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Development of Models for Optimal Selection of Materials for Design of an Oil Palm Fruit Digester using Desirability and Utility Functions

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ABSTRACT

The oil palm fruit digester is the workhorse of small scale oil palm mills scattered throughout Southern Nigeria. Most of these machines are not very reliable due to poor design and material selection. In order to improve the design of these machines, this research is focused on the development of models for optimal selection of materials for digester design using desirability and utility functions. Hence, sixteen possible materials for design of three major components of the digester were selected and ranked using two multi criteria decision making (MCDM) tools namely desirability function (DF) and utility function (UF). The results show that the correlation (R) between the rankings for beater arm materials selection was 0.85, while that for the central shaft and the trough were 0.91 and 0.59. The very high values of R for the beater arm and shaft rankings show that there is a very good agreement between the rankings obtained from the two methods. Furthermore, the not so high R value for the trough rankings shows that though there is some measure of agreement between the two rankings a third MCDM method may be required to validate the two previous rankings.

1. INTRODUCTION

Oil palm is one of the most important cash crops in the world (Murphy et al., 2021). Most vegetable oils used for domestic and industrial use are derived from oil palm. Before the discovery of petroleum, oil palm production had been the main stay of the economy of Nigeria (Gharleghi and Yin-Fah, 2013). Globally the demand for palm oil is on the increase, hence the crop cultivation has served as a means of livelihood for many rural families in Nigeria (Ohimain et al., 2014). These production facilities use a machine called the digester to macerate the boiled oil palm fruits and separate the flesh from the kernel. This is done before being sent to the press to expel the palm oil from the fruit.

Poor design and construction of digesters has been observed in the oil palm processing industry. This problem may partly be caused by the poor material selection for the design and construction of machine. Hence, some researchers have attempted to modify existing palm oil processing machine for improve system performance (Adzimah and Seckley, 2009; Asoiro et al., 2013; Agbonkhese et al., 2018). Material selection is an integral part of engineering design process. The reliability and durability of a machine depends to a large extent on the material make up of its component parts. Hence, appropriate selection of materials during the design of a machine is imperative for its reliability during operation, as well as its durability. For material selection problem to be solved optimally, it could be solved in the context of multi objective optimization or multi criteria decision making (MCDM) problem. Material selection problem is not non-deterministic polynomial-time hardness (NP hard), hence it is often solved using multi criteria decision making tools like desirability function, utility function, technique for order preference by similarity to ideal solution (TOPSIS), visekriterijumska optimizacija i kompromisno resenje (VIKOR), etc (Chatterjee and Chakraborty, 2013; Karande et al., 2013). NP hard optimization problems are usually solved with metaheuristic tools such as genetic algorithm, simulated annealing, particle swarm optimization, ant colony optimization etc (Nwobi-Okoye and Ochieze, 2018; Nwobi-Okoye et al., 2019a; Nwobi-Okoye et al., 2019b; Umeonyiagu and Nwobi-Okoye, 2019; Nwobi-Okoye and Uzochukwu, 2020).

The literature is replete with various attempts to solve material selection problems with MCDM tools. Athawale and Chakraborty (2012) carried out a survey of the performance of 10 most commonly used MCDM methods for ranking of sailing boat, flywheel and cryogenic storage materials. The results show that for a given material selection problem, more attention should be paid to the selection of the relevant criteria and alternatives and not necessarily on the type of MCDM tool used. Berman et al. (2018) used MCDM tool (ARAMIS and AIR/CAIR) which allows for both numerical and verbal estimates of the rankings coupled with an expert system to rank construction materials used in the field of petrochemistry. Khabbaz et al. (2009) used fuzzy logic to solve materials selection problem in mechanical engineering design. From the study they showed that fuzzy logic which is bereft of messy mathematics performed very well as an MCDM tool in comparison to Manshadi's MCDM method. Chakraborty and Chatterjee (2013) used three MCDM methods to demonstrate the effect of number of criteria on the ranking of material alternatives used in design. They observed that the choices of the best suited materials depend solely on the criterion with the maximum weight or priority value. Sometimes the main objective of material selection in certain applications may be sustainability. Such objectives are often part of green design or sustainable design. In such situation such factors as the energy consumption, health risk, waste gas production, waste water production when the material used are taken into consideration in materials selection (Zhao et al., 2016). A further work in this regard by Bhowmik et al. (2018) illustrated the use of TOPSIS for selection of energy efficient materials for an industrial application. Also, Vats and Vaish (2019) used MCDM tools for the selection of smart materials for thermal energy efficient architecture. Material selection could be for applications in certain fields of engineering such as marine, aerospace, nuclear power etc. For instance, Yadav et al. (2019) used hybrid TOPSIS-PSI for selection and ranking of materials used specifically for marine applications. Material selection problem could be for a component used in several fields like the connecting rod of an engine (Sen et al., 2016) or gear (Chatterjee and Chakraborty, 2013; Karande et al., 2013). Sometimes MCDM tools are used to rank newly developed materials for certain applications in comparison to existing ones (Vaziri et al., 2016).

Several directions of research in solving materials selection problem with MCDM methods and non MCDM methods have been reviewed here. This particular research is unique in the sense that it explored the application of MCDM methods in the selection of materials for an agricultural engineering application. It is expected to bridge the gap of dearth of research works dedicated to solving material selection problem of machines used specially in the tropics for agriculture and food processing. It will add to the existing literature on digester design and bring about tremendous improvement in the reliability and durability of future digester designs for small scale oil palm processing plants in the tropics. Consequently, the aim of this research therefore is to optimize material selection of the main component parts of a digester used in oil palm processing using two MCDM tools namely desirability function and utility function, and compare the rankings from these two methods.

