UNIVERSIDAD INTERNACIONAL DEL ECUADOR

FACULTY OF TECHNICAL SCIENCES

SCHOOL OF MECHATRONIC ENGINEERING

Design and construction of a stone cocoa grinding and chocolate making machine for the "La Gran Cascada" farm

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MECHATRONIC ENGINEER

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CERTIFICATE OF AUTHORSHIP

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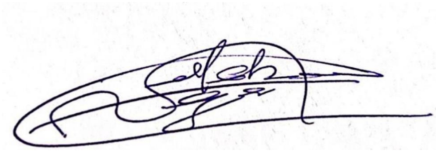

E. Vega Espinosa

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MATERIALS SELECTION

1. Food related materials

Because food must be prepared careful so as not to get people sick, the materials listed here are selected because of their antibacterial properties and their ability not to drop material.

1.1. Granite

Granite is a special material, it has a high density, which removes the possibility for chocolate to be stuck inside cracks and pores, the counterpart is that it is heavy. The measurements for the granite wheels were taken from [1] and [2], their diameter is half of the diameter of the base stone. Fig. 1 shows how the wheels look on top of the base.

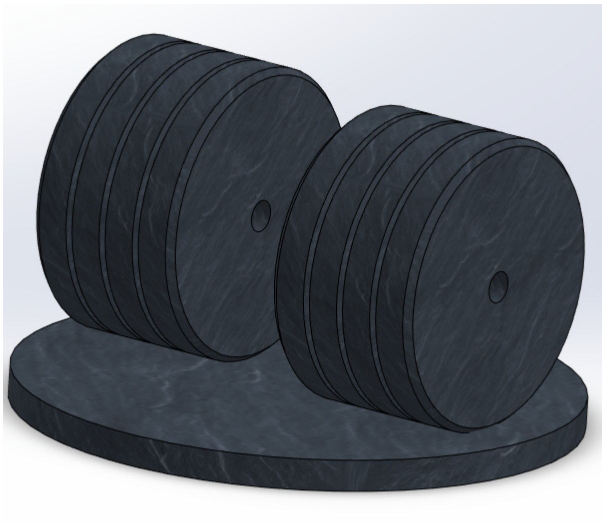

Figure 1. Positioning of the wheels on top of the base.

Some of the granite's properties are shown in Table 1.

Table 1. High-Density Granite Properties

Property	High-Density Granite
Density [g/cm^3]	2.63-2.75
Pressure Resistance [kN/cm^2]	1000-1400
Resistances	Water, Heat and Grease

1.2. Stainless Steel

Stainless Steel was chosen because of its food-grade properties and resistance. Table 2 shows some of the properties of this material.

Table 2. 304 Grade Stainless Steel Properties

Property	SS304	SS304L	SS304H
Tensile Strength[MPa]	540-750	520-700	520-700
Proof Stress[MPa]	230 Min	220 Min	220 Min
Elongation A50[mm]	45 % Min	45 % Min	45 % Min
Density [g/cm^3]		8.00	
Melting Point [$°C$]		1450	
Modulus of Elasticity [GPa]		193	
electrical Resistivity [$\omega.m$]		0.72	
Thermal conductivity [$W/m.K$]		16.2	
Thermal Expansion [$/K$]		17.2*10^{-6}	

1.3. AISI 1045 Steel

The AISI 1045 is a steel used for structures, its mechanical properties are shown in Table 3.

Table 3. 304 Grade Stainless Steel Properties

Property	SS304
Tensile Strength[MPa]	565
Proof Stress[MPa]	310
Elongation A50[mm]	16 %
Density [g/cm^3]	7.87
Melting Point [$°C$]	1400
Modulus of Elasticity [GPa]	200

1.4. Welding Rods

Several types of welding rods or electrodes were used, each one of them has its own use and it will be discussed later in the chapter of calculations, the welding technique used is known as Arc Welding, one of them is purely electric and the other type is gas based. The welding rods used are E6011, E7018, E308L and ER3081.

REGARDING FORCE CALCULATIONS

This section will describe every force the machine suffers and their impact. The forces are shown per part.

