Design and development of small-scale oil palm waste shredder for achieving technical, economic and environmental sustainability

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Abstract. This paper presents the design and development of an economically and technically feasible small-scale oil palm waste shredder. Oil palm waste management has always been a serious issue for palm oil industry in South East Asia. Poor waste management contributes to environmental problem and hence reducing consumers’ confidence in palm oil products. It was found that most available oil palm waste shredders are unaffordable due to high initial investment cost, large, heavy and unportable, which have been the drawbacks for small and medium enterprises (SMEs) to participate in oil palm waste management industry. To rectify the situation, a low cost and small-scale oil palm waste shredder is introduced in this paper. Based on Quality Function Deployment (QFD) results, the main design concept deduced is to compromise acceptable efficiency with affordable price by integrating all mandatory components of oil palm waste shredder into a comparatively small and portable support structure. The innovations made in the modified design are: 2 to 3 multiples of size reduction, adoption of double-shafts cutters with 7 jaws technology, installation of oil palm fibre and waste juice collecting system and deployment of a portable machinery base equipped with caster wheels. Preliminary calculations supported the conceptual design which consists of torque generated from 5.5kW electric motor connected to a ZQ500 reducing gearbox. The cutting force produced is expected up to 19.45kN, which has a safety factor of 4.5 as compared to the maximum compression strength of oil palm fronds (OPFs) which is only 4.351kN. This conceptual design is expected to be able to handle other oil palm wastes like empty fruit bunches (EFBs) as oil palm fronds (OPF) are generally harder than other oil palm wastes.

Keywords. Sustainable manufacturing; Small-scale; Oil palm waste shredder; Design and development; Waste management

1. Introduction

Palm oil is the most produced edible plant oil in the world. Its consumption can be traced back to 5,000 years ago and nowadays, palm oil is consumed by more than three billion people over 150 nations in the world. Palm oil industry is growing substantially in South-East Asia (especially Indonesia and Malaysia), Latin America, and Africa. However, that the scenario of oil palm solid waste treatment is
unhealthy which has led to the uprising of environmental problems. Ultimately this reduces the confidence of consumers in palm oil products. Traditionally, EFB are handled by three approaches, namely composition, incineration and dumped (land-filled) [1]. Incineration is the most widely used method due to its lowest cost and undoubtedly, the consequence is the arising of air pollution issue because incineration of EFB emits white smoke with high ash content [2]. Direct dumping of EFB with residual oils results in oil spills, which not only contaminates the soil but also poses as a wastage [3].

It was reported that both oil palm plantations and palm oil mills are currently facing three main issues, environmental problems, overdependence on crude palm oil (CPO) price in global commodity market and inactive participation of small and medium enterprises (SMEs) in waste management. Current technologies of oil palm wastes management are insufficient to meet the abundant production of oil palm wastes. In addition, current machinery technology (shredders) in handling oil palm solid wastes has portrayed crucial weaknesses such as high cost and large installation area required, which are the key factors to drive away small and medium enterprises (SMEs) from making investment [4].

The main objective of this research is to design and develop an economically and technically sustainable oil palm waste shredding machine to solve the oil palm waste management issue and meanwhile rebound the shredder market for SMEs because SMEs constitute the largest proportion in global economics. The objective of this study is in line with the sustainable palm oil production initiated by Malaysian government to re-instil back confidence to palm oil products. The main focus of solid waste type is on EFB and OPF. Shredding function is achieved by utilizing mechanical cutting force by double shafts rotating mechanism installed with plenty of cutters.

The main design concept adopted is compromising acceptable efficiency with affordable price by integrating all of the mandatory components of complex shredders onto a small and portable device. The main innovations made in this project is the reduction of ordinary size of shredder, adoption of double-shafts cutters with 7 jaws technology to ensure shredding efficiency, installation of waste juice collecting system and integration of electric motor, reducing gearbox, shredder, feeder and juice collecting tank onto a supportive structure installed with caster wheels. The efficient, portable and yet affordable shredder is strongly believed to own high potential in oil palm waste management filed of palm oil industry sector.

