



PERFORMANCE OPTIMIZATION OF A CASSAVA PELLETING MACHINE

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ABSTRACT

Cassava pelleting in most developing countries are usually done manually. This process is very laborious, time consuming and unhygienic. A pelleting machine has been recommended because of its low cost, high capacity of providing pelleted cassava as well as relative ease of operation and maintenance. The machine consists of a screw conveyor for conveying the cassava mash through the dies openings, electric motor, pulley drives and belts. A performance optimization of the system was carried out to maximize the solid product recovery, efficiency and throughput of the machine. The optimization results shows that the responses efficiency, throughput and power consumption of the machine were determined as 58%, 75.76kg/hr and 4106.36W respectively. Mathematical models were developed using dimensional analysis. The independent variables such as screw pitch, conveyor speed and bulk density were used to derive the dimensionless parameters used as input variables for the regression analysis. The dependent variables like the mass number, power number and the processing time number were measured and compared to computed values such as their standard errors, percentage errors and coefficient of determination.

Keywords: pellets, screw conveyor, mass number, power number, processing time number, density number

1. INTRODUCTION

Cassava serves as the major source of carbohydrate in West Africa. In Nigeria the crops can be processed into gari, lafum, fufu, cassava chips and pellets. The cassava roots are also used for livestock and fish feed. The cassava roots are exported in chips or pellet forms. Pelleting is an extrusion process which shapes a plastic or a dough-like material by forcing it through a restriction or die. Examples of pelleted materials include, rolling of noodles and pie crust dough, finger stuffing of chopped meat through animal horns into natural casings, pressing of soft foods through hand ricers to produce string-like particles, and cranking of hand powered meat grinders. Pelleting machines are used to produce pellets. Cassava pellet is an unfermented dried cassava product obtained by compressing raw cassava chips under appropriate processing conditions resulting in the formation of dried bulky product suitable for animal feed and ease of transportation and exportation. Pelleting of cassava decreases the volume of cassava to be transported or exported by 25%. This simplifies transport, handling and storage. It also produces uniform product which is less fragile for export than raw cassava chips. The first

food extruders were based on the use of piston and ram. In Italy, single-screw extruders were used in the mid-1930s for pasta products. They employed low shear, deep flight screws and operated at low speeds [3]. The resulting products were not fully cooked. Moist dough was compressed by turning screw and shaped by the orifice through which the dough was expelled. In addition, these single-screwed Pelleting machines were very expensive and produced low tonnage of pellets. Later simple inexpensive extruders were developed in the United States in the 1960s for on-the farm cooking of soybeans, cereals and cassava feeds. This low cost extruder design was quickly adapted in the mid-1970s for use in nutrition intervention projects in many less developed countries [2]. In early 1980 the machine was modified and it became more reliable and was widely used to process different foods and crudely texturized food, though numerous mechanical problems were experienced. The objectives of this study are; (1) to develop a mathematical model for analyzing the machine using dimensional analysis. (2) to conduct a performance optimization of the machine.

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2.0 MATERIALS AND METHODS

2.1 Machine Description and Evaluation of Parameters

A photograph of the test machine is shown in figure 1. In the housing a rotary supported screw conveyor is located. The cassava pelleting machine comprises of 3 main units. These include; the hopper, transmission and pelleting unit. The hopper is made of stainless material with its wall sloping at 62°. The transmission unit consists of a 30mm shaft carrying the screw conveyor and it is supported in bottom and top bearings. The screw conveyor has varying pitch. The pitch of the screw conveyor at the inlet (i.e. directly below the opening where the hopper is mounted) is larger to maximize transportation of feedstock as it enters the barrel, while at the middle end (i.e. kneading and final cooking zone) the pitch is decreased so as to increase the temperature for cooking the pellets and increase the pressure for uniform forming of pellets in the die or extrusion plate. The die is attached to the end of the barrel by a circular flange point weld in place by five bolts so that the plate can be changed with other plates having different holes diameter for producing different sizes of pellets and for maintenance and cleaning of the machine. There is a knife arrangement at the face of the die that can be adjusted to cut pellets of different lengths as they are coming out of the machine. The entire machine is mounted on a frame made of v-section (angle iron). The drive for the Pelleting machine is an electric motor of 4.125kW. The drive has a pulley which can hold two V- belts. The rotary motion of the drive is transferred from the pulley to the screw conveyor pulley. Vessels are used for collection of the products so that it can be utilized later.