2. Base

The base has compressing and tensile stresses, each of the stresses it suffers is colored by a different color as in Fig. 2. The input forces of this system are both of the

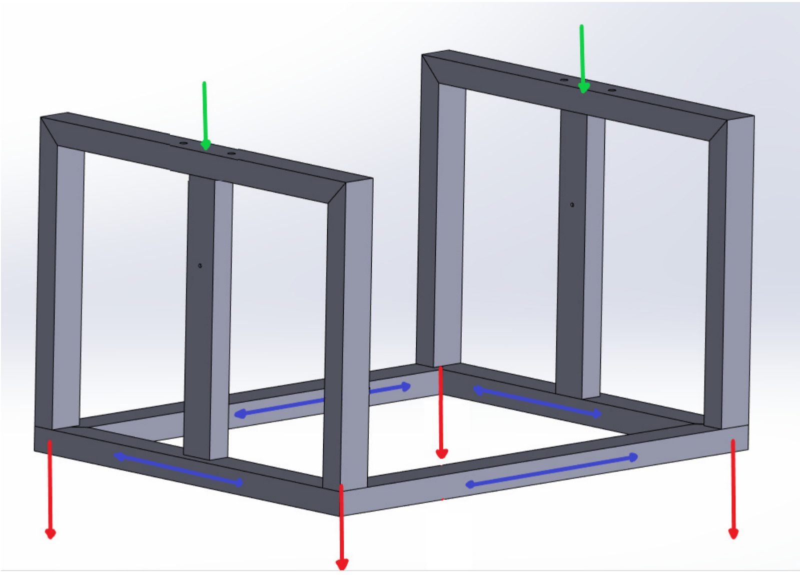

Figure 2. Force distribution in the base.

green arrows on the top, which is the weight of the frame, motor and the pot structure, they weight 120 Kg.

$$\sum F_x = 0$$

$$\sum F_y = 0$$

and

$$\sum F_z = 0$$

The blue lines are the forces on x and z axis, which are non existent, because this structure does not receive any force in the x or z axis, then:

$$\sum F_y = 0 \rightarrow 2 * W_S = 4 * F_W$$

Where: W_S is the weight of the rest of the structure divided by two. F_W is the output force on each of the wheels.

$$2 * \frac{120Kgf}{2} = 4 * F_W$$

$$F_W = 60Kgf$$

And in Newtons:

$$F_W = 60Kg * 9.81m/s^2 = 588.6N$$

The rated maximum weight for the wheels to hold is 600 lbf, which is:

$$600lbf * \frac{1Kg}{2.2lb} * 9.81m/s^2 \approx 2700N$$

Meaning that the wheels can hold this weight. For the base to be able to hold the weight of the whole structure, the rectangular tube was also calculated by its compressing strength and the compressing stress provided by the rest of the machine: Before handling the rest of the equations, the area of the tube is found:

$$A = (0.06m * 0.04m) - ((0.06 - 0.003)m * (0.04 - 0.003)m)$$

$$A = 0.000291m^2 \approx 291mm^2$$

$$CS = \frac{F}{A}$$

Where: CS is the compressing strength. A is the area. F is the supplied compressing force.

$$CS = \frac{588N}{291mm^2}$$

$$CS = 2020618.55Pa \approx 2MPa$$

The yield maximum strength of AISI 1045 is 310 MPa, meaning that the tube is more than enough capable of holding the load.

3. Frame

The frame is responsible of holding the pot, motor and to help to empty the contents of the pot. There are two components of the frame, the first one is shown in Fig. 3, it will be mentioned further as the frame itself and the component shown in Fig. 4 will be mentioned as the top of the frame.

3.1. Lower Frame

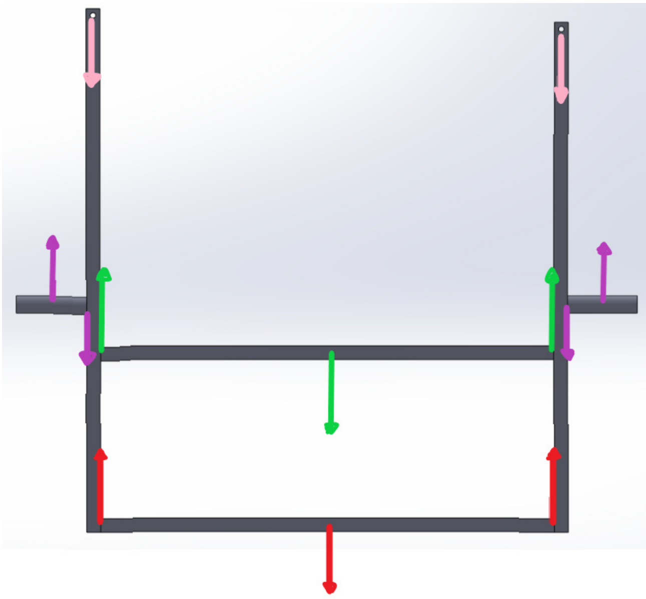

Figure 3. Force distribution in the frame on a vertical position.