The significance of the innovation would be portrayed through its contribution to palm oil industry, nation economy and society. Successful development of the machine poses as a flying start for expanding oil palm waste management sector until the nation achieves fully utilisation of oil palm waste through biomass conversion, which is stated in Malaysian Biomass Industry Action Plan 2020 [4]. Besides, enhancing participation of SMEs in oil palm waste management sector to convert biomass wastes into high value products emerges as an alternative to diversify Malaysian economy. Malaysian oil palm sector is able to gain additional support to endure the fluctuating commodity price in global market especially during an economic downturn. Society would also gain benefit as proper management of abundant oil palm waste enables a better control of pollution level caused by palm oil industry and safeguards a healthy society and environment.

2. Literature review

2.1. Characterization of oil palm solid wastes

Generally, solid wastes generated from both plantation and milling activities comprise of 5 main types, typically known as oil palm frond (OPF), oil palm trunk (OPT), empty fruit bunch (EFB), mesocarp fiber (MF) and palm kernel shell (PKS). Constituents of each type of waste are depicted in table 1.

EFB and OPF are the most abundant solid waste generated from palm oil mill and oil palm plantation respectively. In order to develop or improvise treatment methods of EFB and OPF, their crucial characteristics need to be studied and acknowledged as these parameters own the potential to affect the design considerations of waste treatment machine or methodology in advance.
Table 1. Constituents of various oil palm solid wastes.

| Type of Solid Wastes | Moisture Content (wt.%) | Volatile Matter (wt.%) | Fixed Carbon (wt.%) | Ash Content (wt.%) |
|----------------------|-------------------------|-----------------------|---------------------|-------------------|
| EFB                  | 66.0-69.0               | 86.5-87.7             | 10.8-14.5           | 3.7-5.3           |
| OPF                  | 62.0-77.0               | 83.6-88.3             | 3.2-14.8            | 3.2-3.8           |
| OPT                  | 67.0-81.0               | 86.3-88.3             | 4.9-7.8             | 2.9-3.7           |
| PKS                  | 11.0-13.0               | 82.7-84.4             | 13.2-20.4           | 1.4-4.8           |
| MF                   | 35.0-48.0               | 84.0-85.6             | 7.6-17.4            | 5.0-7.4           |

The size of EFB is quite large as it can be 50cm in maximum diameter whereas its weight can go up to 20 kg [5]. In term of moisture content (MC), EFB usually contain a high proportion of water (>60%) [6]. High MC has made treatment of EFB difficult because it limits the processing duration of EFB. The processing of EFB need to be completed within three days after production. Otherwise, they will start rotting due to high MC [5].

Shredding OPF would not be as easy as EFB because of its structural complexity and also different chemical compositions according to different parts of OPF [7]. OPF is comprised of four major parts, namely rachis, leaflet, stem and petiole, which is shown in the following figure 1 [7].

![Figure 1. Components of OPF.](image)

For physical properties of OPF, its average length and weight were measured to be 675.89cm and 9.5 kg respectively whereas its base has a mean width of 17 cm and height of 6 cm [7]. The dimension of OPF’s base is important as it will influence the design of feeder in later stage. The size and shape of feeder must be appropriate to allow smooth feeding process of OPF into the shredder.

Study conducted in reference [7] shows that the age and storage period of OPF would affect its MC and thus the required compression force for shredding. Compression test result of OPF with different ages and storage periods to give a clear comparison. Based on the same study, it was found that the compression load required to shred OPF decreased in longer storage period. Meanwhile, the base part (petiole) of OPF was found to have the highest compression strength as petiole contains the most compact fibre structure. In term of age, OPF from 20 years old plant was found to have higher compression strength than OPF from 5 years old plant. From the perspective of compression strength, it can be deduced that compression strength of 5 years old and 20 years old petiole falls between the range of 287.56 kgf (2.820kN) and 443.78 kgf (4.351kN) respectively [7]. Thus, the torque of the shredder must be high enough to generate cutting force above 4.351 kN in order to shred the petiole of OPF.
2.2. Commercial values of oil palm fiber

It was reported that the selling price of oil palm fibre falls within RM400-RM600/tonne which is quite lucrative in term of raw fibre [3]. In addition, the value of commercial products made from the fibre will be enhanced by multiple folds. In addition, non-hazardous and biodegradable oil palm fibre has plenty of usage summarised in the figure 2 [3].