2.2 Determination of Dry Matter and Moisture Content

Two grams of cassava mash each from twenty four different genotypes obtained from National Root Crops Research Institute Umudike were weighed into a separate crucible. They were heated for 24hrs in an oven at 100°C, dried to a constant weight and cooled for ten minutes in desiccators. Afterwards they were weighed and the values were recorded. If the weight of cassava mash is W_1 , weight of empty crucible is W_0 , then the weight of crucible plus oven dried sample is W_3 . The equation for calculating the percentage dry matter and moisture content are,

$$\% \text{ Dry matter} = \frac{W_3 - W_0}{W_1 - W_0} \times \frac{100}{1} \quad (1)$$

$$\% \text{ Moisture Content} = 100 - \% \text{ Dry matter content} \quad (2)$$

The dry matter content and moisture content were determined following the procedure of [1].



Figure 1: Photograph of the cassava pelleting machine.

2.3 Determination of the Input Variables

The starch content of the cassava genotypes was determined following the traditional method of starch extraction as described by [7]. 7kg of freshly harvested cassava roots were peeled, washed in water and grated. The grated mash was sieved through a screen and suspended in a 0.01m³ of water. This separates the fibrous and other coarse root material from the mash. The starch was allowed to settle for 4-6hrs before decanting. The supernatant was decanted and the thick sediment is the wet starch.

The starch was dried using a dryer at 60°C for 18hrs and packed. The values of screw pitch, helix angle, conveyor speed were selected to cover the expected operating range of the machine. To calculate the bulk density of the cassava mash, the following equation was used:

$$B_c = \frac{W_2 - W_1}{V} \left(\frac{\text{kg}}{\text{m}^3} \right) \quad (3)$$

where B_c is the bulk density of grated cassava mash in (kg/m³), W_2 is the weight of container + weight of sample in (kg), W_1 is the weight of container in (kg) and V is the volume of cylinder in (m³)

The process was repeated for about three times and the bulk density obtained. The cassava mash viscosity was measured using a cylindrical rotational viscometer which covers a temperature range from -30°C up to 150°C (-22°F up to +302°F). The instrument consists of the control unit Visco-Temp 30150 with a cooling unit and sensors for measurement in low and medium viscosity ranges.

2.4 Model Development using Dimensional Analysis

Buckingham Pi theorem [4, 5, 6] was used in this study to derive equations and expressing one variable in terms of its dependent variables. It is commonly used when the number of variables exceeds four. Its application results in the formation of dimensionless parameters called the Pi ratios. The three fundamental dimensions commonly used for systems in mechanics are used. The basic dimensions are mass M, length L, and time T. The number of dimensionless and independent quantities (Pi terms) required to fully express the relationship between the variables were determined as follows:

$$S = n - b \tag{4}$$

where, S is the number of Pi terms; n is the total number of variables and b is the number of basic dimensions. The pertinent variables that affect the Pelleting machine performances are nine variables, (Table 1) with their corresponding dimensions.

Helix angle, Dry matter content, Moisture content, and starch content are dimensionless parameters. Dry matter content and starch content are linearly related to each other. Thus one of them (Dry matter content) was selected as characteristics of the cassava mash used in the study. Therefore, the number of dimensional variables is n = 7, but since the basic dimensions are MLT = 3, then, number of dimensionless π- terms, S = n-b, S = 7-3=4

Hence, five Pi-terms say, π₁, π₂, π₃ and π₄ were generated. The repeating variables are B_G, B_K and B_D. The basic equations for each π ratio derived are as follows:

$$\pi_1 = \frac{M_o}{D^3 \rho} = \text{Dimensionless Mass Number} \tag{5}$$

$$\pi_2 = \frac{P_w}{D^5 C_s^3 \rho} = \text{Dimensionless power number} \tag{6}$$

$$\pi_3 = \frac{\mu}{D^2 C_s \rho} = \text{Dimensionless density number} \tag{7}$$

$$\pi_4 = t C_s = \text{Dimensionless time number} \tag{8}$$

In the dimensionless terms determination exercise, the two dimensionless terms; Helix angle (H_A), and Dry matter content (D_M) were excluded initially, but have to be added when the other dimensionless terms had been formed. They are represented as π₅ and π₆ respectively. The π-terms are formed based on the principle of dimensional homogeneity. The output π-terms are related to the input π-terms as follows:

$$Y = \theta(\pi_3, \pi_5, \pi_6) \tag{9}$$

where Y is any of the three (3) output or dependable variables π₃, π₅ and π₆

The constants a, b, c, and d are determined using the Minitab software.

