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Design and Construction of a Low Cost Plastic Shredding Machine

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ABSTRACT

The challenge of plastic waste pollution has made it imperative for a systematic approach to environmental waste management. Hence, plastic recycling takes the centre stage due to the numerous associated benefits it offers. Therefore, this study focused on designing and constructing a plastic shredding machine which will assist small and medium scale entrepreneurs in plastic recycling industry. The machine utilizes 3.7kW of mechanical power to produce a torque of 28.49Nm and a shredding force of 1424.5N. With this force, it is able to shred 150kg of plastic in 6.98minutes with an efficiency of 97.8%. Motion simulation analysis run on the machine shows that during operation, the maximum values for buckling amplitude, and deformation of the shaft are 0.1902 Ampres and 0.01634mm respectively. Also the von Mises stress result showed that all regions of the shaft are far below the yield strength of the shaft material, and the FoS corroborated this result with all regions above 1; having a minimum value of 157.7. This shows that the machine will not breakdown even when running at twice its loading capacity. Furthermore, at a production cost of ₦109,840.00 the machine is 21.96% cheaper than the current market value of ₦140,750.00, hence the aim of producing a cost effective, durable and efficient plastic shredding machine was achieved in this study.

Keywords: plastic shredding machine, plastic waste pollution, environmental waste management

INTRODUCTION

It is estimated that the earth's surface area is 510 million km^2, and the oceans account for 70.8% of this surface area while the dry land makes up the remaining 29.2% [1]. Human activities on land such as the indiscriminate disposal of solid, liquid and gaseous wastes have been attributed to be a major culprit and source of concern in global environmental and ecosystem changes. These indiscriminate disposals of solid waste pollute the earth surface because it causes contamination of the soil leading to a reduction in the value of land[2]. The most prominent land pollutant is plastic waste due to its cost friendliness and wide range of application. Plastics find good patronage in all industrial sectors, with the highest application being the packaging sector where approximately 146 million tonnes are used per year[3]. Plastics being polymers take a long time to decompose in landfills as it could last up to 1000 years[4]. Hence, if the rate of cumulative production of plastics continues as seen in 2015 to be 7.8 billion tonnes, [3] then the challenge posed by plastics should be taken quite seriously. It was estimated in 2015 by Jambeck et. al. [5] that Nigeria generates up to 10 million tonnes of plastic per year. 20% of this generated plastic is mismanaged due to inadequate disposal of littering, and is estimated to exceed 20% by 2025[5]. In the long run, a large quantity of these wastes end up in the ocean through waste water outlets, inland water ways, wind, or by deliberate disposal by people, leading to ocean pollution. Hence, proper management of plastic waste is required to avert the attendant consequences of plastic pollution. To achieve this, plastic recycling becomes a viable option as it promotes plastic waste management, and conserves energy and natural resources needed to produce new plastic. Currently, it is estimated that only 9% of global plastic waste is recycled[6]. This implies that more emphasis needs to be laid on activities that will foster plastic recycling.

In recycling plastic, the waste undergoes five different stages viz: sorting of plastic waste into plastic type, washing of sorted plastics to remove impurities, shredding of washed plastics and extruding by melting the shredded pellets into sizes used for different plastic products. Out of these five stages, it is only the shredding and extruding stages that must involve a form of machinery. To this end, the aim of this study is to design and construct a plastic shredding machine that will be cost friendly and efficient for use by small and medium scale entrepreneurs in the country. This will certainly increase recycling and reduce the unpleasant effects of plastic pollution in our environment. There have been attempts to design and produce shredding machines over the years, Anurag [7] designed a plastic bottle crusher to be used in public places, and the intent of the project is to assist people crush plastic bottles quickly in public places once the bottle content is consumed. Hence, the design ensured portability, compactness, and ease of use. The design incorporated the use of manually operated gears and a quick return mechanism in order to achieve the set goals of the project. The end product of the design was able to compress plastics which would further need to be cut/shredded into bits. This limits the machine to be used for commercial purposes. Senthil et. al. [8] showed that the design of a plastic shredder can be such that an optimum load is used to crush plastic waste without straining the operator. Their research achieved this by designing the shredding machine to operate on a slotted lever mechanism powered by a 3-phase induction AC motor. This design proved useful for an industrial application, but costly for a small or medium scale production outfit.

Rana et. al. [9] designed and fabricated a compact sized plastic bottle shredder, in their design pairs of cutting disc with four cutting points were mounted on a pair of shaft. Both shafts where mounted on bearings with an electric motor as the prime mover which is coupled to one of the shafts. Power is transmitted from the driving shaft to the driven shaft by an arrangement of meshing gears. Structural analysis was carried out to determine the total deformation, maximum shear stress and strain of both shaft and cutter. Results show that the design is safe since the maximum stress values exerted on the shaft and cutters did not exceed the yield stress values of the material of both shaft and cutter. The limitation of this design is in the usage, as it cannot function optimally for commercial production of shredded plastic chips. Ayo and Adelabu [10] designed a plastic shredder with an average throughput capacity and recovery efficiency of 27.3 kg/hr and 95% respectively. This was achieved by driving the shredding shaft with a 3-phase electric motor connected by a belt and pulley system. Although this design would serve a commercial production purpose, the cost of production which is ₦140,750.00 ($360.87) is a discouraging factor for small scale entrepreneurs in Nigeria. In a related design, Atadious and Oyejide [11] showed that the throughput of a plastic shredder could be improved upon to be 2070kg/hr with an efficiency of 98.44%. This was achieved by the introduction of a flywheel which is attached to the shaft having most of its weight at the circumference. The flywheel is designed to provide steady rotation of the shaft and even transmission of the torque. This study had the same limitation as that of Ayo and Adelabu. [10] Hence, it is pertinent to design for affordability to enable easy start-ups in the plastic recycling sector for the small and medium scale entrepreneurs.

