Hindawi
Modelling and Simulation in Engineering
Volume 2023, Article ID 1905702, 17 pages
https://doi.org/10.1155/2023/1905702

Research Article

Finite Element and Multibody Dynamics Analysis of a Ball Mill Glass Crusher

Jihad Rishmany[1] **and Rodrigue Imad**[2]

[1]*Department of Mechanical Engineering, University of Balamand, Al Koura, Lebanon*
[2]*Department of Computer Engineering, University of Balamand, Al Koura, Lebanon*

Correspondence should be addressed to Jihad Rishmany; jihad.rishmany@balamand.edu.lb

Received 29 December 2022; Revised 21 February 2023; Accepted 1 March 2023; Published 16 March 2023

Academic Editor: Angelos Markopoulos

Recycling and sustainability constitute a major challenge to preserve human life quality and ensure a good standard of living for future generations. Like other recyclable waste products, glass waste can be a major problem if it is not recycled. When glass waste is turned into powder, environmental impacts are minimized by reducing or eliminating the dependency on landfills. Within this context, the objective of this work is to design a low-cost glass crusher machine that can be acquired by individuals. For this purpose, a glass crusher machine based on the ball mill concept is designed to transform glass waste into powder of 2 mm particle size. The main enhanced features of this machine with respect to state-of-the-art designs are the continuous feed aspect and the powder discharge technique. The design methodology consisted of mathematical modeling coupled with numerical simulations to ensure a safe and functioning design. This was achieved via different types of simulations using SolidWorks: static stress analysis, free vibration analysis, and motion study. Finally, a market study shows that a breakeven period is reached after a period of 5 months.

1. Introduction

Worldwide, the demand over glass has never witnessed a decline due to its diverted use in different scopes and fields. Instead, there are continuously rising consumers who tackle the problem of glass waste disposal. Several million tons of glass bottles are discarded annually [1]. Year after year, the glass waste would accumulate and cause serious harm on environmental aspects due to the huge amount of space required in landfills. Some of these wastes have already been recycled by glass manufacturers. Nevertheless, it is impossible to recycle all glass wastes due to the variation in color, imperfections in glass, and processing costs.

Instead of discarding tremendous volume of glass waste, the latter can be turned into powder, which can be further used in different fields such as agriculture, structural and ecological engineering, construction and building materials, and many more. In this case, a global problem would diminish and offer an opportunity for investments, clean environment, and many more.

The potential for using glass in the production of concrete was first investigated some time ago [2]. The manufacturing of cement backfires a pollution problem by producing greenhouse gases [3]. Aliabdo et al. [4] have shown that cement can be partially substituted by glass powder in the formation of concrete that offers a double advantage: reducing greenhouse gases since the demand of cement will be relatively lower and decreasing the volume of glass waste in filled landmarks. Moreover, the price of concrete will be relatively reduced since the supply and availability of glass are tremendous. Furthermore, the mechanical properties of concrete might be maintained or slightly enhanced with the addition of partial glass powder in the concrete mixture [5].

On the other hand, due to the presence of silica, glass powder can act as a natural supplementary product to pesticides which, at sometimes, might have negative impact on food safety, air and underground water, worker health, and environmental safety. Glass powder dust will react with the outer layer of insects to rupture it and consequently kill it

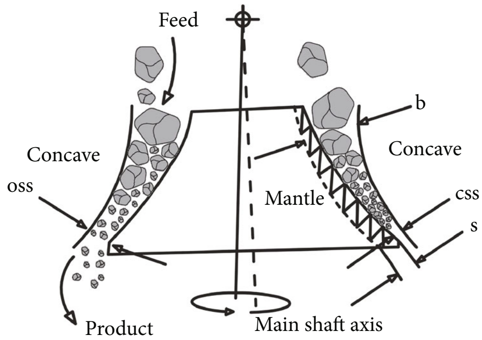


Figure 1: Jaw crusher [8].

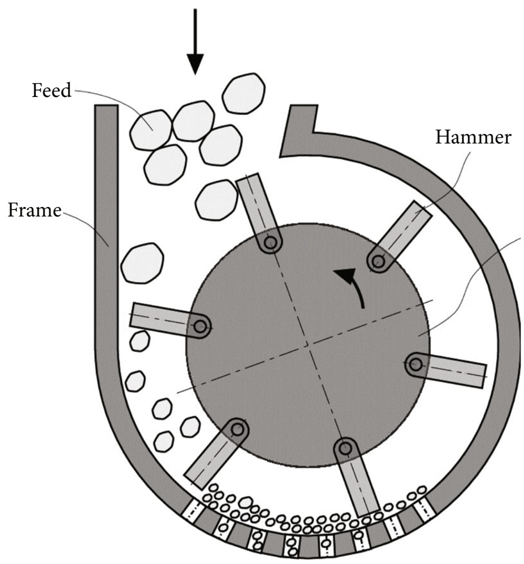


Figure 2: Hammer crusher [10].

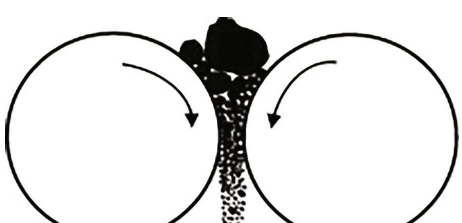


Figure 3: Roller crusher [11].

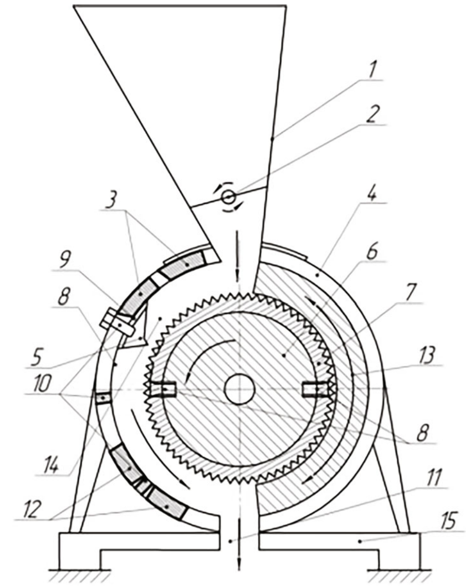


Figure 4: Impact crusher [12].

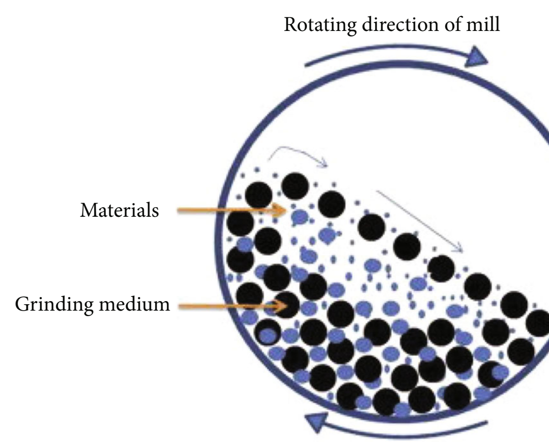


Figure 5: Ball mill machine [13].

providing adequate pest control [6]. Glass powder has shown to level the uptake of nutrients, such as phosphorus, nitrogen, potassium, and many others, that are essential and decisive in plant growth. Silicon can also aid in increasing the photosynthetic efficiency and light absorption, which will lead to more production of oxygen on a big scale.

Glass powder can also be used as fluxes in brick and glaze production, replacing other costly ingredients such as sodium and potassium oxides, with no harmful effects [7]. An important and distinctive benefit to using glass powder in the glazes and ceramics' production is that it acts as a flux in the industrial process, thus lowering the melting temperature and consequently the required energy. In bricks, addition of glass powder (up to 20% by weight) decreases firing temperature, increases mechanical strength, and lowers shrinkage upon firing. Therefore, there would be a decrease in water absorbance and increase in density. In addition, the use of ground glass can reduce crazing if used in quantities up to 30% by weight.