2. MATERIALS AND METHODS

2.1. Digester Design

Palm fruit digester is the machine that does the pounding of boiled palm fruits. Pounding (digestion) is the splitting of the palm fruit mesocarp which contains the oil-component cells. The fast rotating blades (the beaters) of the digester break up the hot mesocarp of the palm fruits thereby getting the fruits ready for oil extraction. The pounding is done inside the cylindrical tower or trough of the digester. The tower or trough bears a receptacle for the evacuation of the pounded hot palm fruits. The palm fruits need to be hot so as to increase the fluidity of palm fruits oil to be extracted. The central shaft is the rod where the blades called the beater arms are welded to. The central shaft is linked to an axle. The axle itself bears a wheel where the belt drive is connected. The digester could be driven by 5 horse power diesel engine or electric motor. Figure 1 is a schematic drawing of the digester. Figures 2 and 3 give more details of some parts of the digester. The ratio of rotation of the wheel to the vertical shaft is 1:7: The digester is capable of macerating over 250 kg of fruits per hour and has the singular attribute of macerating thoroughly the fruits without breaking any nut. Maceration of 250 kg of fruits per hour is for moderately sized digester having about 70 cm internal diameter and 1.2 m height. The trough houses the boiled hot palm fruits for digestion. The former trough lacks heat insulation and hence loses a lot of heat during digestion. The efficiency of the trough therefore was highly reduced. The pounded palm fruits are required to be as hot as possible so as to give high yield of oil during extraction. Again the base of the trough where the central shaft passes through loses oil during digestion because of leakages it possess. These were some of the problems of the former digester in use. The material selection research eliminated these problems with special consideration on thermal conductivity and hardness of materials. Maceration of the oil bearing cell of the mesocarp is done through the fast rotating beater arms. Contamination from iron is greatest during digestion when the highest rate of metal wear is encountered in the milling process (Poku, 2002). Iron contamination increases the risk of oil oxidation and the onset of oil rancidity.

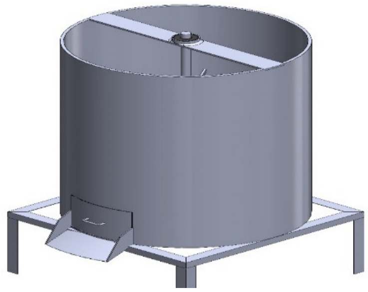


Figure 1: Schematic drawing of the digester

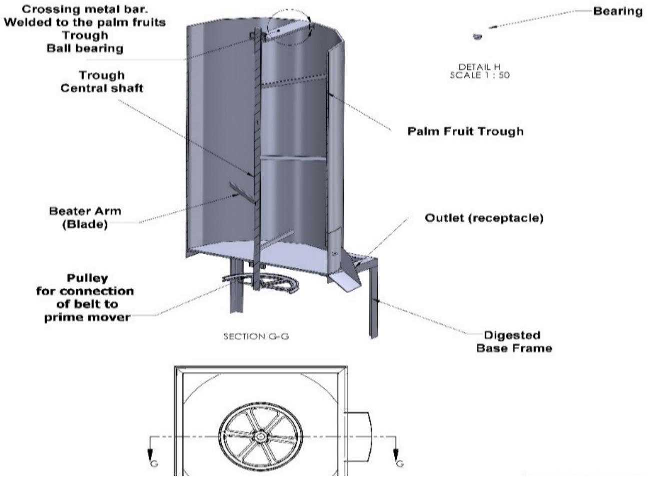


Figure 2: Cutaway of the Palm fruit trough of the digester

Figure 3: Beater arms welded to central shaft

2.2. Digester Materials

Table 1 shows the materials used in the design of oil palm fruits digester, their costs and the values of some of their properties desired in the design of a digester.

Table 1: Materials for trough design and their properties

S/N	Material	Ultimate tensile strength (MPa)	Brinell hardness (MPa)	Corrosion rate (mm/year)	Thermal conductivity (W/mK)	Price per ton ($)
1	Low carbon steel	440	120	0.60	31.50	709
2	Medium carbon steel	603	170	0.50	43.00	800
3	High carbon steel	635	187	0.10	36.00	980
4	Low alloy steel	245	121	0.55	37.00	700
5	Medium alloy steel	310	180	0.50	26.00	800
6	Ferritic stainless steel	430	180	0.40	22.50	1400
7	Martensic stainless steel	800	223	0.42	24.20	5100
8	Precipitation stainless steel	850	420	0.42	18.40	5600
9	Duplex stainless steel	620	201	0.42	19.00	3000
10	Austentic stainless steel	515	175	0.40	10.00	2000
11	Molybdenum high speed	3000	235	0.30	41.00	4200
12	Tungsten high speed steel	1200	330	0.32	20.90	1000
13	Hot work steel	1990	415	0.30	62.00	1200
14	Shock resisting steel	1650	220	0.27	41.00	1455
15	Water hardening steel	1680	490	0.23	48.30	1000
16	Nano alloy steel	1469	228.76	0.85	1.73	3582

2.2.1. Beater arm

The following properties of metal were considered with respect to the beater arms of the digester; hardness, ultimate tensile strength, impact strength. The cost per ton of the several possible metals that can be used for the designing of the beater arms were obtained. Table 2 shows the several metals and their respective properties.