MATERIALS AND METHOD

Machine Description

The plastic shredding machine in this study is designed to apply sufficient amount of shredding force through a cyclic impact loading on the plastic waste material to be shredded. This induces adequate energy in the plastic material causing its molecules to separate or deform relative to each other. This type of machine is made up of five main parts namely: prime mover, hopper, shredding chamber, shredding shaft, and the collector bin. The prime mover is an electric motor which generates the torque needed to rotate the shredding shaft. The hopper is the part of the machine that empties the plastic waste into the shredding chamber. A chute located by the side of the hopper guides the plastic waste into the hopper. The top of the hopper is covered in order to prevent popping/flying plastic waste from escaping during operation. The shredding chamber is made up of a pair of static blades attached by the length of the inner wall and a mesh screen at the base. The mesh screen ensures that only shredded plastic particles smaller than the mesh size are allowed to pass through to the collecting bin. The shredding shaft is housed in the shredding chamber; as it turns, it shreds plastic waste caught between the blades on the shaft and the static blades by the sides of the wall. This action is carried out repeatedly until the plastic waste in the shredding chamber has considerably reduced in size and are no longer been trapped between the shredding blades.

Materials

In Table 1, a summary of the components of the machine and materials used is shown. These materials were chosen based on the in-service condition of the components and comparative cost.

Table 1: Material selection table

S/N	Component	Material/ Specification	Description and Functions
1.	Hopper	Mild steel	A hoper is a funnel-shaped container from which plastic waste can be emptied in to the shredding chamber.
2.	Shredding chamber	Mild steel	Houses the shredding shaft and mesh, also provides the space for shredding of the plastic to take place.
3.	Shredding shaft	**AISI 4340 Steel, normalized**	Produces the shredding force needed to shred the plastic waste.
4.	Prime mover	AC motor (5 Hp)	Converts electrical energy to rotary mechanical energy needed to cause rotation of the shaft.
5.	Belt	Aramid	Transmits mechanical power to the shaft.
7.	Bearing	Cast iron	Provides support for the shaft while allowing it to rotate freely.
8.	Frame	2½" Angle bar	Provides a platform where all the components can be mounted on.

Figures 1 – 5 show orthographic and isometric views of major components of the shredding machine.