Using a first order multivariate regression model, the output parameter is given as

$$Y_{(i)} = a_o + a_1 X_1 + a_2 X_2 + a_3 X_3 \tag{10}$$

where the coefficients a_i, i = 1, 2 ...3 are determined by multiple regression.

The variables are given by the equations below:

$$X_1 = \frac{\mu}{D^2 C_s \rho} \tag{11}$$

$$X_2 = H_A \tag{12}$$

$$X_3 = D_M \tag{13}$$

Similarly, the output variables Y_i are given by

$$Y_1 = \frac{M_o}{D^3 \rho} \tag{14}$$

$$Y_2 = \frac{P_w}{D^5 C_s^3 \rho} \tag{15}$$

$$Y_3 = t C_s \tag{16}$$

If R² > 0.80, R²_{pred.} > 0.80 and R²_{adj.} > 0.80, the first order model may be considered sufficient for correlating the experimental results. A second order multivariate regression model may also be contemplated in case of minor improvements in the regression. The utilization of the second order regression model will only be necessary if a first-order model does not produce satisfactory results. We note that, from equations (5) to (8), the π-parameters already contain among them, various powers of the independent experimental variables listed in Table 1.

Table 1: Variables used in the Study and their Dimensions and Units.

Variables	Type	Symbol	Unit	Dimensions	Number
Mass of pellets formed	Dynamic	M _o	Kg	M	A ₁
Processing time	Kinematic	t	S	T	A ₄
Power consumed	Dynamic	P _w	kgm ² /s ³	ML ² T ⁻³	A ₂
Screw pitch	Geometric	D	M	L	B _G
Conveyor speed	Kinematic	C _s	rad/s	T ⁻¹	B _k
Bulk density	Dynamic	ρ	Kg/m ³	ML ⁻³	B _D
Helix angle	=	H _A	radians	M ⁰ L ⁰ T ⁰	=
Dry matter content	=	D _M	%	M ⁰ L ⁰ T ⁰	=
Viscosity	Dynamic	μ	Kg/ms	ML ⁻¹ T ⁻¹	A ₃

Thus, a first-order regression model involving the dimensionless π -terms would first be investigated. The results of the first order regression gave the values of R^2 , predicted R^2 and adjusted R^2 to be 93.38%, 90.23%, 92.43% for mass number, 97.83%, 97.03%, 97.52% for power number and 89.64%, 86.19%, 88.16% for processing time number which are desirable.

The result did not show any evidence of lack of fit and was used to locate the optimum.

Cassava chips weighing 25kg, 30kg, 35kg, 40kg and 45kg each at different operational speed of 230, 240, 250, 260 and 270rpm was used for the experiment (25 runs). After each operation, the processing time was taken using a stop watch and the mass of the separated products weighed using a weighing balance. Their values were recorded for references. The power consumption of the motor during operation was measured using a clamp wattmeter. The individual test conditions and results of the experiment conducted are presented in Appendix A. The mathematical equation used for computing efficiency and throughput of the machine during the experiment are as follows [8];

$$E_c = \frac{M_o}{M_i} \times 100 \tag{17}$$

$$T_p = \frac{M_i}{t} \times 3600 \tag{18}$$

where: E_c is efficiency of machine in percentage (%),

T_p is machine throughput in kilogram per hour

(kg/hr), M_o is total mass of pellets recovered in kg, m_i is the mass of pre-conditioned cassava used in the experiment, t is the processing time in second and P_w is power consumed by the electric motor in watt.

2.5 Results and Discussions

The measured and predicted responses of the pelleting machine using the first-order are shown in Appendices A (Table A.1). The highest values for the measured mass number (M_n), processing time number (T_n), power consumption number (P_{wn}) (Appendix A, Table A.1) are 38.73, 0.034 and 519696 with its corresponding predictive values of 31.89, 0.032 and 498296 respectively. Their corresponding residuals analyses of 6.84161, 0.00204 and 21400, percentage (%) error values of 0.1766%, 0.06023% and 0.041% were obtained respectively. The compared residual analyses and percentage (%) errors of the responses at maximum values at both cases were close to negligible values. The predicted and measured values of the centrifuge responses were compared (Figure 2). Figure 2 was plotted using the measured and predicted values of the responses shown in Appendices A (Table A.1). There are positive linear relationships between the predicted and measured values of the responses respectively. A good agreement between measured and predicted values was found with high coefficient of determination (R^2).

