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PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Conceptual design of a process plant for the production of plantain flour

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Abstract: Plantain has become an essential source of food in the Nigerian market today and to this effect, it is fast becoming a sought-after fruit, especially for persons diagnosed with diabetics. Being a perishable fruit, plantain is usually processed into flour to extend its shelf life. Hence, there is a need to improve on the quantity and quality of the flour produced from it. This paper presents the conceptual design of a process plant for plantain flour production from green plantain pulp. The process plant consists of washing, slicing, drying, milling and sieving machines. The design analysis of constituent machines and its performance evaluation were carried out using SolidWorks and other appropriate design equations. The designed process plant was simulated to ensure its functionality. The results of its performance were analysed and estimated cost of production presented.

Subjects: Design; Industrial Engineering & Manufacturing; Manufacturing Engineering; Mechanical Engineering; Production Engineering; Systems & Control Engineering

Keywords: conceptual design; process plant; plantain flour; washing; slicing; drying; milling; sieving

1. Introduction

Plantain (*Musa paradisiaca*) is a staple food grown throughout the tropical and subtropical regions of the world. It is one of the major sources of carbohydrate for millions of people in Africa, the Caribbean, Latin America, Asia and Pacific (Frison & Sharrock, 1998). It ranks third, after yam and cassava, for sustainability in Nigeria (Jayaraman & Das Gupta, 2006) and Nigeria is known to be the largest

ABOUT THE AUTHORS

My research team is into development of process plants, Machine & System Design, Automation & Robotics and Applied Ergonomics. Some of the top publications of the team are: Computer Aided Assembly Animation of a Tricycle for Paraplegics; Design of a Process Plant for the Production of Pounded Yam; Development of Yam Peeling and Slicing Machine for a Yam Processing Plant; Animated Simulation of Pilot Soya Beans Oil Production Process Plant; A Control System for Pounded Yam Flour Processing Plant; and Design and Fabrication of an Adaptive Left Throttling Pedal for V-Boot Wagon 230 for Right Paraplegic Patient. Some ongoing works in the team include: Development of an automated process plant for Roselle tea particulate production; Performance evaluation of an automatic Body Mass Index Measuring Machine; Ergonomic Evaluation of Dynamic and Post Effect of Vibration on Earth Moving Equipment Operators; and others.

PUBLIC INTEREST STATEMENT

Plantain has become an essential source of food today and to this effect, it is fast becoming a sought-after fruit, especially for persons diagnosed with diabetics. Being a perishable fruit, plantain is usually processed into flour to extend its shelf life. The need to improve on the quantity and quality of the flour produced is the focus of this work. The conceptual design is a process plant for plantain flour production from green plantain pulp. It consists of washing, slicing, drying, milling and sieving machines. The flour produced will be hygienic and of high quality. The plant will reduce processing time and also extend plantain shelf life which will help to minimize plantain post-harvest losses, retain its freshness and nutritional values, and also meet the high market demand for plantain flour as a result of its capability of controlling type 2 diabetes.

producer of plantain in West Africa (Ibrahim, 2013). Plantain is a highly perishable fruit because it has a very short shelf life. Thus, it is usually processed into durable products like chips and flour (Akalumhe, 1999; Jayaraman & Das Gupta, 2006; Ibrahim, 2013). Plantain can either be used for domestic consumption or used as input by other producers. Plantain flour, apart from being used as a substitute for cassava flour especially for diabetic patients, also serve as a raw material used in the production of cakes, chips, puff-puff, biscuit, bread and pancakes. The products of plantain flour have nutritional and medicinal values which makes plantain a highly sought-after product (Marriott, Robinson, & Karikari, 1981; Marriot & Lancaster, 1983). Plantain flour is a cheap source of iron, protein and vitamin A (Foramfera, 2012a). Plantain flour has advantage over other starchy foods because it contains protein, mineral and vitamins. Medically, plantain can be used to cure a lot of ailments including diabetes, sore throat, tonsillitis, diarrhoea, vomiting and it is said to be a major diet in the production of *soya-musa* which can be used in the treatment of kwashiorkor (Von Loesecke, 1950; Idachaba, 1995).

Plantain flour is the product of dried and pulverized unripe plantain pulp. It is called “*elubo agbagba*” in Yoruba-speaking areas of Nigeria, where it is normally made into a dough called “*amala*”, having being reconstituted in boiling water (Frison & Sharrock, 1998; Ibrahim, 2013; Ukhun & Ukpebor, 1991). The processes involved in plantain flour production are separation into fingers from bunch, peeling, washing, slicing, drying, milling and packaging (Adeboye, Iyanda, Yusuf, Olaniyan, & Oje, 2014; Adeniji, Sanni, Barimalaa, & Hart, 2006; Madamba, Driscoll, & Buckle, 1996). The present processing of plantain into flour takes a lot of time, requires a lot of energy and attention from one stage to the other. Thus, the quality and quantity of the flour produced are usually adversely affected (Ogazi, 1996). This paper therefore presents the conceptual design of a process plant for plantain flour production to solve the problem of hygiene, drudgery, poor quality and others associated with the present methods of producing plantain flour

2. Design concept

The process plant consists of a frame, collection bucket, three electric motors, washing section, slicing, drying, milling and sieving machines (Figures 1 and 2 show the assembly and orthographic view of the

Figure 1. Assembly of the process plant.

Notes: (A) slicing section (B) drying section (C) milling section (D) sieving section (E) flour exit (F) sieving residue exit (G) belt conveyor system (H) sprinkler water input pipe for washing section (I) collection bucket and (J) foot stand platform.