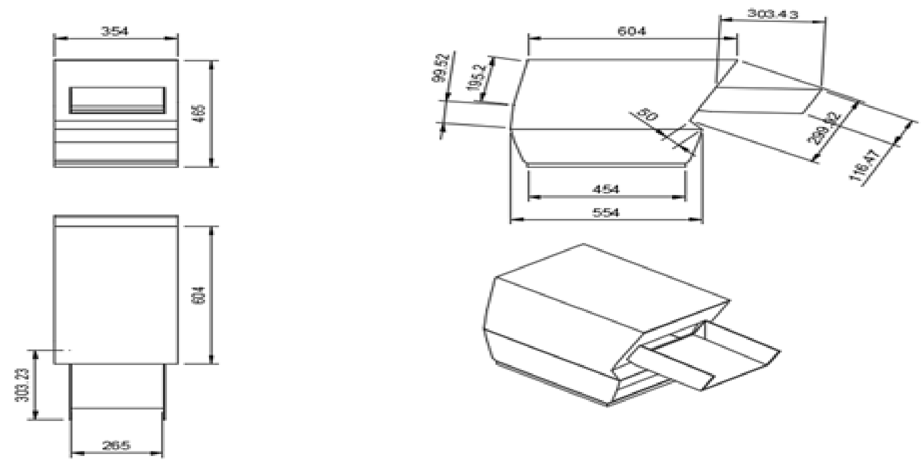


Figure 1: Hopper section

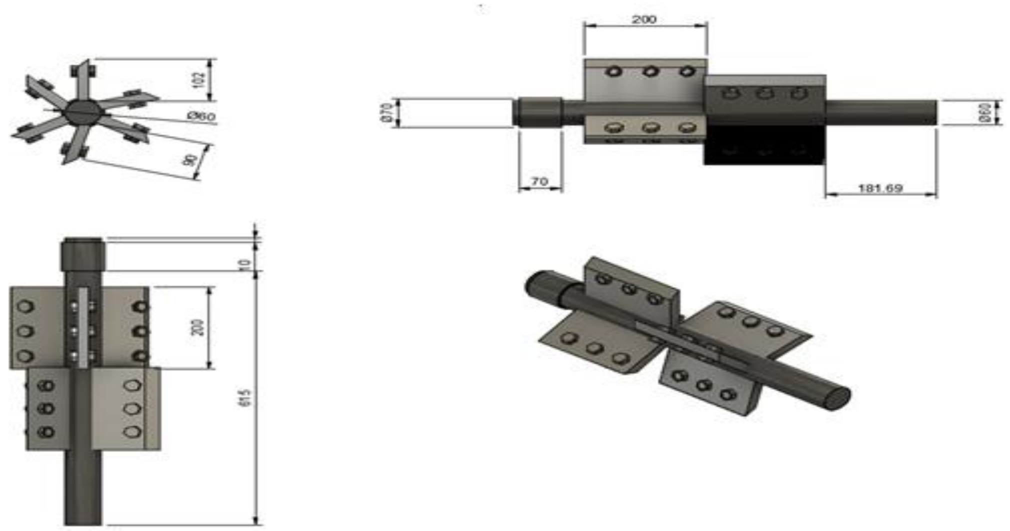


Figure 2: Shredding shaft

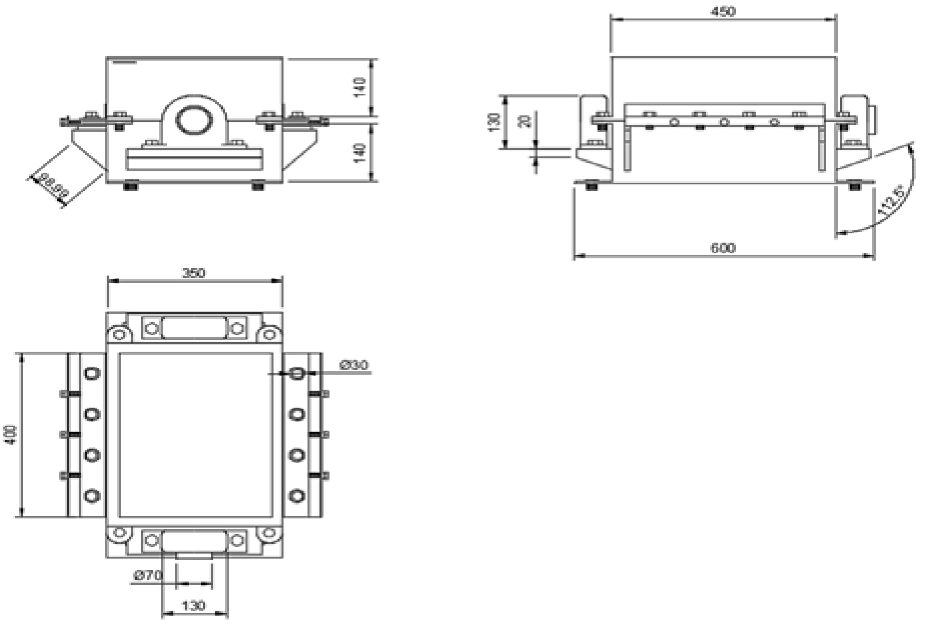


Figure 3: Shredding chamber

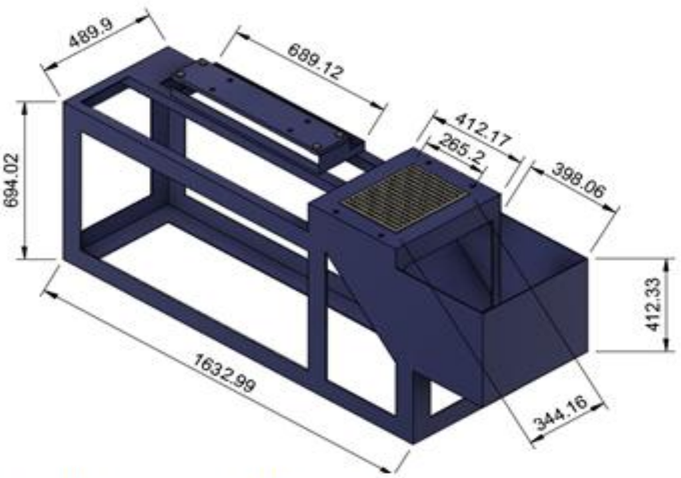


Figure 4: Frame and collecting bin

Design parameters and considerations

Centrifugal Tension

The centrifugal tension in the belt was determined using equation 1.

$$T_c = m.v^2 = m.\frac{\pi d_1 N_1}{60} \quad (1)$$

Where, d_1=diameter of driver pulley=0.24m, N_1=Speed of driver pulley=250rpm, m = belt mass/metre length=160g/m

Maximum Tension

The maximum tension the belt can withstand during power transmission is expressed in equation 2.

$$T_{max} = \alpha . A \quad (2)$$

Where α=permissible stress of belt material, A=cross sectional area of belt material

For aramid belt, α = 2800N/mm^2, [12] A = 0.714mm^2

Tension in tight side

Tension in tight side was obtained using equation 3

$$T_1 = T_{max} - T_c \quad (3)$$

Tension in slack side

Equation 4 was used to determine the tension in the slack side of the belt during power transmission.

$$2.3 \log\left(\frac{T_1}{T_2}\right) = \mu\theta \quad (4)$$

Where μ = coefficient of friction between pulley and belt = 0.24, θ = Angle of lap = 1 rad

Number of plastic bottles/batch

Equation 5 was used to determine the number of bottles to be shredded per batch

$$n = \frac{V_h}{V_p} \quad (5)$$

Where V_h = hopper volume = 1.155 x 10^{-1} m^3, V_p = plastic bottle volume = 7.7 x 10^{-4} (Faiyyaj et al., 2017)

Weight of plastic/batch

The maximum weight that the hopper can accommodate during a processing batch is expressed using equation 6.

$$w = n.\rho.V_p.g \quad (6)$$

Where, ρ = density of PET = 1380kg/m^3 [13]