From the top of the figure:

The pink arrows represent the weight from the top of the frame, which, according to the density of the material is:

$$V = .02 * .07 * .64m^3 = 0.000896m^3$$

$$p = m/V$$

$$m = p * V$$

$$m = 7850\frac{kg}{m^3} * 0.000896m^3$$

$$m = 7kg$$

This mass is added to the total weight of the frame, which, by the same logic is:

$$m_{Frame} = 2 * ((.02 * .07 * .72 + .02 * .07 * .62) + \pi * .013^2 * .1)m^3 * 7850\frac{kg}{m^3}$$

$$m_{Frame} = 31kg$$

$$m_{Structure} = 38kg$$

To this, the weights of the wheels, shaft structure, pot and motor should be added, the mass of each of these is:

$$m_{wheel} = 2691\frac{kg}{m^3} * \pi * .14^2 * .16m^3 = 26kg$$

$$m_{motor} = 30kg$$

$$m_{shaft\_structure} = \pi * (.005^2 * .43 + .01^2 * .43 + .015^2 * .40)m^3 * 7850\frac{kg}{m^3} = 3.54Kg$$

$$m_{pot} = 40kg$$

$$m_{frame+wheels+motor+shaft\_structure} = 188.6kg$$

The next analysis is the part of the shafts, placed on the sides with purple arrows, they show the reaction of the base with respect to this structure. As there are only forces in the Y axis, and the maximum amount of chocolate processed each time, the total weight of this structure is up to 257 kg. The amount is divided by two, because the weight has the same distance between both shafts. Then:

$$W = 257kg * 9.81\frac{m}{s^2} = 2521N$$

And the shear stress is:

$$\tau = \frac{1962N}{.013^2 * \pi m^2} = 47.48MPa$$

Which is around five times smaller than the maximum amount of stress resisted by steel (270-380 MPa). This shaft was selected mainly because of the availability of the rowlock bearing.

The next calculation is for the green arrows shown in the figure, the pot is positioned right on top of the middle beam, this beam (as the rest of this particular component) is made from a 2 cm * 7 cm solid steel bar.
For the following calculation, the weight of the pot must be calculated:

$$m_{shaft} = 7850\frac{kg}{m^3} * \pi * (.015^2 * .1 + .02^2 * .15)m^3$$

$$m_{shaft} = 2.03kg$$

$$m_{granite\_base} = 2691\frac{kg}{m^3} * .275^2 * .02 * \pi m^3 = 12.79kg$$

$$m_{pot} = m_{walls} + m_{base} = 2 * \pi * .275 * .0003 * .4 + .275^2 * \pi * .0005 = 25.6kg$$

$$m_{pot+base+shaft\_structure+shaft+wheels} = 95.92kg$$

As mentioned earlier, the weight of the wheels and shaft structure plus the weight of the pot and the motor shaft is 95.92 kg, meaning the reactions on both ends of this beam is half, or 47.96 kg.
As this beam has a hole in the middle, the maximum yield stress is presented in that point. The yield stress is:

$$\sigma = \frac{95.92 * 9.81[N]}{.02 * .07} = 67.4MPa$$

And, as mentioned earlier, the amount of chocolate processed on each batch can be up to 50 extra kilograms, meaning that the maximum amount of yield stress is:

$$\sigma = \frac{145.92 * 9.81[N]}{.02 * .07} = 102.2MPa$$

And the strength of steel is around 350 MPa, so the safety factor for this particular beam is of around 3.5.
Finally, the lower beam (which has red arrows in the figure) carries with the weight of the motor and the gearbox. The mass for these components is:

$$m_{motor+gearbox} = 30kg$$

Then the reaction on each of the ends is:

$$F = \frac{(m_{beam} + m_{motor+gearbox}) * 9.81\frac{m}{s^2}}{2}[N]$$

$$F = \frac{(7850 * (.02 * .07 * .64)kg + 30kg) * 9.81}{2}$$

$$F = 181[N]$$

$$\tau = \frac{181}{.02 * .07} = 12.9MPa$$

Which, as said earlier, is really low compared with the maximum yield strength of steel. As seen from these calculations, most of the parts of this particular structure are overdimensioned, this is due to the fact that there were no plates or bars in the dimensions that were designed, this increments the weight and the price of construction of the machine significantly.