2.2.2. Central shaft

The central shaft of the digester is the shaft where all the fast rotating beater arms are welded to. Therefore analysis with regard to selection of an optimal material for its design must be critically done. The following properties of metals were considered. Ultimate tensile strength, impact strength, yield strength and hardness. The costs of possible metals for the design were also noted. Table 3 gives the possible metals and the properties.

Table 2: Materials for beater arm design and their properties

S/N	Material	Ultimate tensile strength (MPa)	Impact strength (J)	Corrosion rate (mm/year)	Brinell hardness (MPa)	Price per ton ($)
1	Low carbon steel	440	38	0.6	120	709
2	Medium carbon steel	603	58.7	0.5	170	800
3	High carbon steel	635	200	0.1	187	980
4	Low alloy steel	245	58	0.55	121	700
5	Medium alloy steel	310	61	0.5	180	800
6	Ferritic stainless steel	430	120	0.4	180	1400
7	Martensic stainless	800	118	0.423	223	5100
8	Precipitation stainless	850	63	0.419	420	5600
9	Duplex stainless steel	620	66	0.416	201	3000
10	Austentic stainless	515	37	0.4	175	2000
11	Molybdenum high	3000	67	0.3	235	4200
12	Tungsten high speed	1200	62	0.318	330	1000
13	Hot work steel	1990	76.9	0.295	415	1200
14	Shock resisting steel	1650	116.9	0.272	220	1455
15	Water hardening steel	1680	86	0.216	490	1000
16	Nano alloy steel	469	20.3	0.85	228.76	3582

Table 3: Materials for shaft design and their properties

S/N	Material	Ultimate tensile strength (MPa)	Yield strength (MPa)	Brinell hardness (MPa)	Impact strength (J)	Price per ton ($)
1	Low carbon steel	440	280	120	38.0	709
2	Medium carbon steel	603	310	170	58.7	800
3	High carbon steel	635	490	187	200.0	980
4	Low alloy steel	245	287	121	58.0	700
5	Medium alloy steel	310	310	180	61.0	800
6	Ferritic stainless steel	430	275	180	120.0	1400
7	Martensic stainless steel	800	820	223	118.0	5100
8	Precipitation stainless steel	850	950	420	63.0	5600
9	Duplex stainless steel	620	448	201	66.0	3000
10	Austentic stainless steel	515	200	175	37.0	2000
11	Molybdenum high speed	3000	3250	235	67.0	4200
12	Tungsten high speed steel	1200	1400	330	62.0	1000
13	Hot work steel	1990	1564	415	76.9	1200
14	Shock resisting steel	1650	1850	220	116.9	1455
15	Water hardening steel	1680	1500	490	86.0	1000
16	Nano alloy steel	469	700	228.76	20.3	3582

2.3. Multi Objective Optimization with Desirability and Utility Functions

Optimization of material selection for digester component design is a multi-objective optimization or multi criteria decision making problem. This is because several objectives need to be optimized simultaneously. For example it may be required to select a material with the best hardness and ultimate tensile strength (UTS) values simultaneously. These objectives may not be satisfied simultaneously by a single material because some may have high hardness values but low UTS. Likewise some may have high UTS values but low hardness. Hence, multi criteria decision analysis or multi objective optimization has to be used to select the material that best satisfy the two objectives simultaneously. In this study therefore, desirability and utility functions were used for optimization of digester materials selection problem.

2.3.1. Desirability function development

Desirability function is a popular multi objective optimization tool. The function is such that if the objective is to maximize, the following relationship obtains:

$$di = \begin{cases} 0 & \hat{y} \leq Li \\ \left(\frac{\hat{y}-Li}{Ti-Li}\right)^{s} & Li < \hat{y} < Ti \\ 1 & \hat{y} \geq Ti \end{cases} \tag{1}$$

Similarly, if the objective is to minimize, the following relationship obtains:

$$di = \begin{cases} 1 & \hat{y} \leq Ti \\ \left(\frac{Ui-\hat{y}}{Ui-Ti}\right)^{s} & Ti < \hat{y} < Ui \\ 0 & \hat{y} \geq Ui \end{cases} \tag{2}$$

If it is desired that the response be a target value with an upper and lower limit, the desirability is given as:

$$di = \left(\frac{\hat{y}-Li}{Ti-Li}\right)^{s} \quad Li \leq \hat{y} \leq Ti \tag{3}$$

$$di = \left(\frac{Ui-\hat{y}}{Ui-Ti}\right)^{s} \quad Ti \leq \hat{y} \leq Ui \tag{4}$$

$$di = 0 \quad if\ \hat{y} < Li \tag{5}$$

$$di = 0 \quad if\ \hat{y} > Ui \tag{6}$$

Where d_i = desirability value; L_i = the lower limit of the response; U_i = the lower limit of the response; T_i = the target value and $\hat{y}$ = the lower limit of the response

The variable s is a constant that defines the shape of the desirability function. For $s = 1$, the desirability function is linear, similarly if $s < 1$, the desirability function is convex while for $s > 1$ the desirability function is concave (Karande et al., 2013). The composite desirability (*DC*) is given by:

$$DC = (d_1 \times d_2 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} di\right)^{\frac{1}{n}} \tag{7}$$

Where n is the number of variables.