Torque

Torque transmitted by shaft is given in equation 8 as:

$$T = \frac{60P}{2\pi N_1} \quad (7)$$

Where P = power rating of prime mover = 5hp

Shredding Force

The shredding force exerted by the shaft on the plastic is expressed by equation 8.

$$F_s = \frac{T}{r} \quad (8)$$

Where T = Torque r = radial distance from shaft to the shredding blade tip = 120mm

Belt Length

The length of the belt used to transmit torque from the prime mover to the shaft is given in equation 9 as:

$$L = \pi\,(d_2 + d_1) + 2x + \frac{(d_2 - d_1)^2}{x} \quad (9)$$

Shaft design

As earlier mentioned, the shredding shaft is the rotating member of the machine. The shaft is designed to withstand stresses due to twisting and bending moments. Consider the space and force diagrams of the shredding shaft in Figs 5a and b. The weight of the plastic waste to be shredded per batch is considered as a uniformly distributed load.

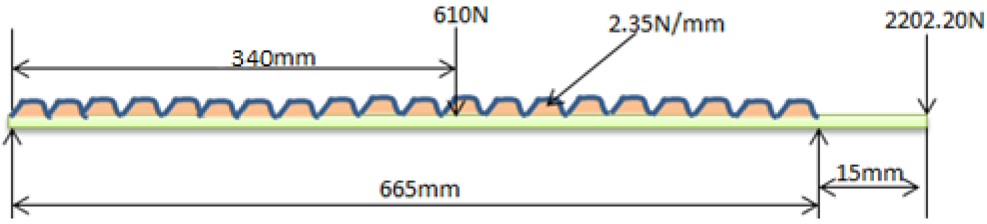


Figure 5a: Space diagram of shredding shaft

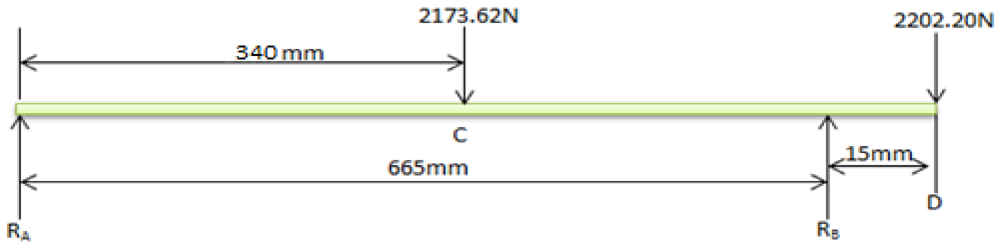


Figure 5b: Force diagram of shredding shaft

Since loading of the shredding chamber will be steady or gradual, then combined shock and fatigue factors for bending and torsion are taken to be K_m = 1.5 and K_t = 1 respectively.

Hence, sizing of the shaft was determined using equation 10.

$$d_s = \sqrt[3]{\frac{32M_e}{\sigma_b \pi}} \qquad (10)$$

Where σ_b = maximum tensile stress = 1110Mpa,

M_e = equivalent bending moment = $\frac{1}{2}\left[K_m M + \sqrt{(K_m M)^2 + (K_t T)^2}\right]$, M = maximum bending moment.

Forces acting on Pulley

Total forces acting on pulley is expressed in equation 11 as:

$$F_p = T_1 + T_2 \qquad (11)$$

Mass of shaft

Equation 12 was used to determine the mass of the shredding shaft.

$$m = \rho . vol \qquad (12)$$

Where ρ = density of shaft material =

Machine Throughput Capacity

This parameter indicates the amount of plastics that can be shredded by the machine in a second. It is expressed in equation 13 as:

$$MTC = \frac{m_s}{t} \qquad (13)$$

Where m_s = mass of shredded plastic, t = time in secs.

Efficiency

The machine efficiency is expressed in equation 14 as:

$$\eta = \frac{m_s}{m_i} \times 100$$

Where m_i = mass of plastic waste introduced into the machine

Motion analysis

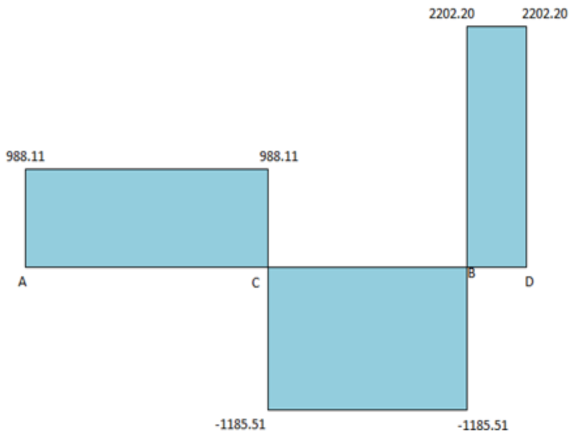
A motion simulation analysis was carried out on the shaft using the SolidWorks motion simulation tool. The aim of the simulation is to determine the buckling behaviour, deformation, von Mises stress and the Factor of Safety (FOS) of the shaft during in-service conditions.

RESULTS AND DISCUSSION

The result of the design considerations and parameters used in constructing the machine is shown in Table 2. From Table 2, it is seen that the shaft is expected to be affected more by a bending moment than twisting moment due to torsion.