Based on the aforementioned utilities of glass powder, transforming glass waste into useful powder can be employed in different sectors. This would ease the burden on landfills. Therefore, the main incentive of this work is to design a low-cost glass crusher, which could be implemented on a small scale level in order to treat glass bottles obtained from pubs, restaurants, hotels, etc. After inspecting different types of existing crushers, several assessment methods are employed in order to select the most suitable concept. Afterwards, sizing is conducted based on performance and safety. Finally, a market study based on customer

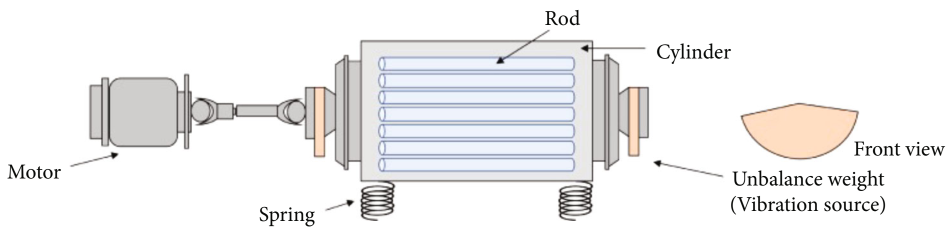


Figure 6: Rod mill [14].

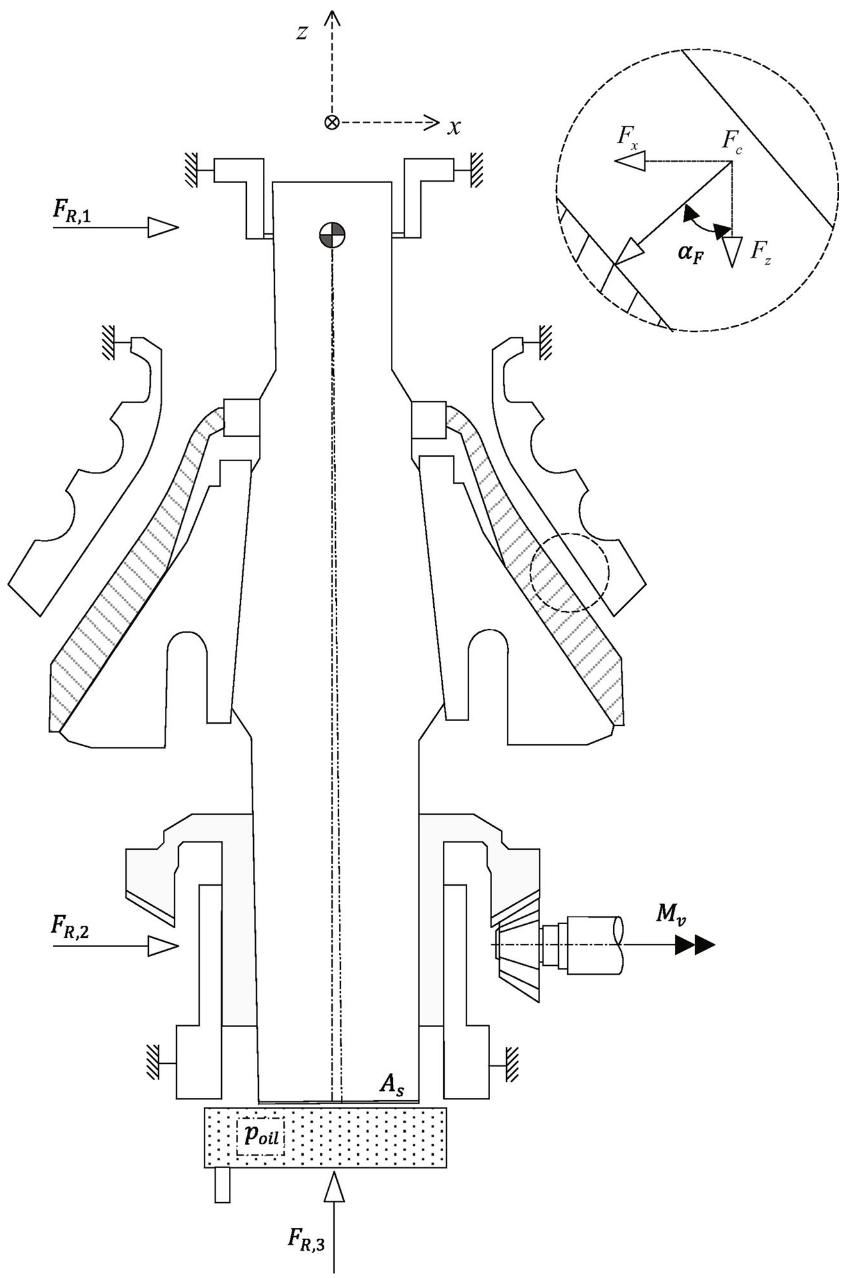


Figure 7: Schematic illustration of the cross-section of a hydrocone type cone crusher [15].

surveys assesses the financial aspect of the proposed design. The novelty of this work lies in the main enhanced features of the proposed design with respect to state-of-the-art designs. These features are related to the continuous feed aspect that this design permits in addition to a practical powder discharge technique.

Table 1: House of quality.

Customer requirements	Weight factor	Engineering Characteristics													
		Rotational speed	Feeding inlet volume	Discharge size	Motor power	Vibration	Material selection	Shaft design	Cost	Exit rate	Dimensions	Weight	Torque	Control system	Maintenance
Good crushing efficiency	5	3		9	3	3	1	1	3	9			3	3	
Good processing capacity	4	3	9	3	3		1	3	3	9	3	3	1	3	
Justified feeding input	3		9						1	9	1	1			
Power efficient	3	3	3	3	9	1	3	3	9	3	1	3	9	9	3
Ease in output extraction	3			1						9	1				3
Low noise	3	1		3	1	9	3		1			3		1	
Ease of maintenance	3	3	3		3	9	1	1	3				3	3	9
Environmentally friendly	2	1		1		3						1			1
Recipient to different conditions of glass	4		3				3		1	3					3
Justified weight	3		3		3		3	1	3		3	9	3		2
Justified price	3		3	3	1	3	3	1	9	3	3	3	1		3
Raw score	1038	50	84	89	78	87	60	35	106	138	36	68	67	66	74
Relative weights%		0.0482	0.0809	0.0857	0.0751	0.0838	0.0578	0.0337	0.1021	0.1329	0.0347	0.0655	0.0645	0.0636	0.0713
Ranking		12	5	3	6	4	11	14	2	1	13	8	9	10	7

Table 2: Pugh chart.

Selection criteria	Ball mill	Concepts Jaw crusher	Hammer	Roller
Exit rate		+	+	−
Cost		+	−	−
Discharge size		−	−	−
Vibration	DATUM	−	s	+
Feeding inlet volume		+	+	−
Motor power		−	−	−
Maintenance		−	s	+
# Of pluses		3	2	2
# Of minuses		4	3	5

Table 3: Criteria comparison matrix.

	Exit rate	Cost	Discharge size	Vibration	Feeding inlet volume	Motor power
Exit rate	1	3	3	5	3	5
Cost	0.33	1	5	3	3	7
Discharge size	0.33	0.2	1	7	5	3
Vibration	0.2	0.33	0.14	1	3	9
Feeding inlet volume	0.33	0.33	0.2	0.33	1	7
Motor power	0.2	0.14	0.33	0.11	0.14	1
Sum	2.39	5	9.67	16.44	15.14	32

Table 4: Normalized criteria comparison matrix.

	Exit rate	Cost	Discharge size	Vibration	Feeding inlet volume	Motor power	Criteria weights $\{W\}$
Exit rate	0.418	0.600	0.310	0.304	0.198	0.156	0.331
Cost	0.138	0.200	0.517	0.182	0.198	0.219	0.242
Discharge size	0.138	0.040	0.103	0.426	0.330	0.094	0.189
Vibration	0.084	0.066	0.014	0.061	0.198	0.281	0.117
Feeding inlet volume	0.138	0.066	0.021	0.020	0.066	0.219	0.088
Motor power	0.084	0.028	0.034	0.007	0.009	0.031	0.032
Sum	1	1	1	1	1	1	1

Table 5: Consistency check for W.