If weights are assigned to d_i, then the weights w_i $(0 < w_i < 1)$ is such that:

$$w_1 + w_2 + w_3 \ldots w_n = 1 \tag{8}$$

w_i could be determined from principal component analysis, rank order centroid method, analytic hierarchical process (AHP), entropy etc (Karande et al., 2013). The composite desirability (*DC*) could further be expressed as:

$$DC = (d_1^{w1} \times d_2^{w2} \times d_3^{w3} \times \ldots \times d_n^{wn})^{\frac{1}{n}} \tag{9}$$

For the three parts of the digester considered in this research, the rank order centroid method (Karande et al., 2013) was used to assign the following weights to the criteria as shown in Tables 4 to 6. The parameter settings for the optimization program were done according to Table 7.

Table 4: Weights assigned to the criteria for beater arm material selection

	Criteria				
	Ultimate tensile strength (MPa)	Impact strength (J)	Corrosion rate (mm/year)	Brinell hardness (MPa)	Price per ton ($)
Weight	0.04	0.09	0.1567	0.2567	0.4567

Table 5: Weights assigned to the criteria for shaft material selection

	Criteria				
	Ultimate tensile strength (MPa)	Yield strength (MPa)	Brinell hardness (MPa)	Impact strength (J)	Price per ton ($)
Weight	0.04	0.09	0.1567	0.2567	0.4567

Table 6: Weights assigned to the criteria for trough material selection

	Criteria				
	Ultimate tensile strength (MPa)	Brinell hardness (MPa)	Corrosion rate (mm/year)	Thermal conductivity (W/mK)	Price per ton ($)
Weight	0.04	0.09	0.1567	0.2567	0.4567

Table 7: Parameter settings

	Ultimate tensile strength (MPa)	Yield strength (MPa)	Impact strength (J)	Brinell hardness (MPa)	Corrosion rate (mm/year)	Thermal conductivity (W/mK)	Price per ton ($)
Best	3000	3250	200	490	0.025	1.728	90
Worst	100	100	10	100	0.9	65	6000

2.3.2. Utility function development

Consider an experiment with n responses namely: $y_1, y_2, \dots, y_n$, if the utility of the i_{th} attribute or response is $U_i(y_i)$, the composite utility of the responses is given by:

$$U(y_1, y_2, \dots, y_n) = f(U_1y_1, U_2y_2, \dots, U_1y_1) \tag{10}$$

$$U(y_1, y_2, \dots, y_n) = \sum_{i=0}^{n} U_i(y_i) \tag{11}$$

If weights are assigned to the attributes, then the utility function is given by:

$$U(y_1, y_2, \dots, y_n) = \sum_{i=0}^{n} w_i U_i(y_i) \tag{12}$$

In utility concepts, a preference number is used to indicate the performance each of the alternatives against each criterion. Each attribute has a preference number which varies from 0 to 9. The preference value of 0 indicates a just acceptable performance while the preference value of 9 indicates the highest performance. The preference number for the i_{th} attribute or response is given by:

$$P_i = A_i \times log\left(\frac{y_i}{y_i'}\right) \tag{13}$$

Where $y_i$and y_i' are the response/attribute values and acceptable values of the attributes respectively.$A_i$is a constant for the i_{th} attribute or response.

For the beneficial criterion or criterion whose value should be maximized, y_i' is taken as the minimum value of the attribute while for the non-beneficial criterion or criterion whose value should be minimized, y_i' is taken as the maximum value of the attribute.

If it is assumed that the best value for the i_{th} attribute or response is y_i^* , the preference number P_i is 9. Consequently:

$$A_i = \frac{9}{log\left(\frac{y_i^*}{y_i'}\right)} \tag{14}$$

The composite utility is therefore given by:

$$U = \sum_{i=0}^{n} w_i P_i \tag{15}$$

where $\sum_{i=0}^{n} w_i = 1$

The weights w_i were obtained through rank centroid method which was equally used to obtain desirability function weights as previously shown in Tables 4 to 6. The parameter settings for the utility function optimization program, which is the same as for the desirability function, were done according to Table 7.

3. RESULTS AND DISCUSSION

3.1. Desirability Function Results

Tables 8 to 10 show the desirability values of materials used in the design of beater arm, shaft and trough respectively. As shown in Tables 8 to 10, A1 to A16 are the materials listed in serial numbers 1 to 16 in Table 1 while C1 to C5 are the criteria shown in Table 4 to 8. The values in Tables 8 to 10 are the desirability values derived from Equations 1 to 6. Table 11 shows the alternative materials for beater arm design and their composite desirability values. As shown in Table 11, alternative A15 was ranked number one while alternative A8 was ranked number sixteen. This means that water hardening steel is the best material for beater arm design while precipitation stainless steel is the worst. Table 12 shows the alternative materials for shaft design and their composite desirability values. As shown in Table 12, alternative A15 was ranked number one while alternative A8 was ranked number sixteen. This means that water hardening steel is the best materials for shaft design while precipitation stainless steel is the worst. Table 13 shows the alternative materials for trough design, their composite desirability values. As shown in Table 13, alternative A12 was ranked number one while alternative A8 is ranked number sixteen. This means that tungsten high speed steel is the best materials for trough design while precipitation stainless steel is the worst.