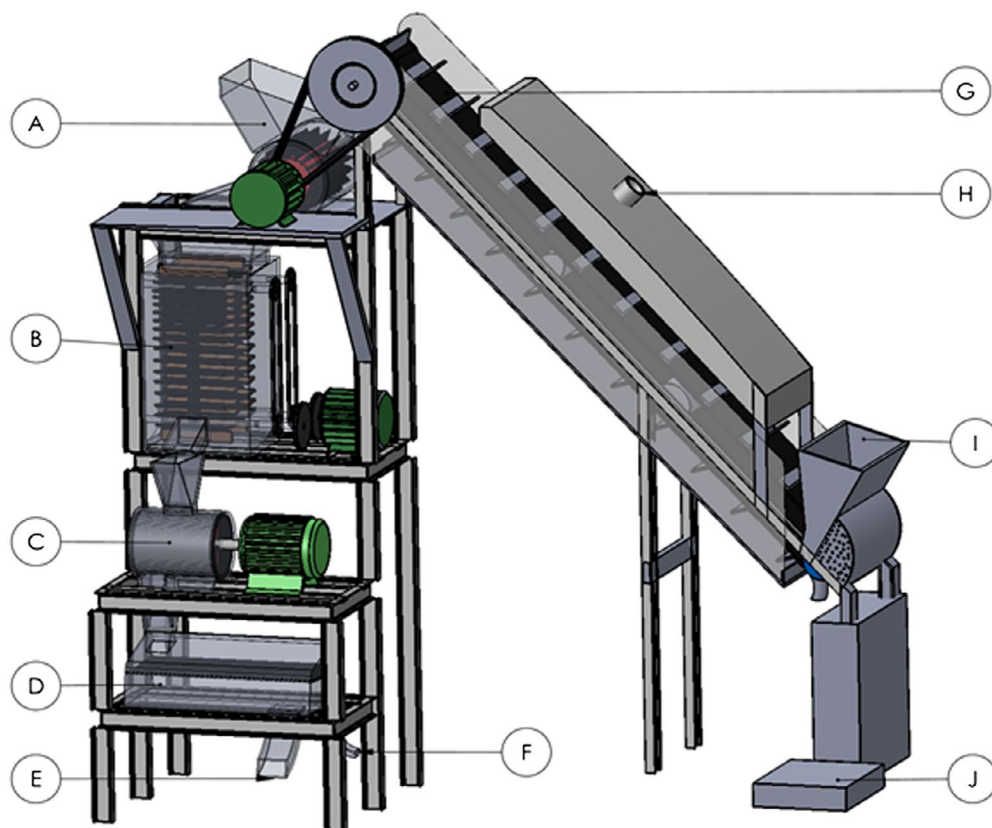
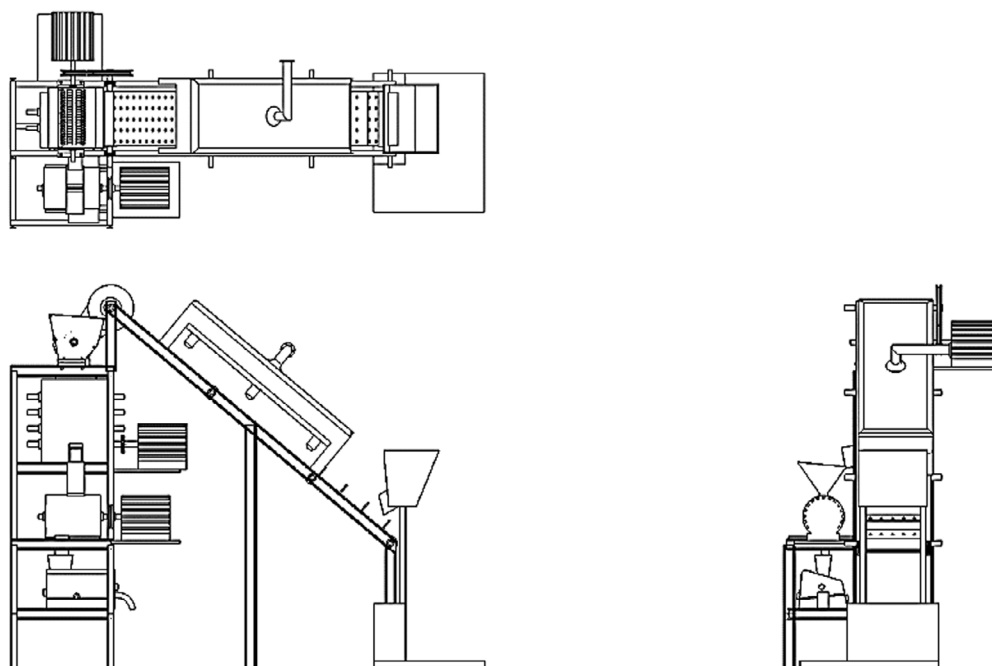


Figure 2. Orthographic view of the process plant.



process plant respectively and Table 1 presents component parts of the process plant). The frame acts as a rigid support for the various components of the process plant. Peeled plantain pulps are temporarily stored in the collection bucket, which delivers a plantain pulp per time into the washing section. The