$W_s = [C]\{W\}$ weighted sum vector	$\{W\}$ criteria weights	$\{\text{Cons}\} = \{W_s\}/\{W\}$ consistency vector
2.637	0.331	7.961
2.137	0.242	8.814
1.706	0.189	9.048
0.844	0.117	7.192
0.579	0.088	6.561
0.220	0.032	6.834
Average of {Cons.} = l		7.735
Consistency index, CI = $(\lambda - n)/(n-1)$		0.123
Consistency ratio, CR = CI/RI		0.091
Is comparison consistent: CR < 0.1		Yes

Table 6: Final rating matrix.

Selection criteria	Ball mill	[F_{rating}] Jaw	Hammer	Criteria weights [W]
Exit rate	0.670	0.087	0.243	0.331
Cost	0.724	0.083	0.193	0.242
Discharge size	0.102	0.687	0.211	0.189
Vibration	0.073	0.644	0.282	0.117
Feeding inlet volume	0.106	0.634	0.260	0.088
Motor power	0.106	0.634	0.260	0.032
	Alternative value			
Ball mill	0.438			
Jaw	0.330			
Hammer	0.232			

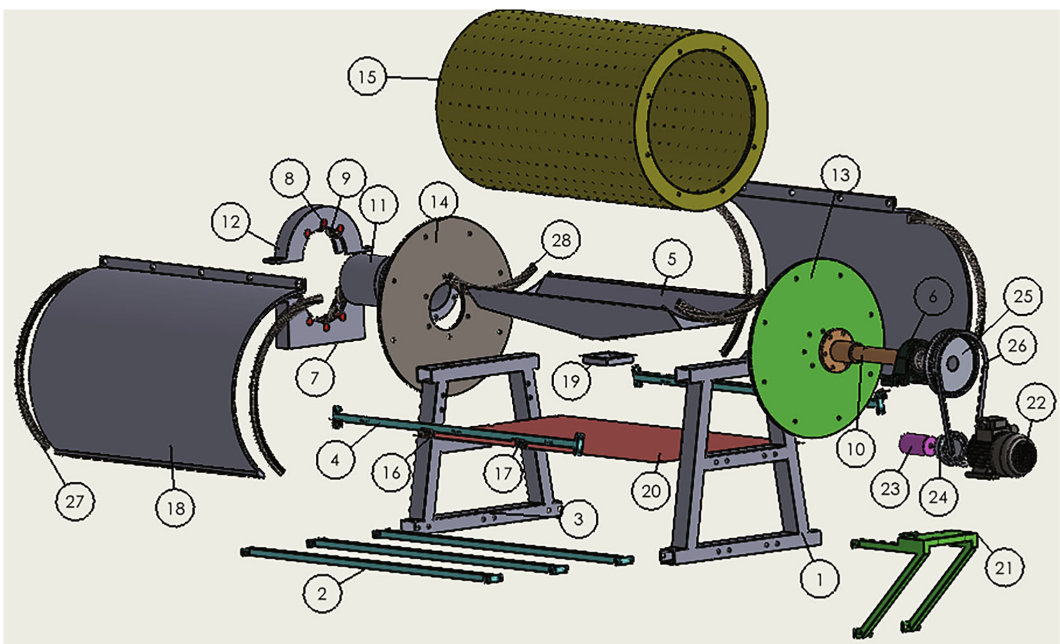


Figure 8: Exploded view of the assembly.

2. Existing Crushers Designs

Different types of crushers exist each relying on a different operating mechanism. Hereafter, several potential crushers are listed for glass with a brief description for each.

The jaw crusher machine is composed of two jaws (Figure 1), where one jaw is stationary while the other is mobile. The jaws are placed in a V-shape, where the inlet is wide to accommodate the large size of the material to be crushed, and the adjustable outlet is narrow to deliver small portions. The moving jaw exerts mechanical pressure on the fixed one, thus initiating the crushing process. This machine can meet different customer requirements because of its slight maintenance requirements, ability to prevent the splash of materials, and reduced noise.

Fladvad and Onnela [9] studied the influence of jaw crusher parameters on the quality of primary crushed aggregates.

In the hammer crusher (Figure 2), hammerheads of high wear resistance and strength are attached to the tip of a rotor placed inside a well-sealed, noiseless, and fixed casing. As the hammerheads rotate with a high speed, they will produce a high impact on the glass breaking them down into smaller pieces. This machine has an adjustable discharge port to control the final size desired. There are two main disadvantages for this machine. First, it cannot process wet or moist materials. Second, the dust resulting from the processing of dry materials may cause bearing damage.

A double roll crusher (Figure 3) consists of two spinning rolls that are responsible for the crushing process. The rollers

Table 7: Bill of materials.

Item no.	Part name	Qty
1	Motor frame new	1
2	Middle frame support	3
3	Inlet frame new	1
4	Middle support	2
5	New fixed container	1
6	UCP—308 bearing 40 mm	1
7	Inlet bearing on base	1
8	Test shaft	8
9	AFBMA 20.1-23-20-8, SI, NC, 8_68	8
10	Wall motor shaft	1
11	Wall inlet shaft	1
12	Inlet bearing top side	1
13	Updated outer wall motor side	1
14	Updated outer wall inlet side	1
15	Updated Drum	1
16	Hinge1	6
17	Hinge2	6
18	Updated door	2
19	Container cone	1
20	Table sheet	1
21	Motor stand	1
22	Electric motor	1
23	Motor shaft	1
24	Motor pulley	1
25	Drum pulley	1
26	Belt 1–3	1
27	Door brush	4
28	Container brush	2

trap the material between the rotating surface until it breaks down and, eventually, discharges. The main advantage of this machine is its adjustable discharge port, which can meet different discharge sizes. However, the prominent disadvantage is the ability of glass to slip between the rollers without being crushed, thus, decreasing the crushing efficiency.

The impact crusher (Figure 4) resembles the hammer crusher machine. It consists of a rotor inside a fixed casing, where blow bars are attached to the rotor to provide an impact on the material. There are different stages of crushing of crushing that reduce progressively progressively glass size until it becomes powder. There are three main advantages for this machine. First, it is highly recipient to products with large water content. Second, the crushing efficiency is substantial due to the hardness of the blow bars. Third, the distance between the blow bars and the impact plate is easily controlled, thus exploring numerous options for the discharged particle size.

In the ball mill machine (Figure 5), the crushing process is due to steel or rubber balls placed inside a rotating cylindrical casing. As the cylinder rotates about its axis, the balls rotate to form an impact against the glass to crush it. It is noticeable that the greatest impact happens when the balls fall from the top until they hit the glass. The discharge size of the glass depends on the material used for the balls, the size of the balls, rotating speed, and the materials used for the cylindrical casing. This machine carries different substantial advantages: high efficiency and high processing capacity, ease of maintenance, high reliability, and safety. As for the disadvantages, the machine has very loud noise along with recognizable energy losses due to friction and heating. There are two main types of ball mills: the grate and overflow ball mills. Each type operates on similar working principles but different ways of discharge. Commercially, such machines are only found for crushing aggregates and coals, but not glass.

The rod mill operates in a way very close to that of the ball mill. As its name indicates, the grinding media are rods that initiate line contact with the material to be grinded. This feature maximizes crushing efficiency due to the large area of contact. The advantages of this machine involve low-cost grinding media, low power consumption, and optimal operation time. The rod mill operates at low-speed relative to the ball mill since the rods are rolled and not cascaded. However, one main disadvantage of the rod mill is that it needs significant operation attention because the rods must be parallel to one another to obtain a high crushing efficiency, otherwise the grinding action will be lost. Rod mills are of different types based on the type of discharge. Potential types for glass crushing include the trunnion, end peripheral, and center peripheral rod mills (Figure 6). However, the rod mill is only present for large scale and industrial grinding for aggregates and not glasses.

The cone crusher (Figure 7) is the most common machine for secondary and tertiary crushing stages in both the aggregates industry and minerals processing comminution operations [15]. The functional principle of a cone crusher is to compress particles between two surfaces. In the cone crusher, the compressive action is realized by inflicting a mutational motion on an inner cone (mantle), while an outer cone (concave) remains fixed. The mutational motion is actualized by an eccentric bushing transferring the rotational motion of the drive shaft via a gear ring to the main shaft. Since the mantle is allowed to rotate freely around the main shaft axis, it will act as a planet wheel in a planetary gear, where the mantle is rolling on the bed of rock particles.