Table 8: Beater arm materials alternatives and their desirability values

	Criteria				
Alternatives	C1	C2	C3	C4	C5
A1	0.12	0.15	0.34	0.05	0.90
A2	0.17	0.26	0.46	0.18	0.88
A3	0.18	1.00	0.91	0.22	0.85
A4	0.05	0.25	0.40	0.05	0.90
A5	0.07	0.27	0.46	0.21	0.88
A6	0.11	0.58	0.57	0.21	0.78
A7	0.24	0.57	0.55	0.32	0.15
A8	0.26	0.28	0.55	0.82	0.07
A9	0.18	0.29	0.55	0.26	0.51
A10	0.14	0.14	0.57	0.19	0.68
A11	1.00	0.30	0.69	0.35	0.30
A12	0.38	0.27	0.67	0.59	0.85
A13	0.65	0.35	0.69	0.81	0.81
A14	0.53	0.56	0.72	0.31	0.77
A15	0.54	0.40	0.78	1.00	0.85
A16	0.13	0.05	0.06	0.33	0.41

Table 9: Shaft materials alternatives and their composite desirability values

	Criteria				
Alternatives	C1	C2	C3	C4	C5
A1	0.12	0.06	0.05	0.15	0.90
A2	0.17	0.07	0.18	0.26	0.88
A3	0.18	0.12	0.22	1.00	0.85
A4	0.05	0.06	0.05	0.25	0.90
A5	0.07	0.07	0.21	0.27	0.88
A6	0.11	0.06	0.21	0.58	0.78
A7	0.24	0.23	0.32	0.57	0.15
A8	0.26	0.27	0.82	0.28	0.07
A9	0.18	0.11	0.26	0.29	0.51
A10	0.14	0.03	0.19	0.14	0.68
A11	1.00	1.00	0.35	0.30	0.30
A12	0.38	0.41	0.59	0.27	0.85
A13	0.65	0.46	0.81	0.35	0.81
A14	0.53	0.56	0.31	0.56	0.77
A15	0.54	0.44	1.00	0.40	0.85
A16	0.13	0.19	0.33	0.05	0.41

Table 10: Trough materials alternatives and their desirability values

Alternatives	Criteria				
	C1	C2	C3	C4	C5
A1	0.12	0.05	0.34	0.53	0.90
A2	0.17	0.18	0.46	0.35	0.88
A3	0.18	0.22	0.91	0.46	0.85
A4	0.05	0.05	0.40	0.44	0.90
A5	0.07	0.21	0.46	0.62	0.88
A6	0.11	0.21	0.57	0.67	0.78
A7	0.24	0.32	0.55	0.64	0.15
A8	0.26	0.82	0.55	0.74	0.07
A9	0.18	0.26	0.55	0.73	0.51
A10	0.14	0.19	0.57	0.87	0.68
A11	1.00	0.35	0.69	0.38	0.30
A12	0.38	0.59	0.67	0.70	0.85
A13	0.65	0.81	0.69	0.05	0.81
A14	0.53	0.31	0.72	0.38	0.77
A15	0.54	1.00	0.78	0.26	0.85
A16	0.47	0.33	0.06	1.00	0.41

Table 11: Beater arm materials alternatives and their overall desirability values

Alternatives	Criteria					Composite desirability	Rank
	C1	C2	C3	C4	C5		
A1	0.00	0.01	0.05	0.01	0.41	0.78	13
A2	0.01	0.02	0.07	0.05	0.40	0.85	8
A3	0.01	0.09	0.14	0.06	0.39	0.90	4
A4	0.00	0.02	0.06	0.01	0.41	0.79	12
A5	0.00	0.02	0.07	0.05	0.40	0.85	7
A6	0.00	0.05	0.09	0.05	0.36	0.86	6
A7	0.01	0.05	0.09	0.08	0.07	0.76	14
A8	0.01	0.03	0.09	0.21	0.03	0.73	16
A9	0.01	0.03	0.09	0.07	0.23	0.83	9
A10	0.01	0.01	0.09	0.05	0.31	0.83	10
A11	0.04	0.03	0.11	0.09	0.14	0.82	11
A12	0.02	0.02	0.10	0.15	0.39	0.92	3
A13	0.03	0.03	0.11	0.21	0.37	0.94	2
A14	0.02	0.05	0.11	0.08	0.35	0.90	5
A15	0.02	0.04	0.12	0.26	0.39	0.96	1
A16	0.01	0.00	0.01	0.08	0.19	0.74	15

Table 12: Shaft materials alternatives and their overall desirability values

Alternatives	Criteria					Composite desirability	Rank
	C1	C2	C3	C4	C5		
A1	0.00	0.01	0.01	0.04	0.41	0.76	13
A2	0.01	0.01	0.03	0.07	0.40	0.82	7
A3	0.01	0.01	0.03	0.26	0.39	0.89	4
A4	0.00	0.01	0.01	0.06	0.41	0.78	11
A5	0.00	0.01	0.03	0.07	0.40	0.82	8
A6	0.00	0.01	0.03	0.15	0.36	0.84	6
A7	0.01	0.02	0.05	0.15	0.07	0.76	14
A8	0.01	0.02	0.13	0.07	0.03	0.70	16
A9	0.01	0.01	0.04	0.08	0.23	0.80	10
A10	0.01	0.00	0.03	0.04	0.31	0.77	12
A11	0.04	0.09	0.05	0.08	0.14	0.82	9
A12	0.02	0.04	0.09	0.07	0.39	0.89	4
A13	0.03	0.04	0.13	0.09	0.37	0.91	2
A14	0.02	0.05	0.05	0.14	0.35	0.90	3
A15	0.02	0.04	0.16	0.10	0.39	0.92	1
A16	0.01	0.02	0.05	0.01	0.19	0.73	15