![Exploitation of Palm Fiber](image)

**Figure 2.** Distribution of patent family among oil palm fibre exploitation technologies.

2.3. Gap analysis

After extensive literature review has been done in the field of oil palm waste management and shredding, the following gaps are found:

- Primary design consideration of shredder machine is efficiency as to handle the abundant oil palm waste in Malaysia. However, efficiency must compromise with costing as SMEs are the main market target.
- The significance of shredder tends to increase with plenty applications of oil palm fibre.
- The shredder should be portable and of appropriate size for convenience and also reduction of investment modal as smaller space is required for machine operation.

3. Methodology

3.1. Research flow process for development of product

3.1.1. Quality Function Deployment (QFD). QFD is an effective tool to precisely transform customer requirement to design specifications of product [14]. QFD analysis process can be simply represented in a well-structured matrix named House of Quality (HOQ). The ranking of design consideration factors is shown in table 2.
Table 2. Ranking of design consideration factors from HOQ.

| Improvement Direction /g315 /g313 /g313 /g313 /g313 /g315 /g315 /g315 /g315 /g315 | Units | kg | L | kg | - | kW | % | m² | m³ | mm | db |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mass | Importance (Weight Factor) | 5 | 0 | 0 | 6 | 9 | 9 | 9 | 0 | 0 | 0 |
| Collection of Waste Juice | Reducing Gear Train Value | 3 | 0 | 6 | 0 | 0 | 0 | 9 | 0 | 0 | 0 |
| Loading Capacity | Motor Power | 5 | 6 | 0 | 0 | 9 | 9 | 0 | 9 | 6 | 0 |
| Motor Jamming Probability | Installation/Operation Area | 4 | 0 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Reducing Gear Train Value | Output Fibre Length | 4 | 6 | 0 | 0 | 0 | 0 | 9 | 9 | 0 | 0 |
| Probability | Dimension/Size | 5 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Installation/Operation Area | Noise Level | 4 | 0 | 0 | 0 | 6 | 6 | 0 | 9 | 9 | 0 |
| Output Fibre Length | Raw Score (942) | 4 | 0 | 0 | 0 | 6 | 6 | 0 | 0 | 0 | 9 |
| Short Fibre Output | 5 | 0 | 0 | 0 | 6 | 6 | 0 | 0 | 0 | 9 |
| Long Fibre Output | 3 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 9 |
| Low Maintenance Cost | 4 | 0 | 0 | 0 | 0 | 0 | 9 | 0 | 6 | 0 |
| Low Noise Level | 3 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 |
| Raw Score | (942) | 54 | 84 | 48 | 156 | 138 | 108 | 117 | 126 | 63 | 57 |
| Relative Weight % | 5.73 | 8.92 | 5.10 | 16.56 | 14.65 | 11.46 | 12.42 | 13.38 | 6.69 | 6.05 |
| Rank Order | 9 | 6 | 10 | 1 | 2 | 5 | 4 | 3 | 7 | 8 |

**Importance: 1-Unimportant; 5-Very Important**

**Relativity: 0-Unrelated; 9-Highly Related**

Based on QFD result, the main important design considerations are:

- High efficiency contributed by high reducing gear train value and motor power
- Affordable price by reducing mass, size and installation/operation area of machine
- High safety by collecting waste juice and reducing noise level
- Portable
- Short fibre output is more preferable than long fibre

4. **Product design specifications (PDS)**

PDS comprises of particulars of product design components which are generated based on QFD results. Table 3 summarizes the PDS.
Table 3. PDS of small-scale oil palm waste shredder.

| No. | Components | Quantity | Material                  |
|-----|------------|----------|---------------------------|
| 1   | Cutters with 7 jaws | 20       | CrSi Steel Alloy           |
| 2   | Rotating Shaft      | 2        | NiCr Steel Alloy           |
| 3   | Shaft Collar        | 20       | NiCr Steel Alloy           |
| 4   | Spacer              | 20       | Aluminium 1060 Alloy      |
| 5   | Shredder Frame      | 4        | ASTM A36 Steel            |
| 6   | Spur Gear with 20 teeth | 2   | 20MnCr5 Stainless Steel   |
| 7   | Bearing Housing     | 4        | ASTM A36 Steel            |
| 8   | Gear Housing        | 1        | AISI 1020 Low-carbon Steel|
| 9   | Feed Hopper         | 1        | Aluminium 1060 Alloy      |
| 10  | Collecting Tanks    | 1        | Aluminium 1060 Alloy      |
| 11  | Support Table       | 1        | ASTM A36 Steel            |
| 12  | Machine Base        | 1        | ASTM A36 Steel            |
| 13  | Handle              | 2        | AISI 1020 Low-carbon Steel|