Han et al. [16] compared the hematite product characteristics in a high-pressure grinding roller and jaw crusher. They found that the grinding roller achieved a more uniform size distribution, more fines, and a higher crushing efficiency.

3. Concept Selection

3.1. Introduction. To assess the selection criteria, it is necessary to explore first the market needs. In that regard, several discussions were held with potential customers such as municipalities, restaurants, and environmental activists. Following this step, the obtained customer requirements are then transformed into engineering characteristics (ECs), and

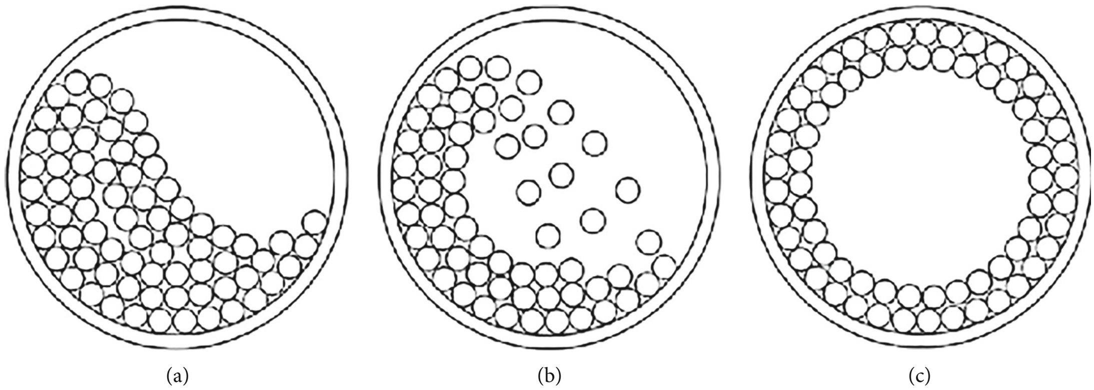


Figure 9: Ball motion pattern in a single pot of a planetary ball mill, (a) cascading, (b) cataracting, (c) rolling [17].

Table 8: Calculation of minimum ball diameter.

Inner drum diameter (m)	Drum length (m)	Compressive strength of glass (MPa)	Modulus of elasticity of glass (MPa)	Ball density (kg/m^3)	Maximum feed diameter (mm)	Minimum ball diameter (mm)
0.46	0.8	1000	72000	7850	3	9.33

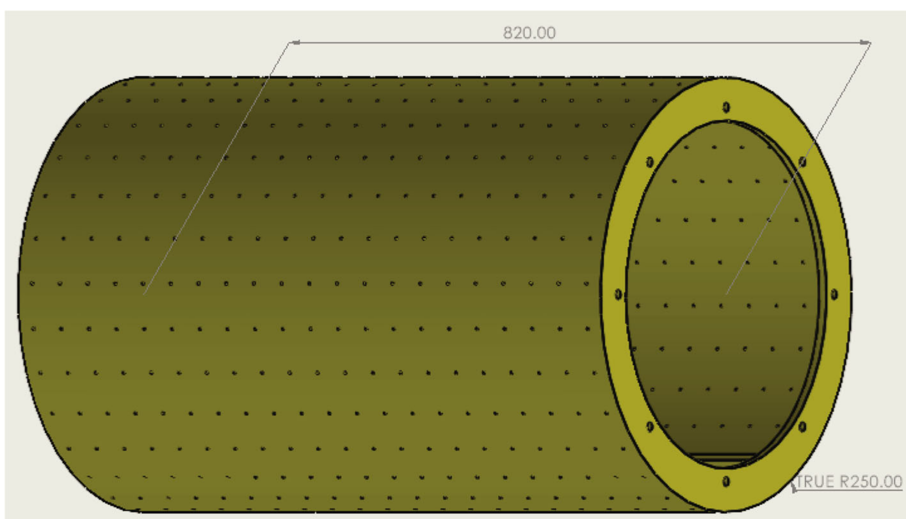


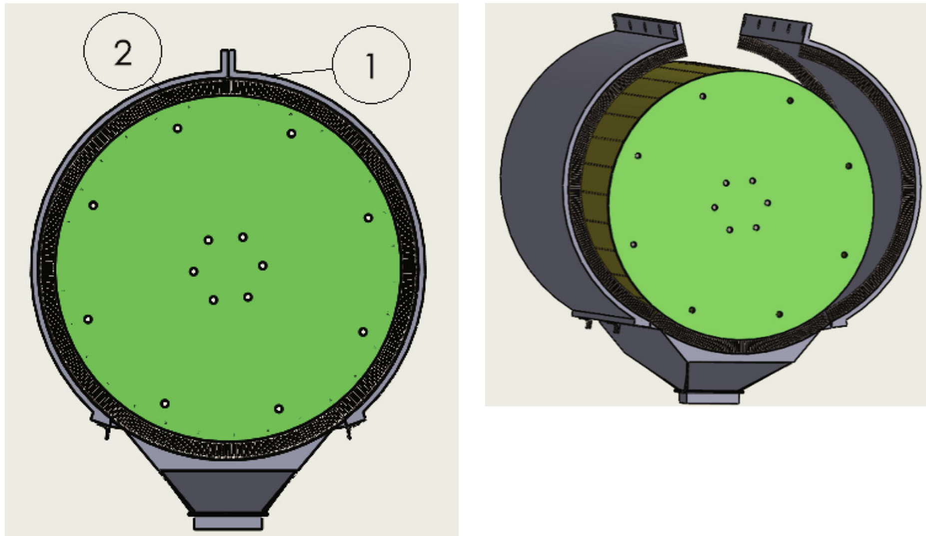
Figure 10: Drum design.

the concept selection process is initiated using different assessment tools.

3.2. House of Quality. Customer requirements are the most important factors for the selection criteria because through them, the importance of ECs will be set. Accordingly, the machine that can satisfy these ECs in the best possible way will be selected as a concept for a qualified design. The house of quality (HoQ) is one way to rank the ECs. This is done through relating each customer requirement to the ECs and specifying the level of relationship between them by associating the numbers 1, 3 and 9, 9 indicating a strong relation. Moreover, each customer requirement was attributed a weight factor depending on its importance with respect to the customer. Once the table is filled, the points are added for every EC, and the answer is multiplied by the corresponding weight factor to give the final score. This enables classifying ECs by order of importance, and consequently considering only the highly ranked for concept selection.

Based on the results obtained from the HoQ (Table 1), the ECs that are most important to the customers are as follows: exit rate, cost, discharge size, vibration, feeding inlet volume, motor power, maintenance, weight, torque, control system, material selection, rotating speed, dimensions of the crusher, and shaft design.

3.3. Pugh Chart. Based on the results of the HoQ, the first seven ECs are selected along four types of mills that are compatible with the ECs and were inserted in the Pugh chart for concept selection (Table 2).



(a) (b)

Figure 11: Door container, (a) front view, (b) isometric view.