Table 1. Component parts of the process plant for plantain flour production

| S/N | Item | Quantity |
|-----|----------------------|----------|
| 1 | Collection bucket | 1 |
| 2 | Conveyor Belt | 1 |
| 3 | Roller | 2 |
| 4 | Cam-shaped Roller | 2 |
| 5 | Flight | 50 |
| 6 | Sprinkler | 3 |
| 7 | Pulley | 2 |
| 8 | Hopper | 2 |
| 9 | Electric motors | 3 |
| 10 | Pulleys | 3 |
| 11 | Sprocket | 7 |
| 12 | Chain | 2 |
| 13 | Slicing Shaft | 1 |
| 14 | Drying chamber Shaft | 4 |
| 15 | Heater | 4 |
| 16 | Blower | 4 |
| 17 | Delivery Chute | 4 |
| 18 | Milling Shaft | 1 |
| 19 | Milling Drum | 1 |
| 20 | Sieve | 1 |
| 21 | Sieve Case | 1 |
| 22 | Vibrator | 4 |

washing section consists of a perforated conveyor belt and three sprinklers, which is connected to one water supply pipe. The conveyor belt, powered by an electric motor, collects and transfers plantain pulps from the collection bucket to the slicing hopper. It is mounted on two rollers and it has flights at intervals to prevent the pulps from falling as they move at the upward slopply direction. The sprinklers supply accelerated water, which impinges on the conveyor, for the washing of the plantain pulps. Proper washing is ensured in this stage by incorporating two cam-shaped rollers between the two main rollers of the conveyor. The cam-shaped rollers will provide jerks on the pulps on the conveyor belt, thereby turning the pulps for proper washing of all the sides of the pulps as the sprinklers provide jet of water on the pulps being conveyed. The perforated portion of the conveyor belt drains water on the pulp. The slicing machine consists of a hopper, a shaft incorporated with slicers and an electric motor which rotates the slicer at a reasonable high speed. The slicing machine reduces the plantain pulps into smaller sizes in order to speed up drying rate in the drying chamber. The drying machine, which helps remove the moisture content of the sliced pulps to 10%, consists of a hopper, housing for the drying chamber, flat plates, heaters, blowers, chain drive mechanism and an electric motor. The flat plates receive sliced plantain pulps from the slicing machine and deliver them dried into the milling machine, where they are pulverized. The heaters supply the needed heat for the moisture removal while the blowers circulate the heat round the drying chamber in order to increase the rate of moisture removal. The pulverized plantain pulps are then sifted in the sieving machine for packaging.

2.1. Design consideration

The design of the process plant took the following into consideration:

- (1) The variation in the plantain geometry.
- (2) The sustenance of the original plantain flavour and colour.
- (3) optimal processing time.
- (4) Minimal Plantain wastage.

2.2. Selection of materials

Material selection is very crucial to the design of any machine or process plant, especially when it is to be used for food processing. Hence, it is of utmost importance to ensure that the components of the process plant have the desired performance requirements. Some components of the process plant will be in direct contact with the plantain pulps and must not corrode or react with the pulp. The material must be resistant to wear to prevent the plantain flour contamination with material chips and debris. To ensure high quality standard, materials with the appropriate engineering properties were carefully chosen for the design to cope with the varying degrees of stress, strain, torque and frictional loads. The following factors were considered in selecting the materials for the design (Table 2), (Eugene & Avallone, 1999).

- (1) Physical and mechanical properties of the material
- (2) Reliability of the material
- (3) Availability
- (4) Maintainability
- (5) Chemical properties
- (6) Aesthetic characteristics, and
- (7) Cost-Effectiveness.

3. Design analysis

3.1. Conveyor

The design of conveyor is shown in Figure 3.

Table 2. A summary of material selection process for the process plant

| S/N | Plant Component | Material used | Reason for selecting the material |
|-----|----------------------|-----------------------|---|
| 1 | Frame | high carbon steel | High rigidity, hardness, adequate toughness and good machining characteristics |
| 2 | Collection bucket | Galvanized steel | Low cost, readily available, durable |
| 3 | Conveyor Belt | Rubber | Excellent corrosion resistant, and cheap |
| 4 | Roller | Mild steel | Strength, smoothness and concentricity no wobbling and cheap |
| 5 | Cam-shaped roller | Mild steel | Strength no wobbling, and cheap |
| 6 | Flight | Plastic | Lightness, most suitable and cheap |
| 7 | Sprinkler | Plastic | Good and appreciable discharge rate, and cheap |
| 8 | Pulley | Wood | Light, high coefficient of friction, good velocity ratio |
| 9 | Hopper | Galvanized mild steel | Strength, firmness, rigidity, does not contaminate, cheap and readily available |
| 10 | Sprocket | Mild steel | Most suitable, cheap, good strength and ability to avoid wobbling |
| 11 | Shaft | Galvanized steel | Cheap, readily available, strength, resistant to shock and torsional deflection |
| 12 | Drying chamber | Teflon | Lightness, does not contaminate, good strength, good inspection and durable |
| 13 | Drying chamber trays | Aluminium | Good conductivity, low cost, readily available, no contamination |
| 14 | Delivery chute | Galvanized mild steel | Low cost, readily available, does not contaminate |
| 15 | Milling drum | Galvanized mild steel | Does not contaminate, shock resistant, torsional rigidity, shearing and bending resistance. |
| 16 | Sieve | Plastic | Corrosion resistance, light, cheap, readily available |
| 17 | Sieve case | Mild steel | Cheap and readily available |

According to Ayodeji, Olabanji, and Adeyeri (2012), the centre distance between the head and tail roller (which is the conveying length) is obtained from:

$$C_{HT}^2 = HTL^2 + (H_s - H_b)^2 \quad (1)$$

$$C_{HT}^2 = 2,500^2 + (2,500 - 950)^2$$

$$C_{HT} = 2,940 \text{ mm}$$

The length of the conveyor belt L_{CB} was obtained from:

$$L_{CB} = 2 \left(C_{HT} + \frac{\alpha}{360} \pi D_H \right) \quad (2)$$

$$L_{CB} = 2 \left(2,940 + \frac{30}{360} \times \pi \times 150 \right)$$

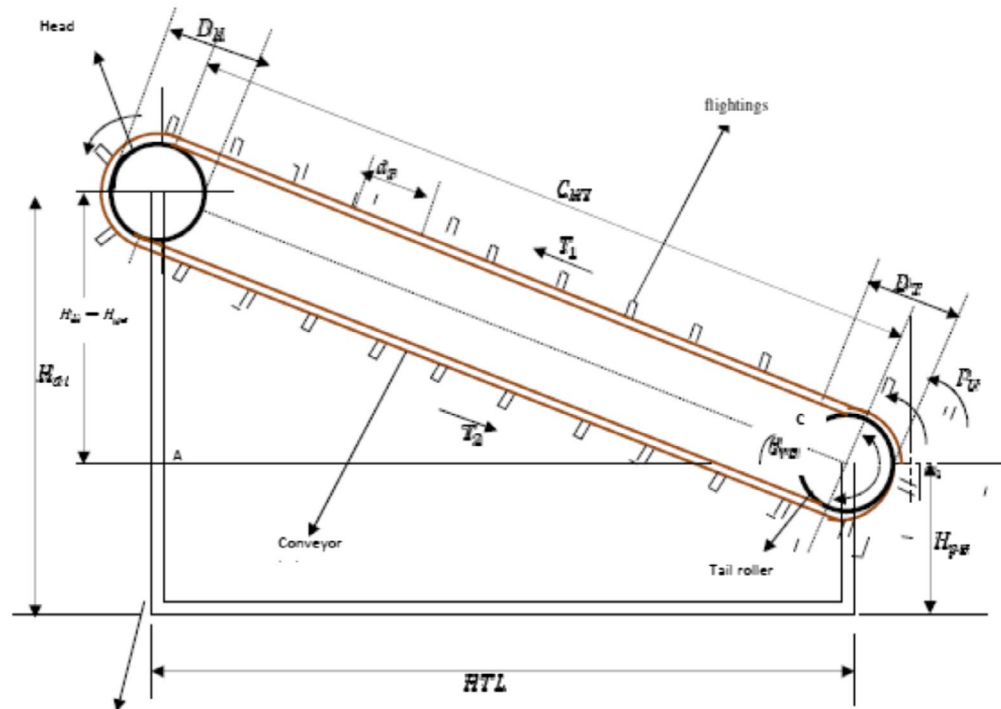
$$L_{CB} = 5,958.5 \text{ mm}$$

The number of Flights on the belt was obtained from:

$$n_f = \left(\frac{L_{cb}}{d_f} \right) \quad (3)$$

Figure 3. Schematic diagram of the conveyor system.

Notes: D_H is diameter of the head roller which is equal to the diameter of the tail roller; d_f is distance between two flights on the belt; C_{HT} is the centre distance between the head and tail rollers = conveying length; θ_{re} is angle of elevation of the rollers; H_b is the height of the loading bucket bottom to the ground; HTL is the horizontal travel distance between the slicer and the vertical support column; H_s is the Height of the slicer exit to the ground; α is the angle of wrap on the rollers; T_1 is the tension in the tight side of the belt; T_2 is the tension in the slack side of the belt.



$$n_f = \left(\frac{5958.5}{300} \right)$$

$$n_f = 19.95 \text{ flights}$$

Therefore, a total of 20 flights will be attached to the conveyor belt.

The load stream volume Q_v (which is defined as the conveying capacity of the conveyor) was obtained from

$$Q_v = 3600 A v \text{ (m}^3\text{/h.)} \quad (4)$$

Where: A and v are the cross sectional area of the load stream and the belt speed, respectively.

$$Q_v = 3600 \times \pi \times \frac{50^2}{4} \times 1,000 \text{ (m}^3\text{/h.)}$$

$$Q_v = 7,068 \text{ m}^3\text{/h.}$$

The mass of load stream which the conveyor can move at a time is called the capacity of the conveyor and it was derived accordingly.

$$Q_m = \rho_m Q_v \text{ (tons/h.)} \quad (5)$$

where ρ_m is the density of the material conveyed.

The power required at the drive sprocket is the summation of the power for empty conveyor and load over the horizontal distance (P_1) and the power required for lift (P_2).

$$P_T = P_1 + P_2 \quad (6)$$

Where:

$$P_1 = \left(\frac{C_B V + Q_m}{C_L + k_f} \right) \quad (7)$$

Where: C_L is length factor of the belt; C_B is width factor of the belt; and k_f is working condition factor.

Where:

$$P_2 = \left(\frac{H_{di} - H_{pc}}{367} \right) Q_m \quad (8)$$

3.2. Slicing machine

The machine works on shear cutting principle. When the cutting blade impacts on the cylindrical surface of the raw plantain, the surface gets cut by shearing along a plane. The machine is made up of the cutting devices, a feeding mechanism through the conveyor, the support frame and an electric motor as a source of power. The cutting mechanism consists of the stainless steel blades, a connecting rod, and a guide frame for the blades. The blades are arranged perpendicularly to the slicing shaft. The base frame suspends and provides a firm support to the machine. Power is transmitted from electric motor to input shaft via coupling. The input shaft transmits power both to the cutting and feeding mechanisms.

The volume of the hopper of the slicing machine is obtained

$$V_{\text{hopper}} = V_{\text{wholepyramid}} - V_{\text{cut away pyramid}}$$

$$V_{\text{hopper}} = \left\{ 0.5 \times L_{b1} \times L_{b2} \times H_p \right\} - \left\{ 0.5 \times L_{c1} \times L_{c2} \times H_c \right\} \quad (9)$$

Where: L_{b1} is length of the top shape of the hopper; L_{b2} is breadth of the top shape of the hopper; L_{c1} is length of the base shape of the hopper; L_{c2} is breadth of the base shape of the hopper; H_p is vertical height of the pyramid; H_c is vertical height of the cutaway pyramid.

3.3. Design for pulleys

Power is transmitted through a single electric motor to the slicing machine and the conveyor roller. The electric motor powers the slicing machine directly while the pulley aids the transmission of power from the electric motor shaft to the conveyor roller shaft through a flat belt.