5. Product design calculations

5.1. Motor power and reducing gear train value

Conventional configuration of motor power in low-cost shredders usually ranges from 1hp (0.7457 kW) to 2hp (1.4914 kW) [11]. Based on QFD result, the most important parameters that would affect the efficiency of machine are motor power and reducing gear train value. As to increase the efficiency of the mini shredder, a three-phase inducted motor with power of 5.5 kW and rotational speed of 1440 rpm is chosen. Meanwhile, the reducing gear train value is selected to be 1/48 to reduce the output rotational speed of the shaft connected to the shredder.

Calculation of output rotational speed, $\omega_{out}$ is as equation (1).

$$\omega_{out} = \omega_{in} \times TV$$  \hspace{1cm} (1)

where $\omega_{in}$ is input rotational speed from motor

TV is reducing gear train value as equation (2).

$$\omega_{out} = 1440 \times \frac{1}{48} = 30\text{rpm}$$  \hspace{1cm} (2)
5.2. Shredder main body case
As reduction in price and size is second design consideration, the shredder main body case design needs to be small and compact. The internal dimension of shredder main body case is shown in figure 3.

![Figure 3. Internal dimension of shredder main body case.](image)

5.3. Cutter design
Figure 4 illustrates the cutter design. Several parameters of cutter are calculated and configured as follows.

![Figure 4. Cutter design.](image)

5.3.1. Number of cutter jaws. The most conventional number of cutter jaws are 3, 5, 7 and 9 whereby the output fibre length decreases accordingly with the increasing jaw number. Based on QFD result, short fibre is more favourable in market. Thus, 7 jaws are chosen for optimum fibre length production.

5.3.2. Thickness of cutter, t. The thickness of cutter would affect the number of cutters to be installed within the small shredder case. In order to install 20 cutters, the thickness is to be calculated as equation (3).

\[
t = \frac{\text{Maximum shredder internal length}}{\text{Number of cutters}}
\]  

(3)
5.3.3. *Outer diameter of cutter, D.* As the height of the shredder case is limited to be 20cm, the outer diameter of cutter has to be less than 20cm. It was found that 18cm will be appropriate from the perspective of compacity and dimensional tolerance.

5.3.4. *Cutting force $F_c$.*

$$F_c = \frac{\text{Torque, } \tau}{\text{Motor Power, } P \text{ (W)}}$$

$$\tau = \frac{5.5 \times 10^3}{30 \times \frac{2\pi}{18}} = \frac{1750.70 \text{ N} \cdot \text{m}}{5\pi}$$

$$r = \frac{2}{9} = 0.22 \text{ cm} = 0.09 \text{ m}$$

Hence, $F_c$ can now be calculated from $\tau$ and $r$.

$$F_c = \frac{1750.70}{0.09} = 19.45 \text{kN}$$

As determined previously, the minimum cutting force required to shred OPF is 4.351 kN. Therefore, the safety factor can be calculated by equation (4).

$$\text{Safety Factor} = \frac{\text{Produced } F_c}{\text{Minimum } F_c \text{ required}}$$

$$= \frac{19.45}{4.351} = 4.47 \approx 4.5$$

5.3.5. *Hub diameter of cutter, d.* Hub diameter of cutter must be equal to the diameter of rotating shaft. To ease and secure the cutter mounting on shaft, the hub shape is designed to be helical. The material used for shaft is NiCr steel with high yield stress, $\sigma_y$ of 275MPa. The calculation of $d$ is by using equation (5) [11].

$$\text{Maximum Shear Stress, } S_s = \frac{\sigma_y \times 0.5}{\text{Safety Factor}}$$

$$S_s = \frac{275 \times 10^6 \times 0.5}{4.5} = \frac{30.56 \text{MN/m}^2}{4.5}$$

$$d = \sqrt[3]{\frac{16 \tau}{\pi S_s}} [15]$$

$$d = \sqrt[3]{\frac{16 \times 1750.70}{30.56 \times 10^6 \pi}} = 0.0663 \text{m} = 6.63 \text{cm}$$

Thus, standard rotating shaft with $d = 8 \text{cm}$ (>6.63cm) is selected [15].
5.4. Transmission ratio and teeth number of spur gears
To ensure the rotational speed of both rotating shafts to be consistent, gear transmission ratio or velocity ratio, VR is chosen to be 1:1.