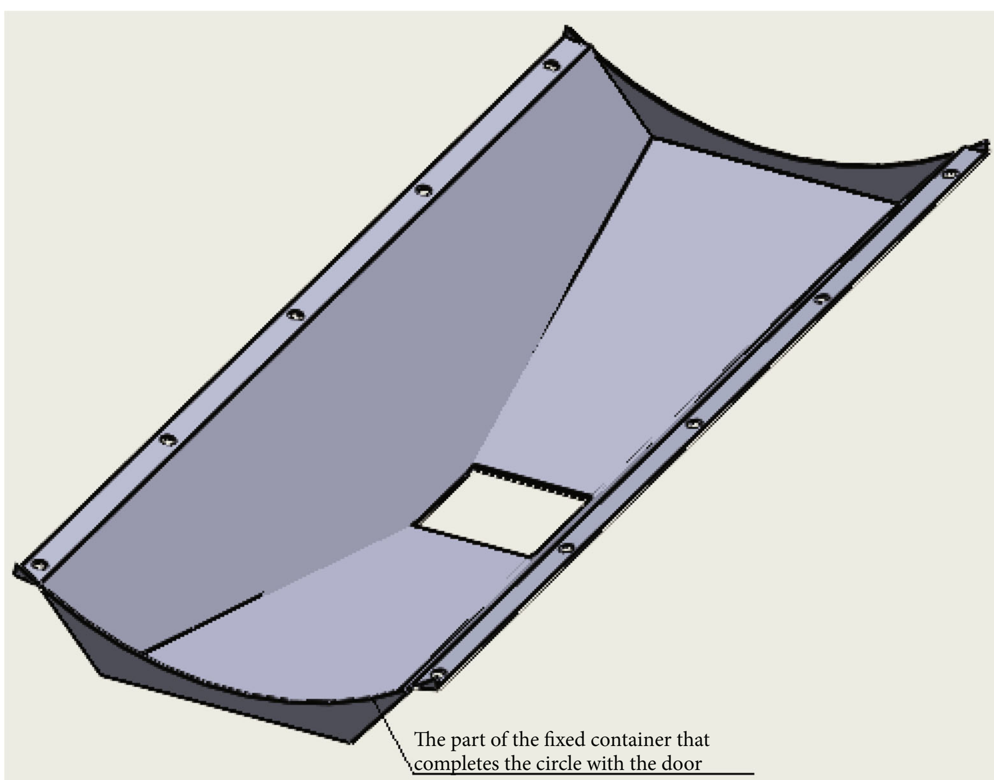


Figure 12: Fixed container.

The ball mill is set as datum, the jaw crusher as concept 1, the hammer crusher as concept 2, and the roller crusher as concept 3. Each of the selected concepts is compared to the datum with respect to the seven ECs, and the table is filled based on the information presented in Section 2. For instance, if concept 1 is better than the datum (ball mill) in a certain EC, a plus sign is assigned to indicate this case. Otherwise, a minus sign is allocated to show that the datum is better. If the two concepts are of equal importance with respect to a certain EC, then an S letter is attributed.

Furthermore, the concept that collects most minus signs and least plus signs is directly eliminated (roller crusher in this case). Consequently, the ball mill, jaw crusher, and hammer crusher will continue to the last phase of the

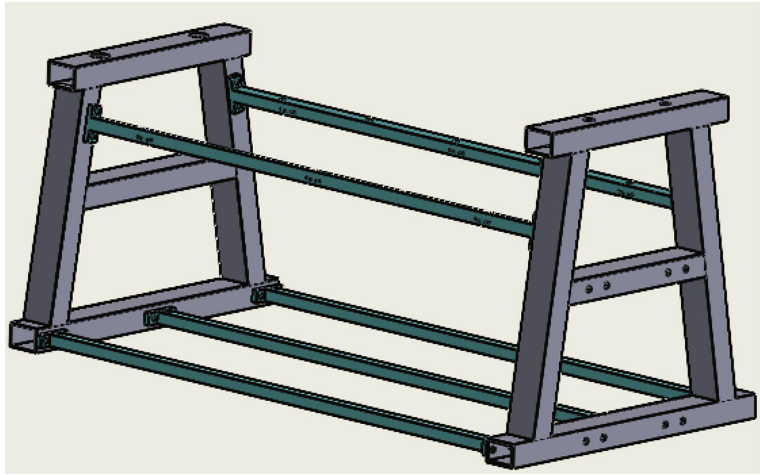


Figure 13: Frame.

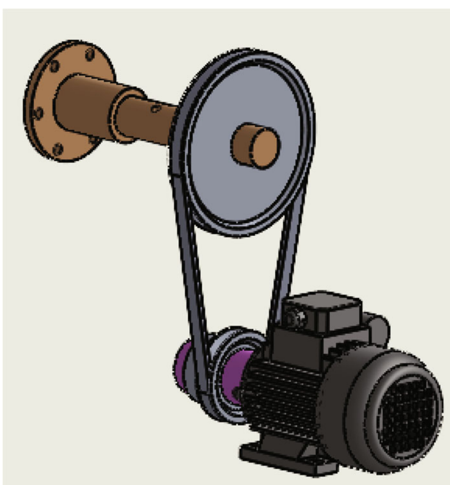


Figure 14: Power and transmission system.

selection methods, which is the analytic hierarchy process (AHP).

3.4. Analytic Hierarchy Process. In the AHP, two types of analysis are conducted. The first analysis compares the ECs against each other by filling a criteria comparison matrix (Table 3), based on the results obtained from the HoQ (Table 1). Then, the results are normalized (Table 4), and finally a consistency check is performed (Table 5) to ensure the validity of the method. This analysis permits classifying the ECs by order of importance according to the obtained score of each.

The second type of analysis includes comparing the concepts against each other with respect to each EC. The same tables are filled as previously for each EC. The results are finally stored in a final rating matrix (Table 6), and the concept with the highest score is selected.

Based on customer requirements, ECs, and the comparison techniques applied (HoQ, Pugh chart, and AHP), the ball mill concept is deemed the most suitable.

4. Design of the Ball Mill Glass Crusher

4.1. Introduction. The design process consists of setting a desired drum diameter and computing the required motor power and operating drum speed. Then, the power supply system is selected accordingly along with the transmission system. The remaining structural parts are initially sized by analytical stress calculations on free body diagrams of isolated members. Final sizing is achieved via finite element analysis (FEA).

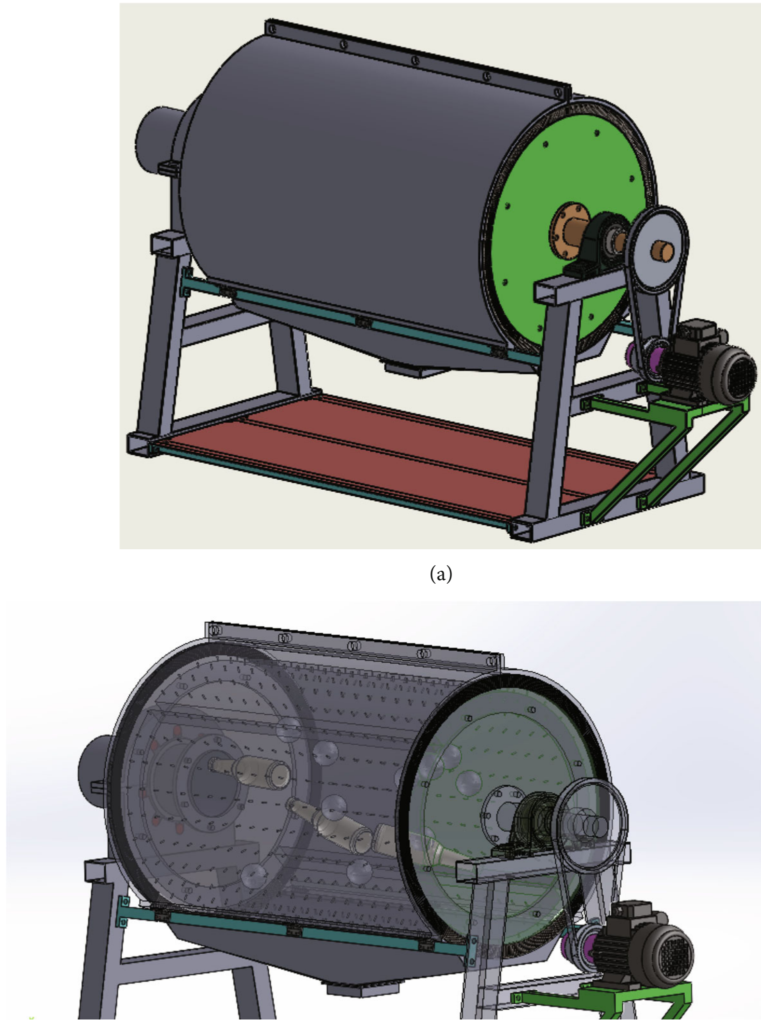
4.2. Design and Component Selection. The main components of the ball mill machine (Figure 8, Table 7) are power supply, transmission system, drum, shaft, bearings, balls, and the frame.

Galvanized ASTM A36-steel is selected for the frame, drum, shafts, and supports.

