging operation, the final shape of screw can be directly achieved while for machining operation, it included turning and milling processes. Both of the turning and milling processes were subjected to material removal stage, where unwanted material in terms of scrap was removed from original work piece in order to get the desired shape. In fact, it is a wasteful approach compared to forging operation.

Based on the data of the environmental impacts for forging operation, it was found that the aluminium alloy resulted in the minimum values followed by low carbon steel, stainless steel and finally titanium alloy in successive manner. Among the three impacts using the same units, it was shown that carbon footprint caused the highest impact to the environment followed by air acidification and finally water eutrophication. On the other hand, regarding to the data of environmental impacts for machining operation, titanium alloy had the most significant impact compared to other materials. However, in terms of water eutrophication measurement, the stainless steel had the highest result, which was 1.179×10^{-4} kg, followed by titanium alloy, magnesium alloy, cast iron, low carbon steel and aluminium alloy in continuous sequence with the values of 6.600×10^{-5}, 2.770×10^{-5}, 9.280×10^{-6}, 6.200×10^{-6} and 6.160×10^{-6} respectively. Relative to the minimal environmental impacts contribution, the cast iron had overwhelmed it. The data that corresponded to the impacts such as carbon footprint, total energy consumed and air acidification were 0.01kg, 0.13 MJ and 7.680×10^{-5} kg. As long as the data of environmental impact were collected and compiled, the study was then proceed to evaluation stage where AHP was undertaken. Figure 5 depicts the hierarchical structure utilized in both forging and machining processes. Then, the assigning of pair-wise comparison matrices were done on criteria and alternatives used in the AHP hierarchy. The 4x4 matrix of Table 5 (a) was constructed in the criteria level for both manufacturing processes.

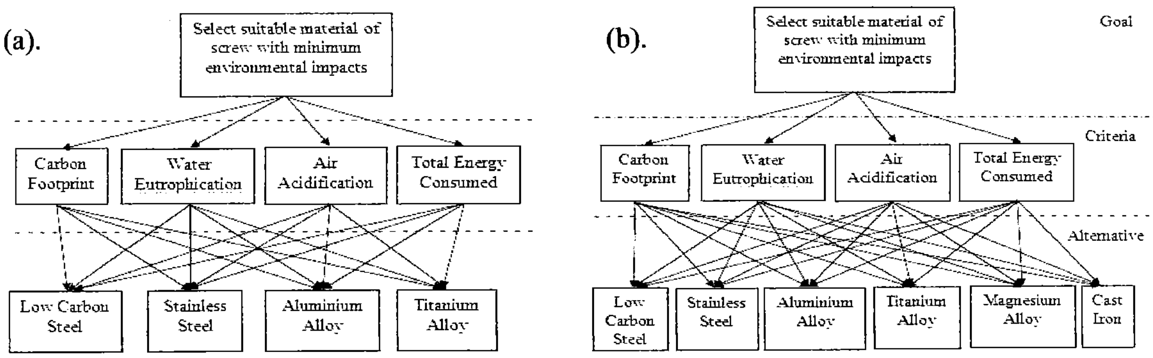

Figure 5: The hierarchical structure used in a. forging, b. machining process

After the rows were summed and normalised, the local priorities for these four impacts were obtained, as illustrated in Table 5 (b). With λ_{max} equal to 4.1767 and CR value at 0.0654 (less than 0.1), improvement is unnecessary. During consistence check, if the check can pass, it indicates that pair-wise comparison matrix is reasonable and the weightage of factors derived from the matrix are also reasonable [8].

Table 5: (a). Pair-wise comparison matrix of the main criteria with respect to the goal, (b). Local priority obtained for each criterion

(a)	SO_2	CO_2	PO_4	Energy
SO_2	1	3	5	7
CO_2	1/3	1	3	5
PO_4	5	1/3	1	3
Energy	1/7	1/5	1/3	1

(b)	SO_2	CO_2	PO_4	Energy	Row Σ	Local priority
SO_2	0.5966	0.6618	0.5357	0.4375	2.2316	0.5579
CO_2	0.1989	0.2206	0.3214	0.3125	1.0534	0.2633
PO_4	0.1193	0.0735	0.1071	0.1875	0.4875	0.1219
Energy	0.0852	0.0441	0.0357	0.0625	0.2276	0.0569
				Total Σ	4.000	1.000
CR = 0.0654						

In the following determination of local priorities on the alternative level, it was based on the data of environmental impacts collected from sustainability analysis. For forging process, the 4x4 matrices were established for each alternative with respect to the four criteria concerned. In contrary, dealing with machining process, the 6x6 matrices were constructed as well. Figure 7 had demonstrated the comparison between local priorities of the alternatives with respect to the four criteria in forging and machining process. The consistency checking for each of the alternatives in forging and machining operation were carried out and completed. The global priorities were determined. Table 9 were regarding to the composite priority weight for alternative in both processes.

Finally, the maximum value found in global priorities was denoted as the best alternative. By referring to Table 11(a) which displays the results of global priority in forging process, aluminium alloy was selected as the best option because had it attained the largest value of global priority, which was 0.6579. The global priorities of low carbon steel (S), stainless steel (SS) and titanium alloy (Ti) were 0.1484, 0.1192 and 0.0746 respectively. In brief, titanium alloy was not an environmental friendly material and was not encouraged to be used if the environment was the concern in the forging process of screw manufacturing. On the contrary, the utilization of aluminium alloy in this process was highly demanded as it exhibited the minimum environmental impacts.