Velocity Ratio, \( VR = \frac{\text{Teeth of Driven Gear}, N_2}{\text{Teeth of Pinion Gear}, N_1} \)

Meanwhile, interference checking is performed to determine the number of gear teeth to ensure a smooth gear meshing.

Diametral Pitch, \( P_d = \frac{\text{Number of teeth, } N}{\text{Pitch diameter, } d} \)

In this case, \( N_1 \) or \( N_2 \) and \( d \) are pre-configured to be 16 and 10.5cm respectively.

\[ P_d = \frac{16}{10.5} = 1.52 \]

Interference checking formula is given by:

\[ N_2 < \left( \frac{N_1^2 \sin^2 \varnothing - 4k^2}{4k - 2N_1 \sin^2 \varnothing} \right) \quad [16] \]

where
\( N_1 \) and \( N_2 \) are teeth number of pinion and driven gears respectively, \( \varnothing \) is standard pressure angle of gear (14.5°, 20° or 25°); 20° is chosen, \( k \)=addendum of gear, \( a \times P_d \) which always equals 1 for \( \varnothing=20^\circ \).

Hence,

\[ \frac{N_1^2 \sin^2 \varnothing - 4k^2}{4k - 2N_1 \sin^2 \varnothing} = \frac{(16^2 \sin^2 20 - 4(1)^2)}{4(1) - 2(16) \sin^2 20} = 101.07 \]

\[ \frac{N_1^2 \sin^2 \varnothing - 4k^2}{4k - 2N_1 \sin^2 \varnothing} = 101.07 \]

Since \( N_2 < \left( \frac{N_1^2 \sin^2 \varnothing - 4k^2}{4k - 2N_1 \sin^2 \varnothing} \right) \) (16<101.07), \( N_1 \) and \( N_2 =16 \) is valid for VR of 1:1 in gear transmission. No interference will occur.

6. Product fabrication and operation
Figure 5 shows the designed CAD model of the shredder machine on the left and fabricated model of the shredder machine on the right.

Slight changes have been made to the design during fabrication, which are enlisted as follow:

- Cover has been installed on the feed hopper to enhance safety when the machine is not in use.
- The alignment of electric motor to reducing gearbox has been changed from horizontal to vertical for easier installation.
- The alignment of two collecting tanks is changed to vertical to ease the fabrication process.
Figure 5. 3D CAD model of shredder machine (left) and fabricated model of shredder machine (right).

Kindly scan the QR code as shown in figure 6 to view the operation process of the developed shredder machine.

Figure 6. QR code linking to the operation video of the developed shredder machine.

7. Results and discussion
The developed shredder machine is operated to carry out shredding test on a few fresh and dry OPF samples as shown in figure 7 and the parameters of output fiber (length and diameter) are measured by scanning electron microscope (SEM). Meanwhile, the moisture content of the OPF fiber is also determined based on oven dry weight basis.
The developed shredder machine is capable of shredding OPF into pieces and producing fiber within several seconds. Hence, it can be deduced that the machine is efficient in oil palm solid waste management since the hard and long OPF can be easily shredded, as shown in figure 8.

Most of the fiber’s cross-sections are in oval or irregular shape as shown in the SEM image in figure 9 (left). To simplify the analysis, the shapes are assumed to be circular and the diameter is calculated from the average of maximum horizontal and vertical distances of the shapes.
Based on figure 9, generally the output fiber is short (between 30mm and 80mm). The length of output fiber decreases significantly with the increase of shredding number undergone by OPF samples. On the other hand, the number of shredding does not affect significantly the diameter of the output fiber. Generally, the output fiber is very thin, with a mean value range of 0.53-0.58mm.