The grinding process in the ball mill is due to the centrifugal force induced by the mill on the balls. This force depends on the weight of the balls and the ball mill rotational speed. At low speeds, the balls are at a fall state (Figure 9(a)). As the operating speed increases, the balls reach a higher helix angle before falling and repeating the cycle. The balls will fall following a parabolic path (Figure 9(b)) when they reach a point, where their respective weight becomes greater than the centrifugal force. In repeating cycles, this is the most prominent way of grinding the feed into small sizes. Beyond the so-called "critical speed", the centrifugal force exerted on the ball would always be greater than the weight, hence preventing the process of grinding (Figure 9(c)). This condition is known as milling and hinders the balls from crushing efficiently. The critical speed of the drum is given by [18]:

$$n = \frac{42.3}{\sqrt{D_{i,m}}}, \qquad (1)$$

where, n: critical speed of the drum (rpm), $D_{i,m}$: inner diameter of the mill (m).



(a)

(b)

Figure 15: Isometric view of the assembly.

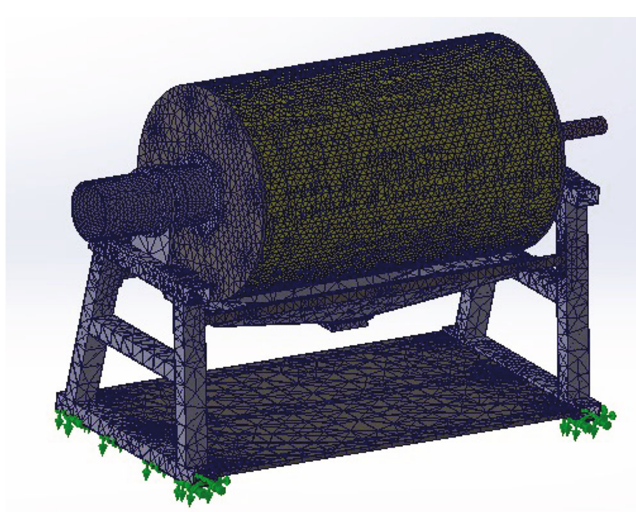


Figure 16: Finite Element Analysis model showing the mesh and supports.

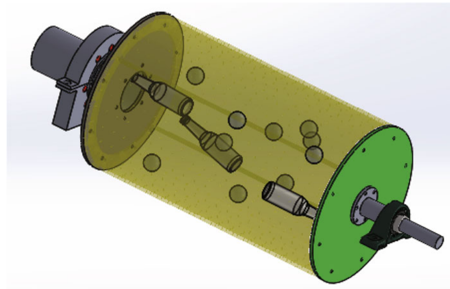
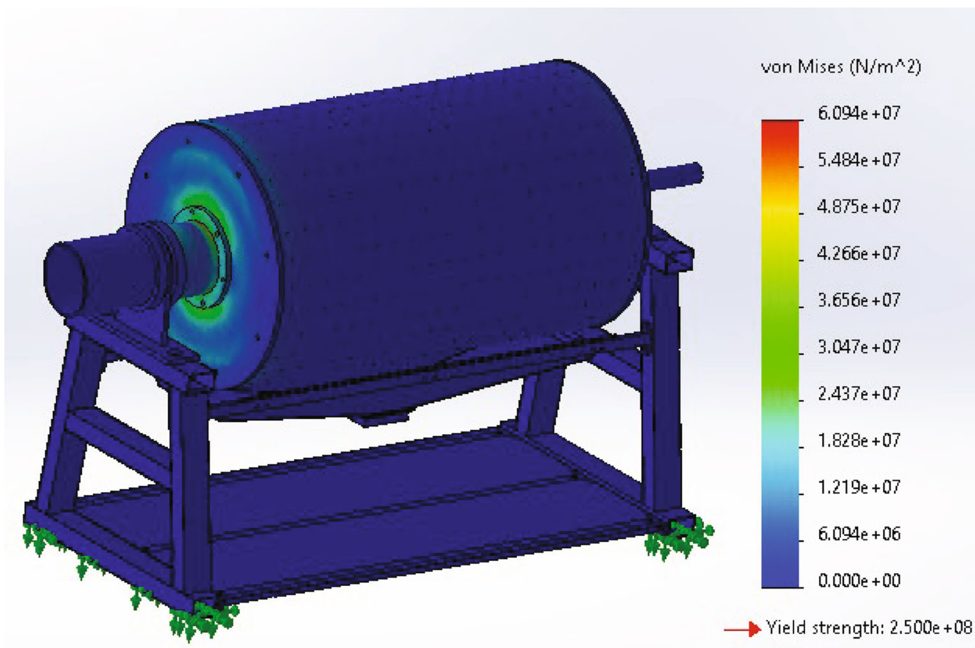
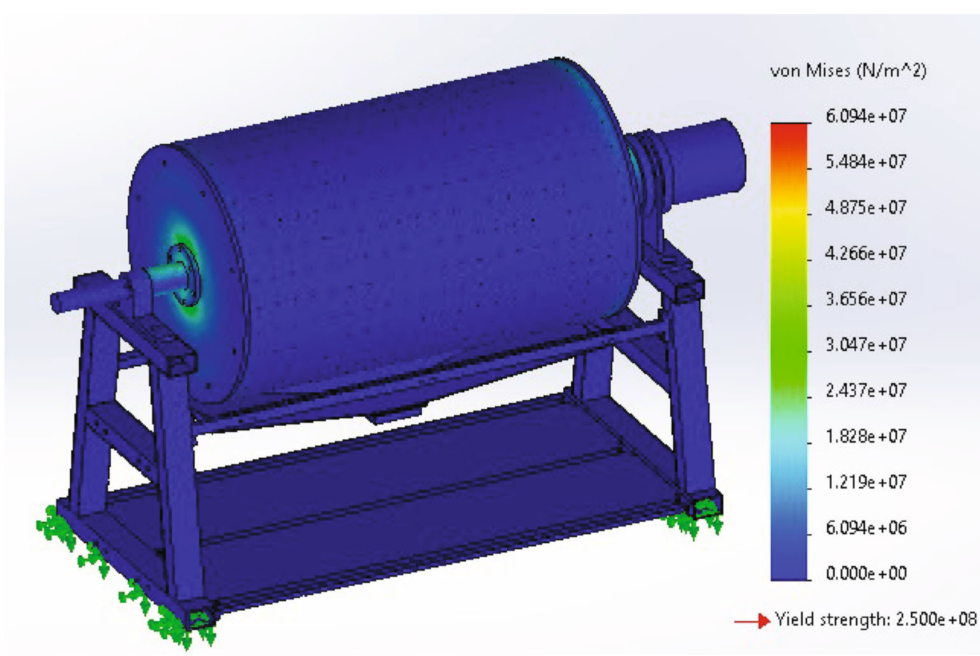


Figure 17: Model for motion simulation.



(a)



(b)

Figure 18: Von mises stress distribution.

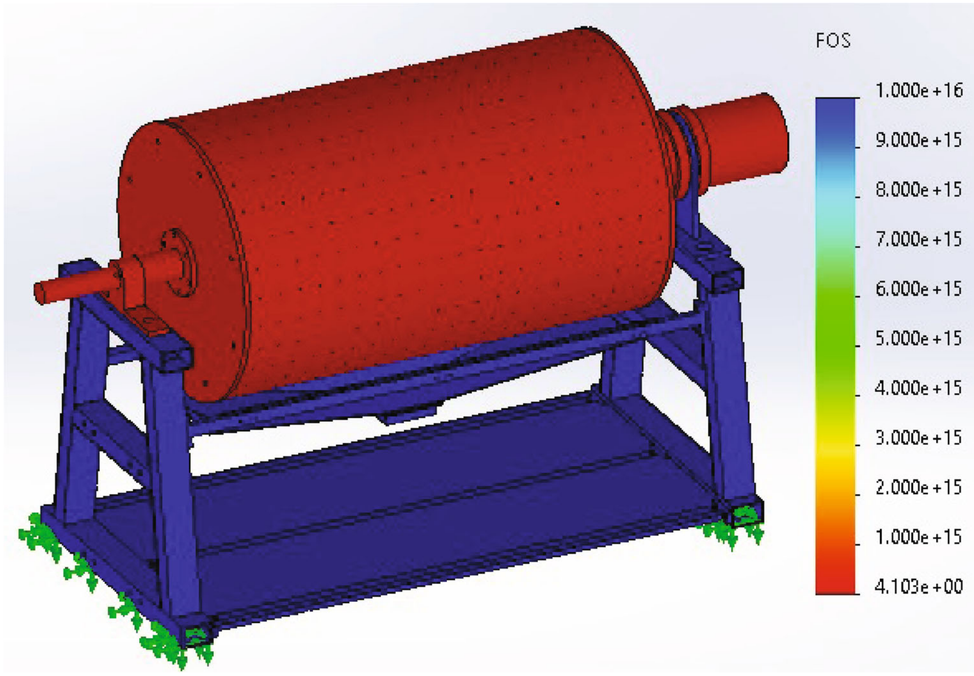


FIGURE 19: Factor Of Safety against yielding.