The length of belt transmitting power between two pulleys of dissimilar diameters was derived from Equation (10).

$$\text{Length of belt } L = \sqrt{4x^2 - (D_2 - D_1)^2} + \frac{1}{2}(D\theta_2 - D\theta_1) \quad (10)$$

$$\text{Note that } D\theta_2 = \frac{\theta_2}{360} \times \pi D_2$$

$$\text{and } D\theta_1 = \frac{\theta_1}{360} \times \pi D_1$$

where: D_1 and D_2 are the diameters of the pulleys; x is centre distance between the two shafts; θ_1 and θ_2 are the angle of lap of the belts on the pulley.

3.4. Determination of the shearing force for the raw plantain

Considering the shear strength of the raw plantain and the area under shear, the impact force required to shear the raw plantain may be obtained from Equation (11):

$$F_p = A_p \times \tau_p \quad (11)$$

where: F_p is the Force required for shearing the raw plantain; A_p is the Area under shear; τ_p is the Shear stress of the raw plantain.

The area under shear can be determined from Equation (12):

$$A_p = \pi \frac{D_p^2}{4} \quad (12)$$

where: D_p is Diameter of raw plantain.

The average force required to shear raw plantain of diameters ranging from 30 to 70 mm is 33.15 N (Obeng, 2004). This force reduces as the plantain ripens and softens. The measured diameter of the raw plantain was in the range of 30–70 mm, averaging 50 mm. From Equation (12), we get

$$A_p = \pi \frac{(0.050)^2}{4} = 1.96 \times 10^{-3} \text{ m}^2$$

Therefore the average Shear force required to slice a plantain is given as:

$$\tau_p = \frac{F_p}{A_p} = \frac{33.15 \text{ N}}{0.00196 \text{ m}^2} = 16.9 \text{ K N m}^2$$

3.5. Determination of the power required by the cutter for slicing the raw plantain

Cutter velocity is another important parameter in the slicing process. The optimum value of cutter velocity required for slicing is 2.65 m/s (Prasad & Gupta, 1975). The power required by the cutter to slice the raw plantain may be obtained from Equation (13):

$$P_c = F_p \times V_c \quad (13)$$

where: P_c is the Power required by the cutter; V_c is the linear velocity of the cutting blade which is 2.65 m/s.

From Equation (13),

$$P_c = 33.15 \text{ N} \times 2.65 \text{ m/s} = 87.85 \text{ W}$$

3.6. Determination of the power required by the electric motor

The power required by the electric motor may be obtained from Equation (14):

$$P_m = P_c \times P_f \quad (14)$$

where: P_m is the Power of electric motor; P_f is the Power factor which is 1.5.

From Equation (14),

$$P_m = 87.85 \times 1.5 = 131.78 \text{ W}$$

Selected capacity of electric motor is 1.11 KW (1.5 hp.)

3.7. Determination of the shaft diameter

The diameter of the slicing shaft was determined from Equation (15):

$$d^3 = \frac{16}{\pi S_s} \sqrt{\left\{ (K_b M_b^2) + (K_t M_t)^2 \right\}} \quad (15)$$

where: d is the diameter of the shaft (m); S_s is the Allowable shear stress N/m^2 ; K_b is the combined shock and fatigue factor applied to bending moment; K_t is the combined shock and fatigue factor applied to torsional moment; M_b is the Bending moment (Nm); M_t is the Torsional moment (Nm).

3.8. Dryer

The dryer is the compartment designed to remove moisture from the sliced pulps with the aid of heating elements (Kashaninejad, Mortazavi, Safekordi & Tabil, 2007). It is powered by a DC 12 V, 0.07 A, 3.5 r.p.m. high-torque gear box electric motor and incorporated with two gears of the same diameter with velocity ratio 1:1. One gear is mounted on the main shaft of the electric motor, and the other gear is meshed with it and consists of shafts that transmit a low speed towards the dryer. These two shafts have on them sprockets at both the external and internal parts of the dryer, one sprocket on the external part of the shafts and two sprockets at the internal part of the shafts in the dryer. The mechanism of the sprockets is replicated at the upward part of the dryer.

The drying mechanism is by forced convection and conduction. The blower blows air into the drying chamber while the dryer tray conducts heat. The dryer has a carousel tray that accommodates the plantain pulps for proper drying as it rotates in the drying compartment. A temperature regulator or thermostat is also connected to the heating coil which is set to regulate the temperature in the chamber to a minimum of 60°C and a maximum of 70°C to prevent loss of nutrient and case hardening of the plantain pulps on the carousel trays. The reason for incorporating a blower is to achieve:

- (1) Proper circulation of heat in the dryer compartment.
- (2) Increase the rate of evaporation of moisture from the plantain pulps (Johnson, Brennan, & Addo-Yobo, 1998).

3.9. Determination of heat generation rate in the drying chamber

The heater has zinc coil with a rating of 1200 W, each heater is 4.8 m long with 0.5 cm diameter. Heat is generated uniformly in the coil. Assuming no loss in energy, a 1200-W heating coil will convert electrical energy into heat in the coil at a rating of 1200 W. Therefore, the rate of heat generation in the heating coil is equal to the power consumption of the coil heating element. Then the rate of heat generation in the coil per unit volume is determined by dividing the total rate of heat generated by the volume of the wire (Yunus, 2002).

$$\dot{g} = \frac{G}{V_{\text{coil}}} \quad (16)$$

where: \dot{g} is the rate of heat generated in dryer; G is the generated heat by the electric heating coil which is 1200 W V_{coil} (volume of the heating coil) = $\left(\frac{\pi D^2}{4}\right)L$; D is the diameter of the heating coil which is 5 mm; L is the total length of the heating coil used which is 4.8 m.

$$\dot{g} = \frac{G}{V_{\text{coil}}} = \frac{G}{\left(\frac{\pi D^2}{4}\right)L} = \frac{1200 \text{ W}}{\left[\frac{\pi(0.5 \text{ cm}^2)}{4}\right](480 \text{ cm})} = 12.7 \text{ W/cm}^3$$

3.10. Design for chains and sprockets

The chains are wrapped round the sprockets to transmit power such that the velocity ratio is 1, hence transmitting same speed at each shafts. This is because the sprockets used are of the same diameter and consist of the same number of teeth.