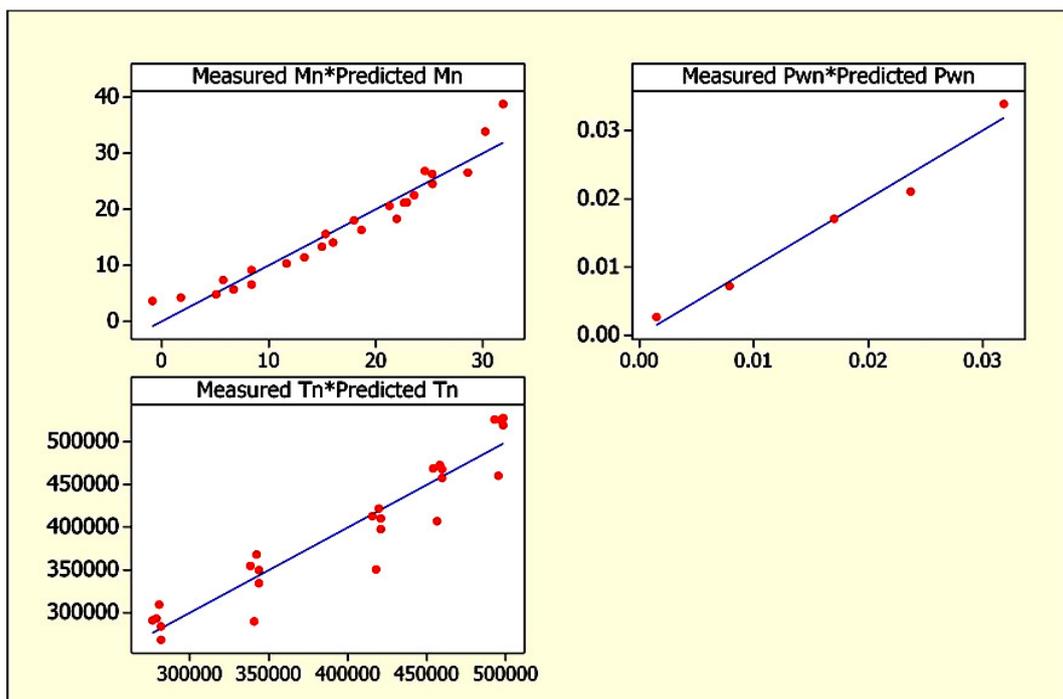


Figure 2: A plot of relationship between Measured and Predicted Mass number (M_n), Power number (P_{wn}), and Processing time number (T_n)

Hence, the empirical models developed (equations 11 – 16) are reasonably accurate since the results of the actual values of the responses are within 95% prediction interval. The 95% prediction interval is the range in which any individual value (predicted) is statistically expected to fall within. Therefore, the models developed were used to determine the optimal setting of the centrifuge performance parameters.

3. OPTIMIZATION OF THE DEVELOPED RESPONSE SURFACE MODELS

The models developed for the performance parameters of the Pelleting machine were optimized using Minitab optimization facility known as response optimizer. The facility provides you with an optimal solution for the input variable combinations and an optimization plot. The calculated dimensionless parameters such as helix angle, density number and dry matter content are coded as X₁, X₂ and X₃, respectively were used as the input variables for the regression. The minimum and maximum values of X₁, Y₁, Y₂ and Y₃ variables of the dimensionless parameters were obtained as follows;

$$X_{1min} = \frac{\mu_{min}}{D_{max}^2 C_{Smax} \rho_{max}} \tag{19}$$

$$X_{1max} = \frac{\mu_{max}}{D_{min}^2 C_{Smin} \rho_{min}} \tag{20}$$

$$Y_{1min} = \frac{M_{o_{min}}}{D_{max}^3 \rho_{max}} \tag{21}$$

$$Y_{1max} = \frac{M_{o_{max}}}{D_{min}^3 \rho_{min}} \tag{22}$$

$$Y_{2min} = \frac{P_{W_{min}}}{D_{max}^5 C_S^3 \rho_{max}} \tag{23}$$

$$Y_{2max} = \frac{P_{W_{max}}}{D_{min}^5 C_S^3 \rho_{min}} \tag{24}$$

$$Y_{3_{min}} = t_{min} C_{Smin} \tag{25}$$

$$Y_{3_{max}} = t_{max} C_{Smax} \tag{26}$$

3.1 Contour Plots

Contour plots are two dimensional and are useful for establishing operating conditions that produce desirable response values. The plot is used in combination with the optimization plot to find the best operating conditions for maximizing and minimizing the responses. The white regions on the plots are the feasible regions or areas that satisfy the criteria for all responses. In figure 3, the white region shows the range of x₁ (0.004 to 0.0125) and x₂ (0.0 to 60) where the criteria for both response variables are satisfied. The optimal settings for the responses are expected to fall within this area.