S/n	Design Parameter	Value
1	Volume of hopper	0.1155m^3
2	Plastic waste weight per Batch	1563.62N
3	Number of bottles per batch	150
4	Length of belt	1m
5	Angle of lap	1 radian
6	Mass of belt	160g/m
7	Centrifugal tension	502N
8	Tension of tight side	1498N
9	Tension of slack side	704.20N
10	Maximum tension	2000N
11	Number of belts	2
12	Torque	28.49Nm
13	Forces acting on pulley	2201.20N
14	Shredding force	1424.5N
15	Equivalent bending moment	269.184Nm
16	Equivalent twisting moment	23.314Nm
17	Speed of motor	250 rpm
18	Power of motor	5 hp
19	Mass of shaft	62.18 kg

In figures 6 and 7, the shaft is expected to continually resist a maximum shear force of 2202.20N exerted by the tight and slack tensions and a maximum bending moment of 335.95Nm.



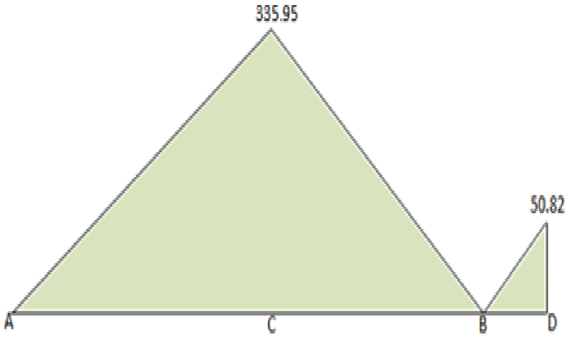


Figure 7: Bending moment diagram

Figure 6: Shear force diagram

Figures 8 to 11 show the buckling amplitude, deformation, FOS and von Mises stress contour plots of the shredding shaft. In figure 8, the buckling analysis reveal that maximum buckling amplitude expected is 0.1902 Ampres. This occurred at the shredding blade edges because the edge is continually being acted upon by the resisting forces which are equal and opposite in direction to the shredding force. The minimum buckling value is 0.00 Ampres and it occurred at the ends of the shaft.

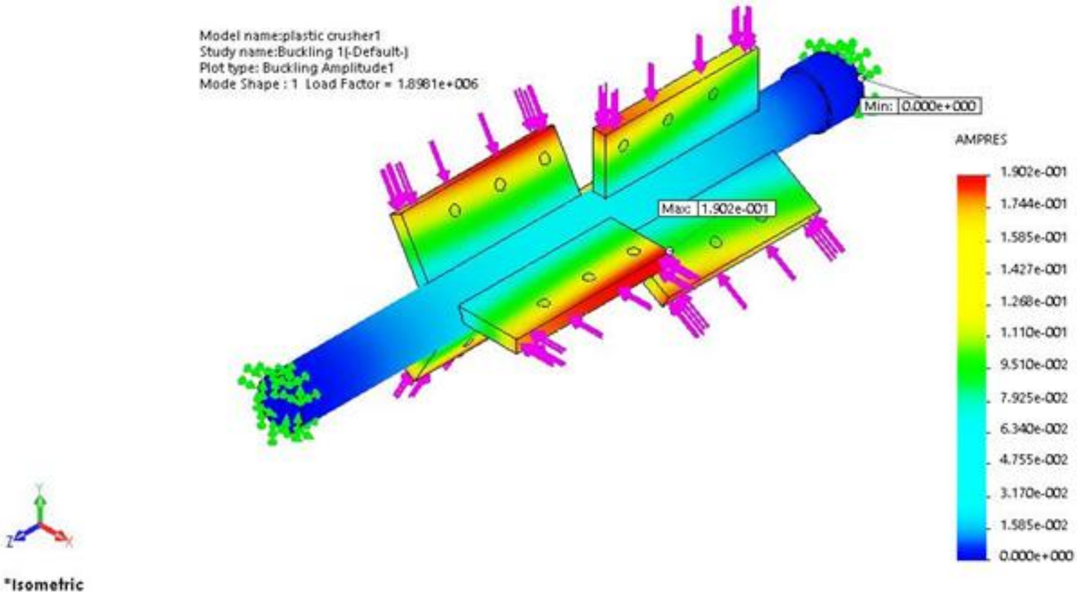


Figure 8: Buckling amplitude of shredding shaft

In figure 9, the deformation plot reveals that the maximum deformation was recorded at the blade edges with a displacement value of 0.01634mm. this is expected and corroborates the buckling analysis result. The opposition to shredding forces offered by the waste over time is expected to deform the blades of the shredding shaft. However, at a displacement value of 0.01634mm, the shredding blades would still be efficient. The minimum deformation is at the ends of the shaft with a 0.001mm displacement value.