3.2. Top of Frame

This component helps deliver pressure to the wheels, which press down and crush the cocoa beans, the pressure comes from an stainless steel bolt, placed on one side, this pressure depends on the amount of turns given to the bolt. Its forces diagram is shown in Fig. 4. It consists on a beam, which applies pressure in the middle and has only

Figure 4. Force distribution in the upper beam.

one reaction force on the end, because the other one is fixed through another couple of bolts, the maximum amount of force a bolt can supply rounds 50 ksi:

$$50ksi = 50.000psi \rightarrow 1psi \approx 6894Pa$$

$$50ksi \approx 350MPa$$

And knowing that the bolt was M10:

$$A = \pi * 0.005^2 m^2 = 7.85 * 10^{-5}$$

And the Applied force is:

$$F = 7.85 * 10^{-5} * 350MPa$$

$$F = 27500N$$

3.3. Frame Lock

This force is also applied to the lock that goes on top of this beam, it is shown in Fig. 5 This specific component was made from a 4mm plate of steel, which has a yield

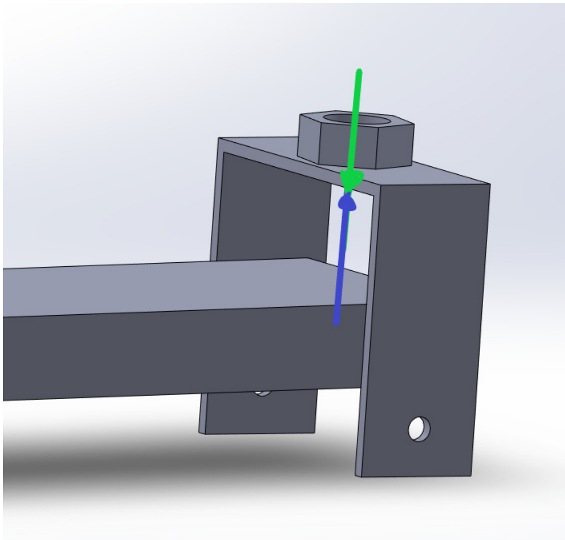

Figure 5. Force distribution in the frame lock.

strength of 350MPa. The yield stress of this specific component is:

$$\sigma = \frac{F}{A}$$

$$\sigma = \frac{27500}{.004 * .03}$$

$$\sigma = 230MPa$$

Which is 1.5 times smaller than the strength. As the pressure should not reach that level to protect the granite, it will not be a problem.

4. Motor Shaft

The next component to discuss is the motor shaft, this shaft was chosen to fit the gearbox, it is overdimensioned regarding torsion, but reducing its size would not have worked because of the fore-mentioned gearbox, then, its diameter is 3cm and has a cotter, everything made out of steel.

ELECTRONICS

5. Component Selection

This section primarily describes the selection of the motor and connections between the components.

5.1. Motor, Gearbox and Frequency Variator

Motor

First of all, the motor was selected because of the mechanical needs of the system, and, because the quantity, consistency and temperature of the chocolate are unknown, the motor has a high safety factor. The stone wheels, base and pot had been designed before choosing the motor, they are shown in Fig. 6 and were designed in the following way: This image shows the movement direction (marked by a purple line and a letter

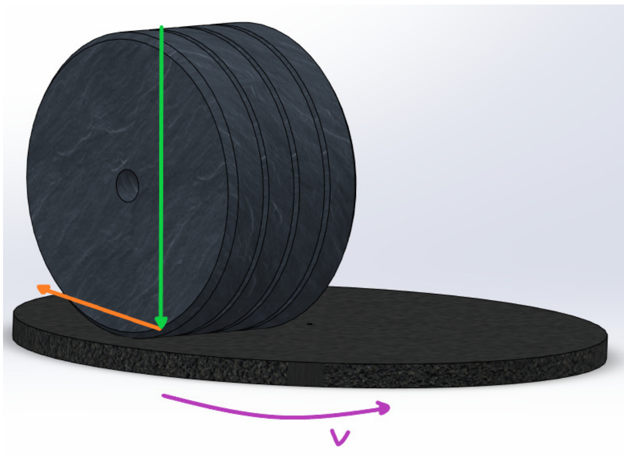

Figure 6. Force distribution in the granite wheels and base.

v), the weight of the wheels (marked in green) and the friction between the wheels and the base (marked in orange).