Table 13: Trough materials alternatives and their overall desirability values

Alternatives	Criteria					Composite desirability	Rank
	C1	C2	C3	C4	C5		
A1	0.00	0.00	0.05	0.14	0.41	0.86	10
A2	0.01	0.02	0.07	0.09	0.40	0.87	9
A3	0.01	0.02	0.14	0.12	0.39	0.91	3
A4	0.00	0.00	0.06	0.11	0.41	0.85	11
A5	0.00	0.02	0.07	0.16	0.40	0.90	7
A6	0.00	0.02	0.09	0.17	0.36	0.90	5
A7	0.01	0.03	0.09	0.17	0.07	0.78	15
A8	0.01	0.07	0.09	0.19	0.03	0.74	16
A9	0.01	0.02	0.09	0.19	0.23	0.87	8
A10	0.01	0.02	0.09	0.22	0.31	0.90	4
A11	0.04	0.03	0.11	0.10	0.14	0.83	12
A12	0.02	0.05	0.10	0.18	0.39	0.94	1
A13	0.03	0.07	0.11	0.01	0.37	0.82	13
A14	0.02	0.03	0.11	0.10	0.35	0.90	6
A15	0.02	0.09	0.12	0.07	0.39	0.91	2
A16	0.02	0.03	0.01	0.26	0.19	0.82	14

3.2. Utility Function Results

Tables 14 to 16 shows the utility values of materials used in the design of beater arm, shaft and trough respectively. As shown in Tables 14 to 16, A1 to A16 are the materials listed in serial numbers 1 to 16 in Table 1 while C1 to C5 are the criteria shown in Table 4 to 8. The values in Tables 14 to 16 are the utility values derived from Equations 10 to 11. Table 17 shows the alternative materials for beater arm design and their overall utility values. As shown in Table 17, alternative A15 is ranked number one while alternative A16 is ranked number sixteen. This means that water hardening steel is the best material for beater arm design while nano-alloy steel is the worst. Table 18 shows the alternative materials for shaft design and their overall utility values. As shown in Table 18, alternatives A15 is ranked number one while alternative A16 is ranked number sixteen. This means that water hardening steel is the best materials for shaft design while nano alloy steel is the worst. Table 19 shows the alternative materials for trough design, their utility values. As shown in Table 19, alternatives A12 is ranked number one while alternative A7 is ranked number sixteen. This means that tungsten high speed steel is the best materials for trough design while martensic stainless steel is the worst.

Table 14: Beater arm materials alternatives and their utility values

Alternatives	Criteria				
	C1	C2	C3	C4	C5
A1	3.92	4.01	1.02	1.03	4.58
A2	4.75	5.32	1.48	3.01	4.32
A3	4.89	9.00	5.52	3.54	3.88
A4	2.37	5.28	1.24	1.08	4.60
A5	2.99	5.43	1.48	3.33	4.32
A6	3.86	7.47	2.04	3.33	3.12
A7	5.50	7.41	1.90	4.54	0.35
A8	5.66	5.53	1.92	8.13	0.15
A9	4.83	5.67	1.94	3.95	1.49
A10	4.34	3.93	2.04	3.17	2.35
A11	9.00	5.71	2.76	4.84	0.76
A12	6.58	5.48	2.61	6.76	3.84
A13	7.91	6.13	2.80	8.06	3.45
A14	7.42	7.39	3.01	4.47	3.04
A15	7.47	6.46	3.58	9.00	3.84
A16	4.09	2.13	0.14	4.69	1.11

Table 15: Shaft materials alternatives and their utility values

Alternatives	Criteria				
	C1	C2	C3	C4	C5
A1	3.92	2.66	1.03	4.01	4.58
A2	4.75	2.92	3.01	5.32	4.32
A3	4.89	4.11	3.54	9.00	3.88
A4	2.37	2.73	1.08	5.28	4.60
A5	2.99	2.92	3.33	5.43	4.32
A6	3.86	2.62	3.33	7.47	3.12
A7	5.50	5.44	4.54	7.41	0.35
A8	5.66	5.82	8.13	5.53	0.15
A9	4.83	3.88	3.95	5.67	1.49
A10	4.34	1.79	3.17	3.93	2.35
A11	9.00	9.00	4.84	5.71	0.76
A12	6.58	6.82	6.76	5.48	3.84
A13	7.91	7.11	8.06	6.13	3.45
A14	7.42	7.54	4.47	7.39	3.04
A15	7.47	7.00	9.00	6.46	3.84
A16	4.09	5.03	4.69	2.13	1.11

Table 16: Trough materials alternatives and their utility values

Alternatives	Criteria				
	C1	C2	C3	C4	C5
A1	3.92	1.03	1.02	1.80	4.58
A2	4.75	3.01	1.48	1.03	4.32
A3	4.89	3.54	5.52	1.47	3.88
A4	2.37	1.08	1.24	1.40	4.60
A5	2.99	3.33	1.48	2.27	4.32
A6	3.86	3.33	2.04	2.63	3.12
A7	5.50	4.54	1.90	2.45	0.35
A8	5.66	8.13	1.92	3.13	0.15
A9	4.83	3.95	1.94	3.05	1.49
A10	4.34	3.17	2.04	4.64	2.35
A11	9.00	4.84	2.76	1.14	0.76
A12	6.58	6.76	2.61	2.82	3.84
A13	7.91	8.06	2.80	0.12	3.45
A14	7.42	4.47	3.01	1.14	3.04
A15	7.47	9.00	3.58	0.74	3.84
A16	7.11	4.69	0.14	9.00	1.11