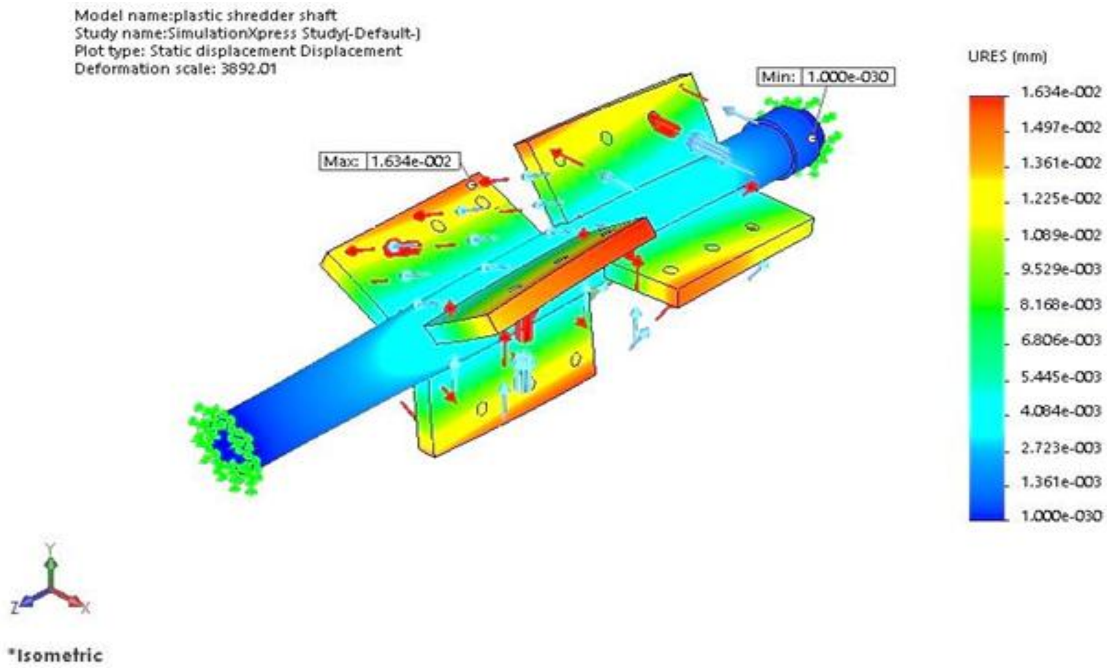


Figure 9: Deformation of shredding shaft

The FoS plot in figure 10 shows that all regions of the shaft have FoS values above 1 with the maximum value of 2.136×10^{5} occuring at the ends of the shaft and a minimum of 157.7 occuring along the shaft length. This implies that the shaft is safe during operation and effectively withstands the bending moments and shear forces induced in the shaft by in-service conditions.

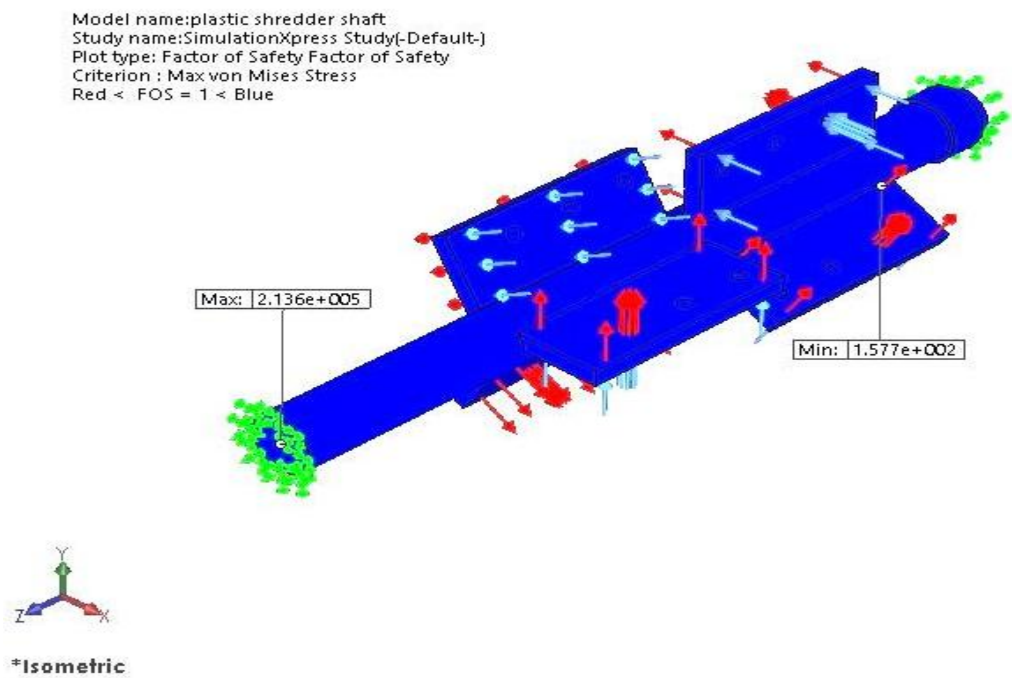


Figure 10: FOS plot of shredding shaft

The von Mises stress plot indicates if the shaft material will yeild or fracture during operation. In figure 11, it is seen that the stress regions indicated by the contour plots are all far below the yeild stress of the shaft material. This means that the shaft material can effectively withstand induces stresses in the shaft during operation as a result of torsion, bending, tensile or compression.