3.11. Determination of the average velocity and pitch of the chains

$$v = \frac{\pi D N}{60} = \frac{T p N}{60} \quad (17)$$

where: D is the Pitch circle diameter of the sprocket in metres which is 80 mm (0.08 m); N is the Speed of rotation of the sprocket in r.p.m. which is 3.5 r.p.m; T is the Number of teeth of the sprocket which is 31; p is the Pitch of the chain in metres.

\therefore The average velocity of the chain; $v = \frac{\pi \times 0.08 \times 3.5}{60} = 0.0147 \text{ m/s}$; and the pitch of chain;
 $p = \frac{60 \times v}{TN} = \frac{60 \times 0.0147}{31 \times 3.5} = 0.0081 \text{ m}$ (Khurmi & Gupta, 2005).

3.12. Determination of average time taken for each pulp to spend in the dryer

$$t = \frac{x}{v} \quad (18)$$

where: x is centre distance which is 500 mm (0.5 m) ; v is the average velocity of the chain which is 0.0147 m/s.

Hence, the average time spent by each pulp in the dryer; $t = \frac{0.5 \text{ m}}{0.0147 \text{ m/s}} = 34 \text{ s}$ (Khurmi & Gupta, 2005).

3.13. Determination of the length of each chain

$$L = K.p \quad (19)$$

$$K = \frac{T_1 + T_2}{2} + \frac{2x}{p} + \left[\frac{T_1 + T_2}{2\pi} \right]^2 \frac{p}{x} \quad (20)$$

where: K is the number chain links; P is the Pitch of the chain in metres.

Hence, $K = T + \frac{2x}{p}$ as the number of teeth in all sprockets are the same.

$$K = 31 + \frac{2 \times 0.5}{0.0081} = 155 \text{ links}$$

$$L = 155 \times 0.0081 = 1.26 \text{ m}$$

3.14. Determination of the number of trays on each chain connection

$$n_t = \frac{L}{l_t} \quad (21)$$

where: L is the Length of chain which is 1.26 m; l_t is the Distance between each tray which is 50 mm (0.05 m).

$$n_t = \frac{1.26}{0.05} = 25 \text{ plates}$$

Therefore, the total number of trays in the dryer is;

$$2 \times n_t = 2 \times 25 = 50 \text{ trays}$$

3.15. Design of spur gears

Two spur gears were used to transmit power from an electric motor to the twin rotating shafts that elevate the plates in the drying chamber.

Circular pitch:

$$p_c = \pi D / T \quad (22)$$

where: D is the Diameter of the pitch circle; T is the Number of teeth on the wheel.

Tangential tooth load:

$$W_T = \frac{P}{v} \times C_s \quad (23)$$

where: W_T is the Permissible tangential tooth load in newton; P is the Power transmitted in watts, v (Pitch line velocity in m/s) = $\frac{\pi DN}{60}$; D is the Pitch circle diameter in metres; N is the Speed in r.p.m; C_s is the safety factor. (1.25; for steady continuous work).

The speed ratio of the gears will be 1, as they both have the same pitch circle diameter and the same number of teeth.

3.16. Design for milling machine

The Milling machine is a hammer mill. It has hammer-like projection mounted on a shaft. The hammer revolves at high speed and beats the pulps to fine particles. The machine can mill only the dry pulps. It is incorporated with a detachable sieving mechanism to sieve the milled plantain pulp, consequently ensuring the fineness of plantain grain. The milling operation is powered with a one horsepower (1 h.p.) electric motor at the speed of 1,400 rev/min.

Determination of the hammer weight:

$$W_h = m_h g \quad (24)$$

where m_h is the total mass of all the beating hammer; g is the acceleration due to gravity taken as 9.81 m/s.

It can be seen that the action of the weight of hammer shaft on the main shaft is negligible.

Determination of the centrifugal force exerted by the hammer:

$$F_c = \frac{mv}{r} \quad (25)$$

The angular velocity of the hammer:

$$\omega = \frac{2\pi r N}{60} \quad (26)$$

Determination of the shaft diameter:

The diameter of the milling shaft was determined using the below empirical equation:

$$d^3 = \frac{16}{\pi S_s} \sqrt{\{(K_b M_b)^2 + (K_t M_t)^2\}} \quad (27)$$

where d is the diameter of the shaft (m); S_s is the Allowable shear stress N/m²; K_b is the combined shock and fatigue factor applied to bending moment; K_t is the combined shock and fatigue factor applied to torsional moment; M_b is the Bending moment (Nm); M_t is the Torsional moment (Nm).

The Volume of the Hopper of the Milling Machine is obtained:

$$V_{\text{hopper}} = V_{\text{whole pyramid}} - V_{\text{cutaway pyramid}} \quad (28)$$

$$V_{\text{hopper}} = \{0.5 \times L_{b1} \times L_{b2} \times H_p\} - \{0.5 \times L_{c1} \times L_{c2} \times H_c\} \quad (29)$$

where: L_{b1} is the length of the top shape of the hopper; L_{b2} is the breadth of the top shape of the hopper; L_{c1} is the length of the base shape of the hopper; L_{c2} is the breadth of the base shape of the hopper; H_p is the vertical height of the pyramid; H_c is the vertical height of the cutaway pyramid.

$$PFT = \frac{W_s}{W_t} \times 100 \quad (30)$$

where: PFT is the per cent finer than, otherwise known as percentage of flour retained on a sieve; W_s is the weight of flour retained on the sieve; W_t is the total weight of flour taken.