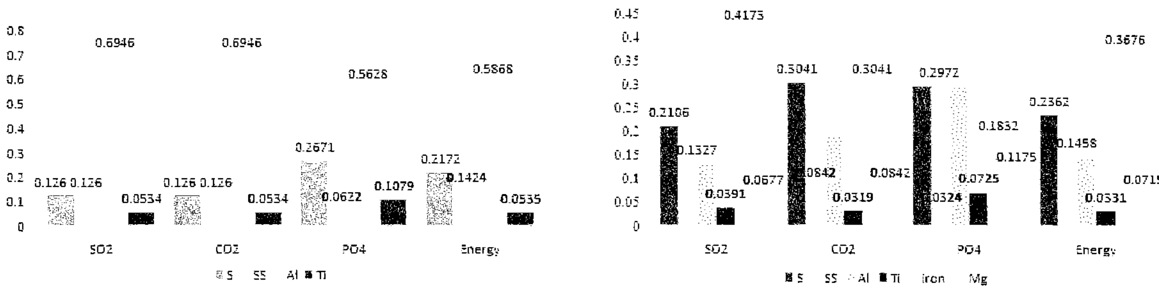

Figure 7: Comparison between local priorities of the four alternatives with respect to the criteria (a). Forging, (b). Machining

Table 9: The composite priority weightage for alternative in (a). forging and (b). machining

(a) Criteria	Local priority	Alternative	Local priority	Global weight
CO_2	0.2633	S	0.1260	0.0332
		SS	0.1260	0.0332
		Al	0.6946	0.1829
		Ti	0.0534	0.0141
PO_4	0.1219	S	0.2672	0.0326
		SS	0.0623	0.0076
		Al	0.4435	0.0541
		Ti	0.2272	0.0277
SO_2	0.5579	S	0.1260	0.0703
		SS	0.1260	0.0703
		Al	0.6946	0.3875
		Ti	0.0534	0.0298
Energy	0.0569	S	0.2172	0.0124
		SS	0.1425	0.0081
		Al	0.5869	0.0334
		Ti	0.0535	0.0030
			Total	1.0000

(b) Criteria	Local priority	Alternative	Local priority	Global weight
CO_2	0.2633	S	0.3041	0.0801
		SS	0.0842	0.0222
		Al	0.1916	0.0504
		Ti	0.0319	0.0084
		Iron	0.3041	0.0801
		Mg	0.0842	0.0222
PO_4	0.1219	S	0.2972	0.0362
		SS	0.0324	0.0039
		Al	0.2972	0.0362
		Ti	0.0725	0.0088
		Iron	0.1832	0.0223
		Mg	0.1175	0.0143
SO_2	0.5579	S	0.2106	0.1175
		SS	0.1327	0.0740
		Al	0.1327	0.0740
		Ti	0.0391	0.0218
		Iron	0.4173	0.2328
		Mg	0.0677	0.0378
Energy	0.0569	S	0.2362	0.0134
		SS	0.1458	0.0083
		Al	0.1458	0.0083
		Ti	0.0331	0.0019
		Iron	0.3676	0.0209
		Mg	0.0715	0.0041
			Total	1.0000

However, when referring to Table 11(b), it can be deduced that cast iron was the most desirable outcome since it had obtained the highest value of global priority that was 0.3561 compared to other material. The low carbon steel normally used in screw products had achieved the second place, with the value of global priority of 0.2472. Furthermore, the scores of global priority of other material such as aluminium alloy, stainless steel, magnesium alloy and titanium alloy were 0.1690, 0.1084, 0.0783 and 0.0409 respectively. In a nut shell, titanium alloy was not recommended to be used in screw manufacturing because neither in forging nor machining process, it had given the smallest value in global priority which means that it is not an environmental friendly material.

Table 11: Results of global priority in (a). forging and (b). machining process

(a)	CO_2	PO_4	SO_2	Energy	Global priority
S	0.0332	0.0326	0.0703	0.0124	0.1484
SS	0.0332	0.0076	0.0703	0.0081	0.1192
Al	0.1829	0.0541	0.3875	0.0334	0.6579
Ti	0.0141	0.0277	0.0298	0.0030	0.0746

(b)	CO_2	PO_4	SO_2	Energy	Global priority
S	0.0801	0.0362	0.1175	0.0134	0.2472
SS	0.0222	0.0039	0.0740	0.0083	0.1084
Al	0.0504	0.0362	0.0740	0.0083	0.1690
Ti	0.0084	0.0088	0.0218	0.0019	0.0409
Iron	0.0801	0.0223	0.2328	0.0209	0.3561
Mg	0.0222	0.0143	0.0378	0.0041	0.0783

Conclusion

As a conclusion of this study, the objectives of this study which were to investigate the environmental impacts of screw manufacturing and to choose the material and manufacturing process of screw for the best performance with minimum environmental impacts were achieved. This was done by ranking the priorities using the AHP. The results obtained from environmental impacts analysis had focused on screw head and screw shape formation, and not other parts such as screw thread and screw treatment in the screw manufacturing process chain. The only two methods considered here for screw head and screw shape formation were forging and machining. The environmental impacts considered throughout this study were carbon footprint, water eutrophication, air acidification and total energy consumed. These impacts were assessed by life cycle assessment (LCA) using *SolidWorks* Sustainability approach. Based on the results concerning the minimum environmental impact performance for screw manufacturing, the most suitable material to be used for forging method is aluminium alloy whereas cast iron is the most suitable in machining process. On the other hand, the titanium alloy is not recommended to be used in either process as it will cause the greatest impact to the environment compared to other materials such as stainless steel, low carbon steel, aluminium alloy, cast iron and magnesium alloy. In a nut shell, AHP is a user friendly decision making method. To become winner in today's market place, manufacturers realize that they cannot ignore sustainability assessment in their products. Moreover, if they fail to respond to environmental pressure, they might lose the business opportunities as well.

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