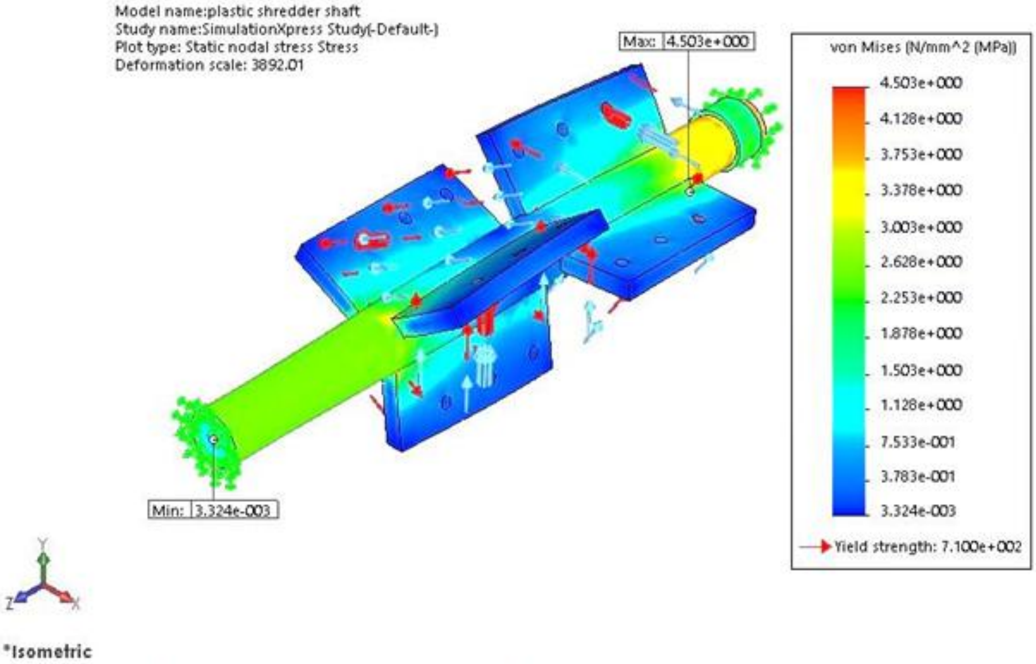


Figure 11: von Mises stress plot of shredding shaft

Performance Evaluation

Compressed plastic bottles and other plastic waste materials were used to evaluate the performance of the machine after its construction. The MTC of the machine was determined by observing the shredding time using a stop watch for various input masses starting from 15kg to 300kg. Table 3 shows the MTC and efficiency of the machine for various masses tested during the performance evaluation.

Table 3: Performance evaluation result

Mass input (kg)	Mass Shredded (kg)	Time(sec)	MTC(kg/s)	Efficiency
15	14.64	183	0.08	0.976
30	29.16	310.2	0.094	0.972
45	43.69	437	0.1	0.971
60	58.2	293.9	0.198	0.97
75	72.97	356	0.205	0.973
90	87.48	332.6	0.263	0.972
105	102.69	349.3	0.294	0.978
120	117.24	389.5	0.301	0.977
135	131.76	399.3	0.33	0.976
150	146.7	419.1	0.35	0.978
165	161.04	503.3	0.32	0.976
180	174.96	729	0.24	0.972
195	189.93	949.7	0.2	0.974
210	204.33	1269	0.161	0.973
225	219.375	1828	0.12	0.975
240	233.76	2541	0.092	0.974
255	248.625	2763	0.09	0.975
270	262.17	3237	0.081	0.971
285	276.735	3844	0.072	0.971
300	291	4279	0.068	0.97

In figure 12, it is seen that the efficiency of the machine remains relatively constant regardless of the variations in the mass of plastic waste introduced into the machine for shredding. However, the MTC of the machine is affected by the input mass as it is seen to increase as volume occupied by the input mass increases, peaking at 150kg. When this mass is increased to 300kg, the MTC is noticed to decline. This is because at a designed shredding force of 1424.5N, increase in mass beyond 150kg will lead to increase in the time needed to shred the plastic waste. From the graph in figure 13, it can be deduced that shredding two batches of 150kg plastic will save more time than a batch of 300kg plastic waste.