The cumulative per cent of plantain retained is obtained from Equation (31):

$$CPFT = (PFT_L + PTF) \quad (31)$$

where: PFT_L denotes the per cent on sieve size.

Another useful statistics in percentage analysis is percentage finer than the sieve under reference (PFTR). This is calculated as:

$$PFTR = 100\% - CPFT \quad (32)$$

The grain-size distribution curves are widely used in particle shape analysis. The values of the shape parameters, Coefficient of Uniformity and Coefficient of Curvature are obtained as:

$$C.O.U = \frac{D_{60}}{D_{10}} \quad (33)$$

For well-graded flour, C.O.C must lie between 1 and 3.

4. Performance test

SolidWorks CAD software was used to perform a linear stress analysis on the plant frame structure. The stress analysis was performed using finite element method in the CAD software. This helped to determine the permissible load which the plant frame can withstand at normal working condition, and to check if the design can be modified to increase the factor of safety. Load of 1,730 N was evenly distributed on the plant frame. Figure 4 shows forces acting normally on the plant frame while Table 3 shows physical properties of the plant frame material. The simulation results of the stress analysis are shown in Figures 5 and 6. The stress analysis for the trusses, beams and other members were carried out based on:

Figure 4. Diagram of forces acting normally on the plant frame.

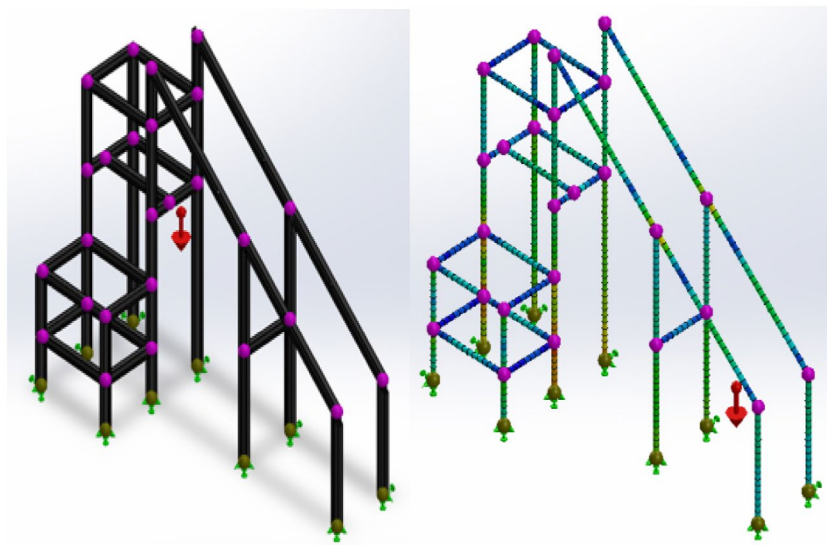
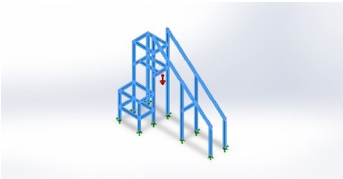


Table 3. Physical properties of the plant frame material

| Model reference | Properties |
|---|---|
|  | Name: Gray Cast Iron |
| | Model type: Linear Elastic Isotropic |
| | Default failure criterion: Mohr-Coulomb Stress |
| | Tensile strength: 1.51658e + 008 N/m ² |
| | Compressive strength: 5.72165e + 008 N/m ² |
| | Elastic modulus: 6.61781e + 010 N/m ² |
| | Poisson's ratio: 0.27 |
| | Mass density: 7200 kg/m ³ |
| | Shear modulus: 5e + 010 N/m ² |
| | Thermal expansion coefficient: 1.2e-005/Kelvin |
| | Yield Strength: 1000000000N/m ² |

- (1) The mass concentrated at the centre of gravity.
- (2) The beam simplified as a line segment (same cross section) with accurate representation of the frame complex geometry.

Since the design geometry is complex, the accuracy requirement is a lot higher, SolidWorks software was used to:

- (1) predict the performance and behaviour of the design, to calculate the safety margin and to identify the weakness of the design accurately;
- (2) determine the permissible load which the plant frame can withstand; and
- (3) identify the optimal design with confidence.

Figure 5. Simulation run showing the axial and bending stress.