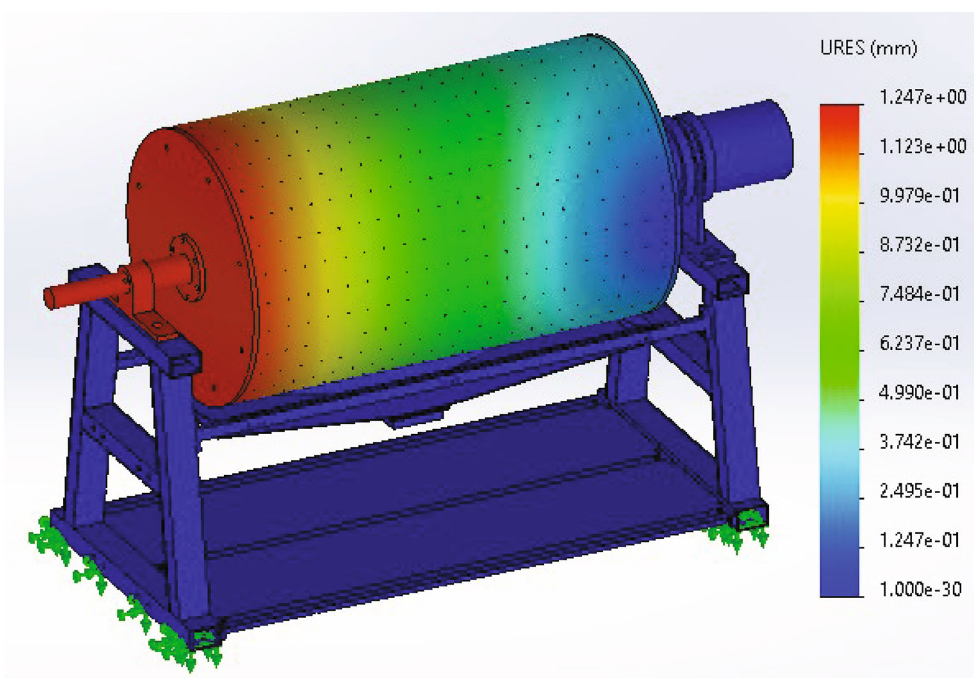


FIGURE 20: Deformation results (mm).

The operational speed of the mill is usually taken between 50% and 70% of the critical speed (considered as 0.62% in this study).

$$\mathrm{OS} = 0.62 \times n, \quad (2)$$

where OS: operating speed (rpm).

Setting the drum diameter to 48 cm and applying equations (1) and (2) yield around 63 rpm and 39 rpm for the critical and operating speeds, respectively.

For proper milling, the length to diameter ratio of the drum must be around 2 [19]. Another perceptible feature is the degree of filling of the mill. With excessive filling, the possibility of collision between the rising balls and the falling balls is higher, leading to lower milling efficiency.

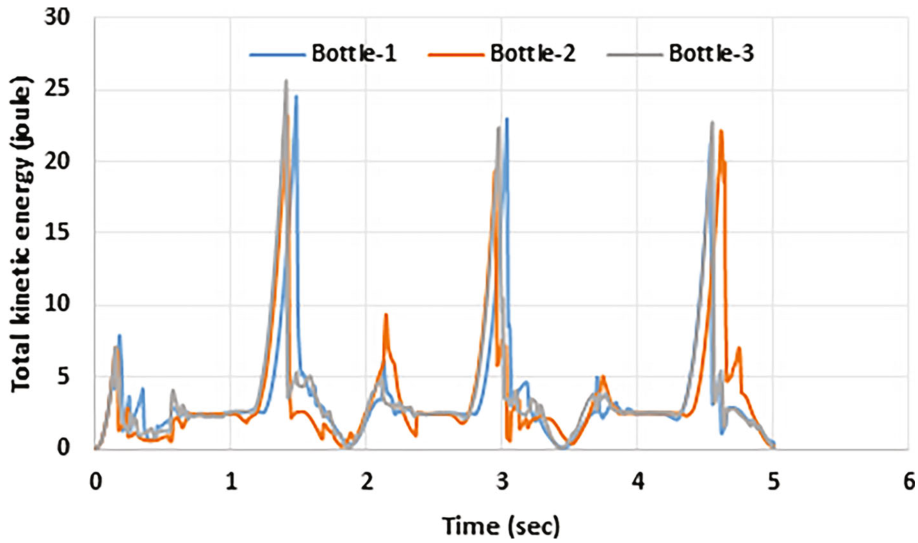


Figure 21: Total kinetic energy for the glass bottles.

Table 9: List of first five natural frequencies.

Mode	Frequency (Hz)	Frequency (rpm)
1	78	4666
2	103	6197
3	133	7980
4	143	8609
5	148	8870

On another hand, a small number of balls will not be sufficient for crushing. Therefore, critical analysis shows that the volume of the balls must be between 30% and 35% of the drum's total volume.

The minimum ball diameter is given by [11]:

$$d_{\mathrm{b,min}} = 10 d_{\mathrm{f,max}} \sqrt[3]{\frac{{\sigma_{\mathrm{c}}}^{2}}{0.128 E \rho_{\mathrm{b}} D_{i,D}}}, \quad (3)$$

where $d_{\mathrm{b,min}}$: minimum ball diameter (mm), $d_{\mathrm{f,max}}$: maximum feed diameter (mm), σ_c: compressive strength of glass (MPa), E: modulus of elasticity of glass (MPa), ρ_b: density of the ball (kg/m^3), $D_{i,D}$: inner diameter of the drum (m).

Based on the result given by equation (3) (Table 8), a minimum ball diameter of 50 mm is obtained. However, this will result in a huge number of balls considering a volume of the balls of 32% with respect to the drum's total volume. Therefore, a ball diameter of 50 mm is selected, resulting in a total of 650 balls.

The productivity of the ball mill depends on several other important features as well such as the physical and chemical properties of the feed material, the armor surface, and the milling finesse. The power required to rotate the drum at the desired operating speed is given by [20]:

$$P = 9.9 M \times N \times D_{i,m}, \quad (4)$$

where P: power required for drum operation (W), M: total mass of the balls and the feed (kg), N: frequency in Hertz (Hz), $D_{i,m}$: inner mill diameter (m).

From equation (4), the power required to drive the drum is 3 Hp. The torque available at the drum is 242 N m.

4.2.1. Drum. The drum is the main component in the ball mill, where balls rotate and crash with the feeding material to produce glass powder. In the present study, the drum is used not only for rotating and finessing powder, but also discharging it through its milled holes. For this purpose, holes of 2.5 mm diameter are spread through the whole drum cylinder (Figure 10).

4.2.2. Door Container. As the powder discharges outside the drum, the door container (Figure 11) holds them to be fed to the fixed cone collector. The door container consists of two symmetrical semi-cylindrical metal sheet hinges at the bottom. In order to avoid any possible fleeing of the powder outside, brushes are installed on both sides of the door container.

4.2.3. Fixed Container. When the glass powder is discharged through the milled holes of the drum, a collector is needed to gather them. A cone-like shape fixed container (Figure 12) is placed at the bottom to collect powder by gravity action. Similar to the door container, brushes are installed above the cone collector to avoid fleeing of the glass powder outside the controlled volume.