Table 17: Beater arm materials alternatives and their overall utility values

Alternatives	Criteria					Overall utility	Rank
	C1	C2	C3	C4	C5		
A1	0.16	0.36	0.16	0.26	2.09	3.03	11
A2	0.19	0.48	0.23	0.77	1.97	3.64	7
A3	0.20	0.81	0.86	0.91	1.77	4.55	4
A4	0.09	0.48	0.19	0.28	2.10	3.14	10
A5	0.12	0.49	0.23	0.85	1.97	3.67	6
A6	0.15	0.67	0.32	0.85	1.42	3.42	8
A7	0.22	0.67	0.30	1.17	0.16	2.51	15
A8	0.23	0.50	0.30	2.09	0.07	3.18	9
A9	0.19	0.51	0.30	1.01	0.68	2.70	14
A10	0.17	0.35	0.32	0.81	1.08	2.73	13
A11	0.36	0.51	0.43	1.24	0.35	2.90	12
A12	0.26	0.49	0.41	1.73	1.75	4.65	3
A13	0.32	0.55	0.44	2.07	1.58	4.95	2
A14	0.30	0.66	0.47	1.15	1.39	3.96	5
A15	0.30	0.58	0.56	2.31	1.75	5.51	1
A16	0.16	0.19	0.02	1.20	0.50	2.08	16

Table 18: Shaft materials alternatives and their overall utility values

Alternatives	Criteria					Overall utility	Rank
	C1	C2	C3	C4	C5		
A1	0.16	0.24	0.16	1.03	2.09	3.68	11
A2	0.19	0.26	0.47	1.36	1.97	4.26	7
A3	0.20	0.37	0.56	2.31	1.77	5.20	3
A4	0.09	0.25	0.17	1.36	2.10	3.97	9
A5	0.12	0.26	0.52	1.39	1.97	4.27	6
A6	0.15	0.24	0.52	1.92	1.42	4.25	8
A7	0.22	0.49	0.71	1.90	0.16	3.48	13
A8	0.23	0.52	1.27	1.42	0.07	3.51	12
A9	0.19	0.35	0.62	1.45	0.68	3.29	14
A10	0.17	0.16	0.50	1.01	1.08	2.92	15
A11	0.36	0.81	0.76	1.47	0.35	3.74	10
A12	0.26	0.61	1.06	1.41	1.75	5.10	4
A13	0.32	0.64	1.26	1.57	1.58	5.37	2
A14	0.30	0.68	0.70	1.90	1.39	4.96	5
A15	0.30	0.63	1.41	1.66	1.75	5.75	1
A16	0.16	0.45	0.73	0.55	0.50	2.40	16

Table 19: Trough materials alternatives and their overall utility values

Alternatives	Criteria					Overall utility	Rank
	C1	C2	C3	C4	C5		
A1	0.16	0.09	0.16	0.46	2.09	2.96	8
A2	0.19	0.27	0.23	0.26	1.97	2.93	9
A3	0.20	0.32	0.86	0.38	1.77	3.53	4
A4	0.09	0.10	0.19	0.36	2.10	2.85	12
A5	0.12	0.30	0.23	0.58	1.97	3.21	5
A6	0.15	0.30	0.32	0.68	1.42	2.87	10
A7	0.22	0.41	0.30	0.63	0.16	1.71	16
A8	0.23	0.73	0.30	0.80	0.07	2.13	14
A9	0.19	0.36	0.30	0.78	0.68	2.31	13
A10	0.17	0.29	0.32	1.19	1.08	3.04	7
A11	0.36	0.44	0.43	0.29	0.35	1.87	15
A12	0.26	0.61	0.41	0.72	1.75	3.76	1
A13	0.32	0.73	0.44	0.03	1.58	3.09	6
A14	0.30	0.40	0.47	0.29	1.39	2.85	11
A15	0.30	0.81	0.56	0.19	1.75	3.61	2
A16	0.28	0.42	0.02	2.31	0.50	3.54	3

3.3. Comparison of Desirability and Utility Function Results

Tables 20 to 22 shows the comparison of the desirability and utility function ranks for materials for design of beater arm, shaft and trough respectively. From Table 20, A3, A12, A13, A14, and A15 had the same rank from the two MCDM methods, while other materials had different ranks. The differences could be attributed to the different methods adopted by the MCDM tools to rank the alternatives. While desirability function is linear, utility function is non-linear, hence the differences in the rankings. From Table 21, A2, A12, A13, A14, and A15 had the same rank from the two MCDM methods, while other materials alternatives had different ranks. The differences could be attributed to the different methods adopted by the MCDM tools to rank the alternatives. While desirability function is linear, utility function is non-linear, hence the differences in the rankings. From Table 22, A2, A12 and A15 had the same rank from the two MCDM methods, while other materials alternatives had different ranks. The differences could be attributed to the different methods adopted by the MCDM tools to rank the alternatives and the weights assigned to the criteria which were different from the weights assigned to the criteria in the ranking of the materials for beater arm and shaft design. Furthermore, while desirability function is linear, utility function is non-linear, hence the differences in the rankings.