The way torque is calculated is:

$$T = I * \ddot{\theta} + F_{friction} * d$$

$$T = \frac{1}{2} * m_t * R^2 * \frac{150RPM}{5s} + 2 * \mu * N * R$$

$$T = \frac{1}{2} * m_t * R_1^2 * \frac{150RPM}{5s} + 2 * \mu * m_s * g * R_2$$

Where: m_t is mass of the pot, motor shaft, wheels, base and shaft structure. m_s is mass of the wheels, base and shaft structure. R_1 is the radius of the base. R_2 is the radius until the middle of the wheels. μ is the friction coefficient (in granite, this value is 0.32). N is the normal force, supplied by the weight of the wheels and the shaft structure and by the pressure of the bolt in the lock discussed earlier. Then:

$$T = 0.5 * 95.92kg * 0.27^2m^2 * \frac{15.8\frac{rad}{s}}{5s} + 2 * 0.32 * 64.79kg * 9.81\frac{m}{s^2} * 0.16m$$

$$T = 11.03 + 65.08[Nm]$$

$$T = 76.11Nm$$

And knowing that the nominal speed of the motor is 1750 RPM, but the maximum required velocity is 150 RPM and that the torque needed is 76.11 Nm, its power can be calculated:

$$T[Nm] = 9.5488 * \frac{P[kW]}{V[RPM]}$$

$$76.11 = 9.5488 * \frac{P}{150}$$

$$P = 1.2kW \approx 1.6HP$$

As there are no 1.6HP motors and the chocolate resistance is unknown, the motor selected has a torque of 3HP.

Gearbox

The selected gearbox was a 10:1 gearbox, it decreases the velocity by a factor of ten and it increases the torque by that same factor. The selected gearbox fits perfectly with the selected motor and consists of a worm and gear reductor.

Frequency Variator

The frequency variator must be compatible with the motor's nominal voltage and current, in this case, as the motor used is three-phase, so the frequency variator must be able to deliver. As the ACS150 is not able to deliver more than 350V on its output, and as the motor has two configurations as seen in Fig. 7, the configuration needed to be changed from delta into a star configuration so that the nominal voltage dropped from 380 V to 220 V, but its nominal current rised from 4.8 A up to 8.3 A.

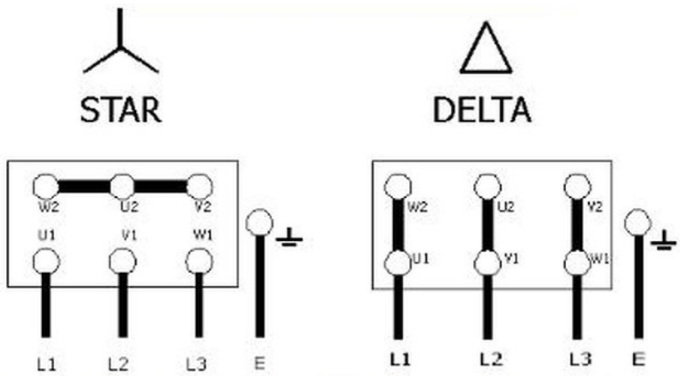

Figure 7. Motor configuration.

5.2. Cable Selection

The cables used were dimensioned before implementing the machine, although higher gauge cables can be used without a problem, this increases the overall cost of the machine in exchange for an increased safety factor. The maximum amount of current of the machine mostly depends on the current that the motor draws, the current drawn from the DC supply, indicator light bulbs, micro-controller, etc is less than 2 A. Then, the maximum amount of current is around 11 A, according to Table 4, from [3].

Table 4. Conductor properties

AWG	Diameter (mm)	Current
10	2.59	50
12	2.05	30
14	1.63	20
16	1.29	10
18	1.02	7
20	0.82	5
22	0.64	3

The cables used for the logic circuit handle less than 0.5 A, but because of the price and the resistance they provide, gauge 20 cable was used. As the frequency variator's digital pins handle low current, and, according to the ACS150 Frequency variator guide, a gauge 26 cable should be used, and because of the suggestion that it gives, UTP CAT VI was used, it consists on eight strands of 24 gauge twisted wires.

5.3. Indicator Light Bulbs

These components are rated for different voltage levels and types, in the case of this project, the selected light bulbs are rated for 12 V to 24 V DC. This property is listed on the side of them as shown in Fig. 8.