Based on figure 10, moisture content of fresh OPF fiber is approximately double the dry OPF fiber (64.85% versus 32.88%). It was found that the storage period and condition of the OPF affect the moisture content of output OPF fiber significantly, likewise in the case above (fresh OPF sample is stored within 7 days while dry OPF sample is stored more than 1 month).

Hence, the moisture content of output fiber can be controlled by the storage period of OPF depending on the exploitation of the fiber. Typically, palm fiber with high moisture content is ideal raw material for producing bio-fertilizers whereas dry palm fiber is ideal to be feedstock for industrial boilers.
8. Conclusions
The developed small-scale oil palm waste shredder machine in this research project has several outstanding features to cater for technical, economic and environmental sustainability, which are highlighted as follow:

- Affordable and feasible for SMEs to invest and participate in oil palm waste management sector.
- Efficient in handling abundant oil palm solid wastes such as OPF and EFB.
- Significance is drawn towards safety and user-friendly in operation (transmission gear system and cutters are enclosed to safeguard operators).
- Secondary pollution/contamination is prevented as the machine is equipped with waste juice collecting tank.
- Portable and space-saving, unlike the rigid and huge waste shredder machine which requires large installation area
- High potential to widen the scope by enhancing its universality in organic waste management field which includes a variety of agricultural wastes and food wastes.

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References
[1] V. I. Otti, H. I. Ifeanyichukwu, F. C. Nwaorum, and F. U. Ogbuagu, “Sustainable Oil Palm Waste Management in Engineering Development,“ vol. 6, no. 5, pp. 121–126, 2014.
[2] S. K. Loh, “The potential of the Malaysian oil palm biomass as a renewable energy source;” Energy Convers. Manag., 2016.
[3] D. H. Wang, “Patent Landscape Report: Palm Oil Production and Waste Treatment Technologies,” 2016.
[4] N. I.-G. G. for H. T. Abd Rahman, “Driving SMEs Towards Sustainable Future;” Malaysian Biomass Ind. Action Plan 2020, vol. 1, no. Driving SMEs Towards Sustainable Future, pp. 1–80, 2013.
[5] Malaysian-German Chamber of Commerce and Industry (MGCC), “Oil Palm Biomass & Biogas in Malaysia, 2017,” 2017.
[6] N. Abdullah, F. Sulaiman, and H. Gerhauser, “Characterisation of Oil Palm Empty Fruit Bunches for Fuel Application,”” vol. 22, no. 1, pp. 1–24, 2011.
[7] R. Bulan, T. Mandang, and W. Hermawan, “Physical and Mechanical Properties of Palm Frond for the Development of Palm Oil Waste Chopper and Pressing Machine Design,” vol. 6, no. 2, pp. 117–120, 2015.
[8] P. B. Khope and J. P. Modak, “Design of Experimental Set-up for Establishing Empirical Relationship for Chaff Cutter Energized by Human Powered Flywheel Motor,” vol. 9, no. 4, pp. 779–791, 2013.
[9] Ant Spirits Sdn Bhd, “Low Speed Mini Granulator,” Ant Spirits Sdn Bhd, 2018. [Online]. Available: info@antspirits.com.m.
[10] M. Sakthivel, G. Rajeshkannan, M. Naveenkumar, and D. M. Muralimanokar, “Design and Analysis of Twin Shaft Shredder Using Pro-E and Hyperworks Software,” Int. J. Adv. Res.
Basic Eng. Sci. Technol. Des., vol. 3, no. 24, pp. 836–858, 2017.

[11] I. M. S. Kumar, “Design and Development Of Agricultural Waste Shredder Machine,” vol. 2, no. 10, pp. 164–172, 2015.

[12] S. B. Pavankumar, K. R. Sachin, R. Shankar, B. Thyagaraja, and T. Madhusudhan, “Design and Fabrication of Organic Waste Shredding Machine,” vol. 7, no. 6, pp. 26–31, 2018.

[13] R. Ramli et al., “Ligno-ripper machine for processing of fibrous biomass,” 538, 2013.

[14] P. Akkawuttiwanich and P. Yenradee, “Fuzzy QFD approach for managing SCOR performance indicators,” Comput. Ind. Eng., no. May, 2018.

[15] G. Augusto, “Shaft Design,” 2017.

[16] W. L. and D. Cleghorn, Mechanics of Machines. 2016.