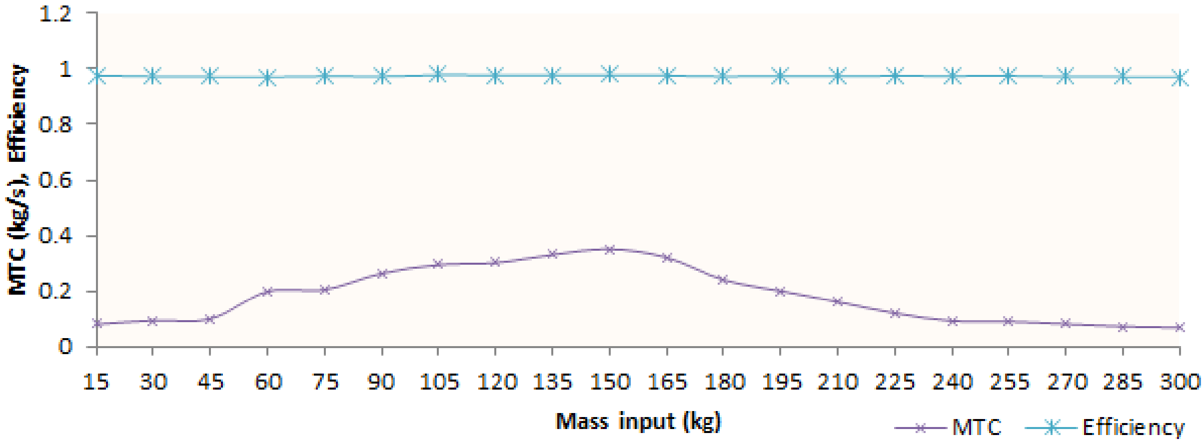


Figure 12: Variation of MTC and Efficiency with Mass input

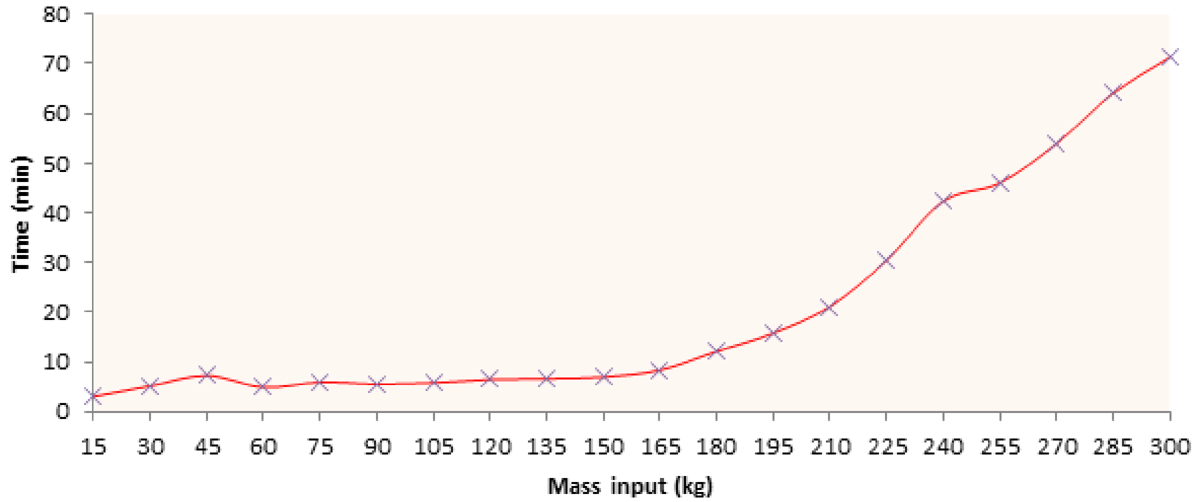


Figure 13: Variation of Time with Mass input

In Table 4, the Bill of Engineering and Management Evaluation (BEME) is presented. It is seen that the material cost for the production of the shredding machine is 21.96% lower than the amount previously quoted by similar research works. Figures 14a and b show the 3D model and image of the constructed shredding machine.

Table 4: BEME

S/N	Item	Quantity	Amount (₦)
1.	AC Electric Motors (5 Hp)	1	25,000
2.	Pulley	2	8,000
3.	Belt	2	6,000
4.	Sheet Metal 2mm Thickness	1½	33,000
5.	Shaft 700mm	1	7,000
6.	Bearing	2	5,840
7.	Paint	4 litres	2,000
8.	Bolts and Nuts	30	6,000
9.	Sheet Of 4mm Plate	½	8,000
10.	Hinges	4	2,000
11.	3 Length Of 2½ Inch Angle Iron 19ft	1	7,000
	Total		109,840.00

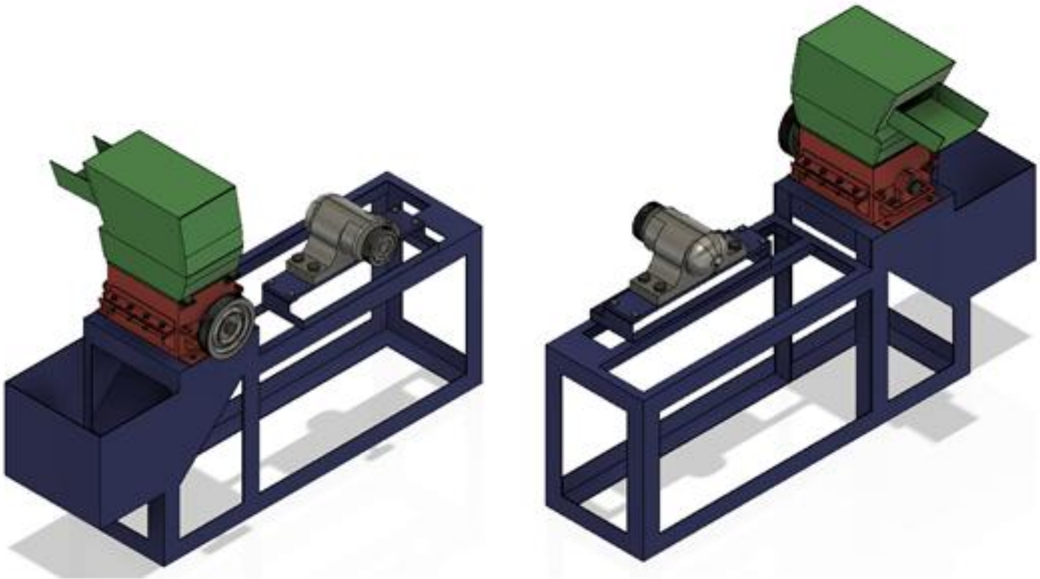


Figure 14a: 3D model of the Shredding Machine

Figure 14b: Plastic Shredding Machine

CONCLUSION

Small and Medium scale enterprises (SMEs) contribute effectively in the GDP growth of a nation. Despite this known fact most processing machines are produced with the large-scale industrialists in mind. With the menace posed by plastic waste pollution/littering, it becomes obvious that plastic waste management behoves the participation of all key players. To this end, in this research the design and construction of an effective low cost plastic shredding machine for use by SMEs was carried out. The machine utilizes 3.7kW of mechanical power to shred 150kg of plastic waste in 6.98mins at an efficiency of 97.8% and an MTC of 0.35kg/s. the buckling, deformation, FoS and von Mises results of the shaft operation under in-service conditions show that the machine is reliable and durable. It is opined in the study that a large scale production of this machine will improve the recycling culture in the plastic production industry, thereby helping keep our environment safe from plastic waste littering.

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