3.2 Optimization of the Machine Performance

In order to determine the optimal machine performance, constraints and the objective functions for the dependent variables are defined and the best values of input parameters are determined. The objective functions for the three dependent variables are;

1. Maximize Mass number (M_n)
2. Minimize Power number (P_{Wn})
3. Minimize processing time number (T_n)

Subject to the following constraints obtained from equations (19-26);

1. 6.04 ≤ Mass number ≤ 52.42
2. 0.0014 ≤ Power number ≤ 0.067
3. 228390 ≤ Processing time number ≤ 617544

The optimal results from the response optimizer are based on the developed models.

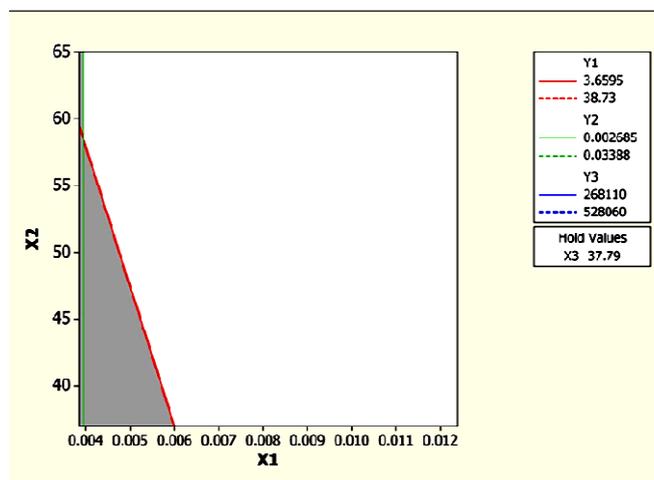


Figure 3: Contour plots of responses Y₁, Y₂ and Y₃

Table 2: Result of response optimizer for minimizing two responses and maximizing one response

Goal	Lower	Target	Upper	Weight	Import
Y1 Maximum	3	52	52	1	1
Y2 Minimum	0	0	0	1	1
Y3 Minimum	228390	118390	617544	1	1

Starting Point

X₁ = 0.0104

X₂ = 51

X₃ = 37.79

Global Solution

X₁ = 0.0123876

X₂ = 37

X₃ = 33.83

Predicted Responses

Y1 = 29, desirability = 0.518970
 Y2 = 0.03, desirability = 0.565673
 Y3 = 273220, desirability = 0.884801

Composite Desirability = 0.638045

The optimal values for mass number, power number and processing time number are 29, 0.03%, and 273220 respectively. The optimal values of efficiency, throughput and power consumed were calculated using equations (17), (18) and (15) respectively. The individual desirability and composited desirability fall within the acceptable range of 0 (zero if one or more product characteristics are unacceptable) to 1 (1 if all product characteristics are on target). The efficiency, throughput and power consumed were calculated using values in Appendix A (Table A.2) as reference values.

Equation 27 was used to calculate the optimal value of power consumed by the machine and it was derived by equating equations 14 and 15.

$$P_W = \frac{M_o Y_2 D^2 C_s^3}{Y_1} \quad (27)$$

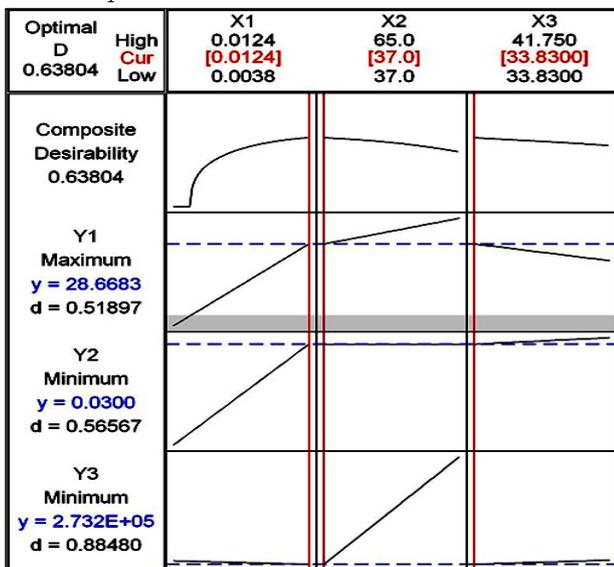


Figure 4: The result of response optimizer for minimizing two responses and maximizing one response

The optimal values of efficiency, throughput and power consumed are 58%, 75.76kg/hr and 4106.36W. The corresponding optimal values of the input parameters that gave these optimal responses are density number (0.0104), helix angle (37°) and dry matter content (33.83%).