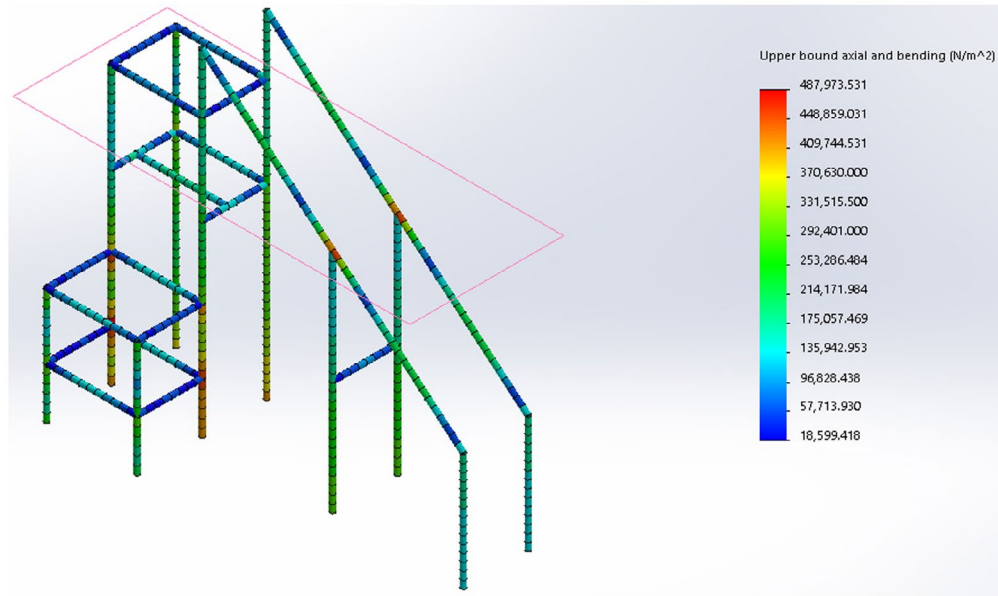


Figure 6. Resultant displacement of the plant frame.

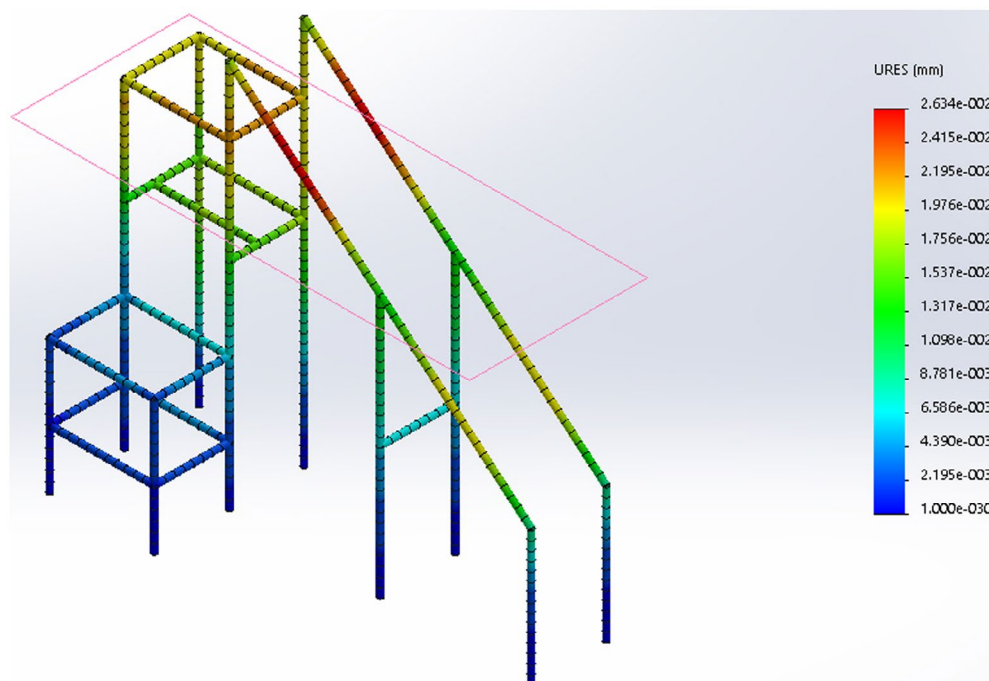
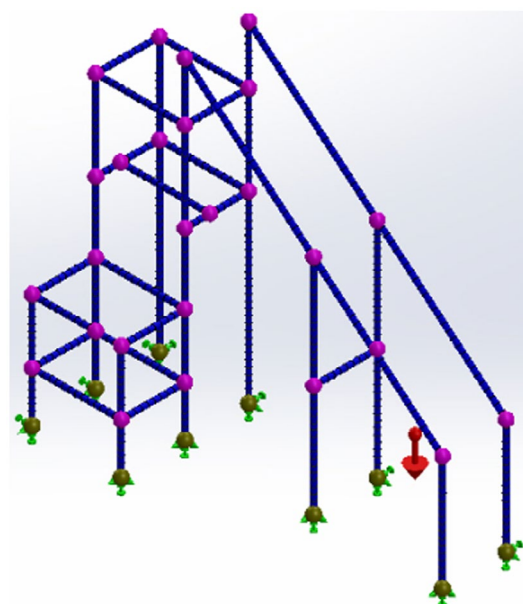


Figure 7. Factor of safety plot of the plant frame.



5. Discussions

The stress result is shown by default through the simulation stress analysis in Figure 5. The red portions on the plant frame indicate where stresses are maximal, while the portions with blue colour show where the stresses are minimal. The highest stress $487,974 \text{ N/m}^2$ is below the material yield strength ($1,000,000,000 \text{ N/m}^2$). The resultant displacement of the plant frame is indicated by Figure 6. The maximum displacement of 0.0263424 mm was obtained when the tensile load of $1,730 \text{ N}$ was applied on the plant frame. The red portions on the plant frame indicate where the displacement is high, while the portions with blue colour show where the displacement is low.

The factor of safety of the designed plant frame was estimated at every point of the frame, to check if the design is safe. It can be observed that the plot as shown in Figure 7 is free from the red colour indicating that all locations are safe. The results generated therefore portray that the design is safe under normal working conditions of the process plant.

6. Conclusions

The project was designed with materials sourced locally; the processing techniques used in the processing plant are similar to the indigenous techniques. The machine components of the plantain flour processing plant are assembled to permit ease of disassembly, maintenance and servicing. The plantain flour processing plant is functionally reliable for a reasonable period of time. It is cheap, and economically viable for medium-scale industries for plantain flour production. In the design of the plant, portability, reliability, hygiene, safety, serviceability, ergonomics, maintainability, and cost of construction were given due consideration. The processing plant minimizes human involvement and drudgery in the production of plantain flour.

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