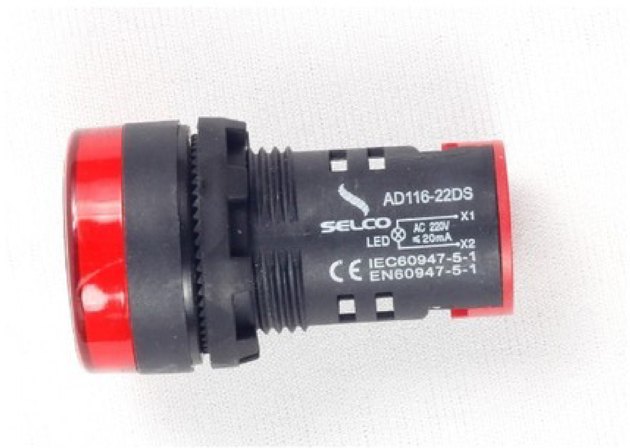

Figure 8. Light bulb properties.

5.4. Push-Buttons

Push-buttons were selected to be robust and fit into the control panel, they are rated for high levels of voltage and current.

5.5. Circuit Breaker and On - Off Switch

The circuit breaker was selected because of its rated current level, and, as mentioned earlier, there are no 12 A rated circuit breakers or On - Off switches, so 20 A rated current components were chosen.

ANNEX

6. Construction Cost and Retail Price Analysis

This section will describe the cost of the making of the machine and its value and retail price if sold.

6.1. Material cost

Table 5 shows the total cost of the materials, components and price of construction.

Table 5. Construction cost

Component / Material	amount	Cost
3 mm Stainless Steel plate	2 m^2	$ 250
5 mm Stainless Steel plate	1 m^2	$ 30
1 in Granite plates	2 m^2	$ 120
6 cm * 4 cm * 3 mm Steel Tube	10 m	$ 100
2 cm * 7 cm Steel plate	3.5 m	$ 80
Caster Wheels	4	$ 30
1 cm, 2 cm and 3 cm Stainless Steel rods	1.5m	$ 100
Rowlock Bearings	2	$ 20
Axial Bearing	1	$ 9.80
Granite Processing Cost	-	$ 75
Steel Processing Cost	-	$ 500
3 HP Motor	1	$ 259
Gearbox	0.64	$ 308
Frequency Variator	0.64	$ 492
Push-Buttons and Indicator Light bulbs	11	$ 50
On-Off Switch and Circuit Breaker	1	$ 60
Cables and terminals	-	$ 50
ESP 32 and LCD screen	1	$ 25
Total		2558.8

The total price of this machine is relatively high, but some components add up the value of the machine, for example, the frequency variator and the ESP32 are not completely necessary, but they help to optimize the chocolate process' resources and time in which it processes. The use of AI and the capability to use a micro-controller is good to log gathered data to use it later.

6.2. Retail Price

After researching about similar machines with the same capacity of the implemented one, these machines are sold at around $ 7000 up to $ 20000, these machines only work with a dimmer circuit and are operated fully manually. The addition of the design, component selection, and, with the analysis of the increase in price of chocolate versus raw cocoa beans shown in Table 6, the price of the machine is a big investment with high money-back increase, the increase of the intelectual property to the cost of the machine adds it up to a cost of $ 5000, making it cheaper than the available stone mills in the market and optimizing processes, making it ideal for the industry of chocolate.

Table 6. Cocoa bean process and retail price per Kg

Cocoa Bean Process	Cost per Kg [$]
Cocoa on the Cob	$ 0.90
Fermented Cocoa Beans	$ 1.70
Dry Cocoa Beans	$ 2.40
Toasted Cocoa Beans/Nibs	$ 10
Cocoa paste	$ 15
Chocolate	$ 23

As the maximum amount of chocolate processed in this machine is 50 kg, and taking into account that buying dry cocoa beans, it is cheaper to buy 50 kg of dry cocoa beans at around $ 100 then toasting, crushing, and making chocolate, the overall price of chocolate is $ 1500 and the overall profit per batch is around $ 1050.

REFERENCES

[1] E. O. Afoakwa, *Chocolate Science and Technology*, 2010.

[2] “Schokolade, die süße last,” *hautnah dermatologie*, vol. 29, no. 3, pp. 136–136, 2013.

[3] *Wire Size and Current Rating Guide*.