Table 20: Comparison of the desirability and utility function ranks for beater arm materials

Alternatives	Desirability function	Utility function
A1	13	11
A2	8	7
A3	4	4
A4	12	10
A5	7	6
A6	6	8
A7	14	15
A8	16	9
A9	9	14
A10	10	13
A11	11	12
A12	3	3
A13	2	2
A14	5	5
A15	1	1
A16	15	16

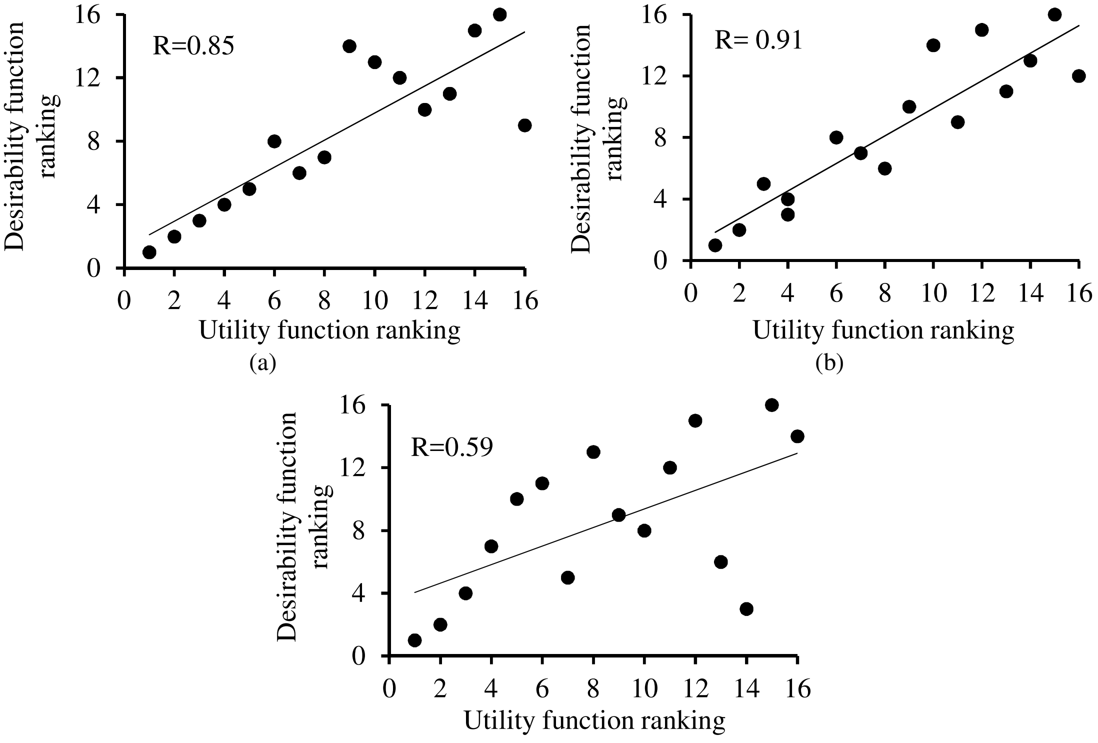
Table 21: Comparison of the desirability and utility function ranks for shaft materials

Alternatives	Desirability function	Utility function
A1	13	11
A2	7	7
A3	4	3
A4	11	9
A5	8	6
A6	6	8
A7	14	13
A8	16	12
A9	10	14
A10	12	15
A11	9	10
A12	4	4
A13	2	2
A14	3	5
A15	1	1
A16	15	16

Table 22: Comparison of the desirability and utility function ranks for trough materials

Alternatives	Desirability function	Utility function
A1	10	8
A2	9	9
A3	3	4
A4	11	12
A5	7	5
A6	5	10
A7	15	16
A8	16	14
A9	8	13
A10	4	7
A11	12	15
A12	1	1
A13	13	6
A14	6	11
A15	2	2
A16	14	3

Figure 4 shows a plot of the rankings of the desirability function against utility function rankings for materials used in digester components design. Figure 4a shows that the correlation coefficient between desirability function ranking and utility function ranking was 0.85 for beater arm materials. This is an indication that there is a very strong agreement between desirability function ranking and utility function rankings. Figure 4b shows that the correlation coefficient between desirability function ranking and utility function ranking is 0.91 for central shaft materials. This also indicates that there is a very strong agreement between desirability function ranking and utility function rankings for central shaft materials. Figure 4c shows that the correlation coefficient between desirability function ranking and utility function ranking is 0.59 for trough materials. This also indicates that there is a measure of agreement between desirability function ranking and utility function rankings for trough materials.



(a)

(b)

(c)

Figure 4: Desirability vs. utility function predictions for materials of digester components (a) Desirability vs. utility function rankings for beater arm materials; (b) Desirability vs. utility function rankings for shaft materials; (c) Desirability vs. utility function rankings for trough materials

From the results of the analysis, it is always imperative to use at least two MCDM tools in solving materials selection problems. The second MCDM tool acts as a validation tool to reinforce the results of the first MCDM tool. In cases where there is a strong disagreement between the two rankings, then it is advisable to use a third MCDM tool for validation of the previous two results. Hence, although there is a measure of agreement between the desirability and utility functions rankings for trough materials selection, it may be necessary that a third MCDM tool like TOPSIS be used for further validation of the first two results. This study is not exhaustive. There are several new materials and composites that have not been considered in this research. What is important is that models for optimal selection of materials for the design of a digester have been developed. Thus, a designer can always select a material not considered in this research and put it into the model to see its ranking in comparison with other materials. Also, slight modifications of the weights assigned to various criteria could affect the results slightly.

4. CONCLUSION

The results have shown that desirability and utility functions are very good MCDM tools for optimal selection of materials for the design of a digester. It is imperative that engineers use these tools for optimal design of oil palm fruit digester. Improving the reliability and durability of the digester would boost the operations and profitability of small scale oil palm mills all over the world.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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