4.2.4. Frame. The frame is designed to withstand the whole mechanism during operation. Two A-shape structures are placed on each side of the ball mill's longitudinal axis and connected to each other using five connecting rods (Figure 13). Each part of the door container is hinged on a connecting rod. Similarly, the cone collector is screwed on two rods. Moreover, another frame housing the motor is attached to one A-shape structure.

Table 10: Cost estimation.

Item no.	Part name	Material description	Qty.	Price per m or square m ($)	Total length (m) or area (square m)	Material price/item	Manufacturing cost ($)	Total price ($)
1	Motor frame	60 × 40 × 4 hollow steel	1	4.5	2.19	9.87	12	21.87
2	Middle frame support	10 mm metal sheet	3	120	0.00	0.29	2	18.18
		20 × 20 steel bar		3.8	0.99	3.77		
3	Inlet frame	60 × 40 × 4 hollow steel	1	4.5	2.07	9.31	12	21.31
4	Middle support	10 mm metal sheet	2	120	0.0024	0.29	2	12.27
		20 × 20 steel bar		3.8	1.01	3.85		
5	Fixed container	2 mm metal sheet	1	24	0.38	9.17	15	24.17
6	UCP—308 bearing 40 mm	Pillow bearing	1			15.00		15
7	Inlet bearing on base	10 mm metal sheet	1	120	0.10	12.57	10	22.57
8	Test shaft	20 mm diameter steel rod	8	3	0.50	1.50	0.5	16
9	Inlet small bearings	6304 bearing	8			3.22		25.76
10	Wall motor shaft	10 mm metal sheet	1	120	0.0013	0.15	5	6.94
		28 mm diameter steel rod		6.67	0.27	1.79		
11	Wall inlet shaft	10 mm metal sheet	1	120	0.03	3.40	10	20.92
		5 mm metal sheet		57	0.13	7.52		
12	Inlet bearing top side	10 mm metal sheet	1	120	0.10	12.57	10	22.57
13	Outer wall motor side	10 mm metal sheet	1	120	0.20	23.56	5	28.56
14	Outer wall inlet side	10 mm metal sheet	1	120	0.20	23.56	7	30.56
15	Drum	10 mm metal sheet	1	120	1.26	150.80	80	230.80
16	Hinges	—	12			1.25		15.00
17	Door	2 mm metal sheet	2	24	0.59	14.07	10	48.15
18	Container cone	2 mm metal sheet	1	24	0.01	0.22	5	5.22
19	Table sheet	1 mm metal sheet	1	12	0.56	6.69	2	8.69
20	Motor stand	10 mm metal sheet	1	120	0.03	3.30	5	8.30
		20 × 20 steel bar		3.8	1.28	4.85		
21	Electric motor	—	1			75.00		75
22	Motor shaft	40 mm diameter steel rod	1	7.5	0.10	0.75	1	1.75
23	Motor pulley	—	1	—	—	7.00		7
24	Drum pulley	—	1	—	—	12.00		12
25	Belt	—	1	—	—	8.00		8
26	Door brush	—	4	—	—	0.25		1
27	Container brush	—	2	—	—	0.15		0.3
						Total machine cost		$ 708

4.2.5. Power and Transmission System. The power and transmission system consists of one electric motor, two shafts, two pulleys, and a belt (Figure 14). The pulley and belt system regulates drum speed to the desired rpm.

Figure 15 shows two isometric full-scale views of the assembly.

4.3. Finite Element Analysis. To ensure the structural integrity of the ball mill, a quasi-static stress analysis simulation was conducted on SolidWorks. The entire parts were meshed using 4-node solid tetrahedral elements (Figure 16) of minimum element size of 8 mm in zones with high stress gradients. This was set following a mesh sensitivity analysis to ensure that the selected mesh provides the required accuracy. The model comprised a total of 285922 nodes and 148823 elements. All parts were made of ASTM A36 steel having a yield strength of 250 MPa. A pressure was applied on the lower part of the drum container representing the weight of the steel balls in addition to the inertia effect. The impact force was computed using the impulse equation by considering a conservative case where

Table 11: Survey on weekly glass bottles disposal.

Local businesses	Weekly disposal of glass bottles 330 ml	750 ml
Restaurant 1	500	900
Restaurant 2	100	120
Restaurant 3	60	220
Restaurant 4	24	30
Restaurant 5	100	130
Restaurant 6	300	150
Restaurant 7	100	72
Average	169	232
Total	1184	1622
Weight of bottles (kg)	0.3	0.506
Total weight (kg)	355.2	820.732
Price of glass per (kg)	0.25	0.25
Total price of glass per (kg)	88.8	205.18
Total income	293.98	
Cost of glass per (kg)	35.52	82.073
Labor cost	40	
Transportation Cost	30	
Electricity cost	25	
Total Profit	81.39	

the drum contains a total of 650 balls, among which 100 of them fall from the top of the drum container.

4.4. Motion Analysis. Once the design is completed, a motion study is conducted on SolidWorks to ensure that the collision energy between the glass bottles and the steel balls is sufficient for crushing the bottles at the selected rotational speed of the drum. The model (Figure 17) comprised the following parts: rotating drum, bearings, seven steel balls, and three glass bottles. The bearings were fixed, and a motor rotating at 38 rpm was attached to the drum shaft. The model was simulated for 5 seconds, and the total kinetic energy of the bottles was recorded.

5. Results

Stress results (Figure 18) show that the highest stresses are localized at the junction between the drum and the shafts from both sides of the drum. The corresponding factor of safety (FOS) against yielding is 4.103 (Figure 19). Deformation results (Figure 20) show a maximum value of 1.247 mm localized in the region of the smallest shaft.

The motion study shows a collision energy higher than 20 joules for the three bottles (Figure 21). This energy is sufficient to break the glass bottles according to experimental studies conducted by [21–24].

The first five natural frequencies resulting from the free vibration analysis are listed in Table 9. Since the operating rpm is much lower than the natural frequencies, hence there is no risk of resonance.

6. Economic Analysis

After finalizing the design, an economic study was conducted. The total cost of the machine is estimated at 700$ (Table 10). Moreover, surveys were conducted on a sample of seven medium-sized restaurants (seating capacity of 50–100) located along the coast regarding the weekly disposal of 330 ml and 750 mm glass bottles (Table 11). Customers who want to operate the glass crusher machine will buy the glass bottles for 0.1 $/kg [25] [26] and sell it for 0.25 $/kg to sectors that benefit from the powder, i.e., construction companies, ministry of agriculture, etc. In this case, the breakeven point will be reached after a period of 5 months.

7. Conclusions

Today, and every day, glass is essential for the existence and sustainability of many industries, and the demand over it is in continuous increase. Therefore, dumping such product in an arbitrary way is a disgrace to its potential at one hand and a risk for the environment at the other hand. Within this context, a glass crusher machine was designed to turn glass bottles into powder. This way large volumes of left glass can be turned into very small quantities with a very promising recycling potential. After exploring different existing designs, concept selection tools were employed such as HoQ, Pugh chart, and AHP. The glass crusher was designed based on the ball mill concept with further enhancements that targeted its weak points such as powder discharge. Sizing criteria were based on both performance and safety via different types of simulations using SolidWorks: static stress analysis, free vibration analysis, and motion study. The first two studies ensured an optimized and safe design of the machine, while the latter confirmed the desired parabolic-like path of the steel balls as well as the glass powder discharge through the holes of the drum. Compared to existing glass crusher machines, the one proposed in this paper presents several advantages in terms of cost, simplified discharge mechanism, and continuous feed.

Abbreviations

ρ_b: Density of the ball
σ_c: Compressive strength
$d_{b,min}$: Minimum ball diameter
$d_{b,max}$: Maximum ball diameter
$D_{i,D}$: Inner diameter of the drum
$D_{i,m}$: Inner diameter of the mill
E: Modulus of elasticity
M: Total mass of the balls and the feed
n: Critical speed of the drum
N: Frequency
OS: Operating speed
P: Power required for drum operation.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Authors' Contributions

JR carried out the mathematical modeling, realized the CAD drawings, and the numerical simulations. RI conducted the state-of-the-art study and concept selection. Both authors contributed to the writing of the manuscript. Both authors have read and approved the manuscript.

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