The optimal size and the correct variable combinations have been successfully determined using the optimization tool of the RSM.

4. CONCLUSIONS

The study was conducted to obtain a statistically well-ordered data set to understand the main effects of key process parameters on the performance of the Pelleting machine. Critical to this investigation is to maximize the throughput, efficiency and minimize the power consumption. The models were simulated by systematically varying desired process parameters to study their main effects on the 3 process responses. The optimal result of the responses efficiency, throughput and power consumption of the machine were determined as 58%, 75.76kg/hr and 4106.36W.respectively.

5. REFERENCES

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6. APPENDIX A:

Table A.1: Verification of Measured and Predicted Responses of the Pelleting Machine (First-Order)

Measured M_n	Predicted M_n	Residual	% error	Measured P_{wn}	Predicted P_{wn}	Residual	% error	Measured T_n	Predicted T_n	Residual	% error
3.6595	-0.8682	4.5276	1.2372	0.00268	0.00147	0.00120	0.4493	309396	280425	28970	0.0936
4.2399	1.7709	2.4690	0.5823	0.00268	0.00147	0.00120	0.4493	368046	342270	25776	0.0700
4.7699	5.0699	-0.299	-0.062	0.00268	0.00147	0.00120	0.4493	421866	419575	2291.2	0.0054
5.6533	6.7194	-1.066	-0.188	0.00268	0.00147	0.00120	0.4493	473064	458227	14836.	0.0313
6.5871	8.3688	-1.781	-0.270	0.00268	0.00147	0.00120	0.4493	526056	496880	29176.	0.0554
7.3939	5.7246	1.6692	0.2257	0.00721	0.00787	-0.0006	-0.091	293472	278852	14620.	0.0498
9.1684	8.3638	0.8046	0.0877	0.00721	0.00787	-0.0006	-0.091	289584	340696	-51111	-0.176
10.3514	11.662	-1.311	-0.126	0.00721	0.00787	-0.0006	-0.091	350784	418001	-67217	-0.191
11.4359	13.312	-1.876	-0.164	0.00721	0.00787	-0.0006	-0.091	407232	456654	-49421	-0.121
13.3082	14.960	-1.652	-0.124	0.00721	0.00787	-0.0006	-0.091	460368	495306	-34938	-0.075
15.5729	15.324	0.2482	0.0159	0.01707	0.01702	0.00005	0.0029	291000	276406	14594	0.0501
18.0462	17.963	0.0824	0.0045	0.01707	0.01702	0.00005	0.0029	354750	338250	16500.	0.0465
20.6112	21.262	-0.651	-0.031	0.01707	0.0170	0.00005	0.0029	413250	415555	-2305	-0.005
21.2524	22.91	-1.659	-0.078	0.01707	0.01702	0.00005	0.0029	468900	454208	14692	0.0313
26.8404	24.561	2.2786	0.0849	0.01707	0.01702	0.00005	0.0029	526500	492860	33639.	0.0638
14.0883	16.000	-1.912	-0.135	0.02104	0.02368	-0.0026	-0.125	284076	281842	2234.1	0.0078
16.2912	18.640	-2.348	-0.144	0.02104	0.02368	-0.0026	-0.125	349908	343686	6221.9	0.0177
18.2892	21.938	-3.649	-0.199	0.02104	0.02368	-0.0026	-0.125	410436	420991	-10555	-0.025
22.5413	23.588	-1.047	-0.046	0.02104	0.02368	-0.0026	-0.125	468312	459644	8668.1	0.0185
26.2811	25.237	1.0432	0.0397	0.02104	0.02368	-0.0026	-0.125	528060	498296	29763.	0.0563
21.1681	22.654	-1.486	-0.070	0.03388	0.03183	0.00204	0.0602	268110	281841	-13731	-0.051
24.5089	25.293	-0.784	-0.032	0.03388	0.03184	0.00204	0.0602	334692	343685	-8993	-0.026
26.5513	28.59	-2.040	-0.076	0.03388	0.03184	0.00204	0.0602	397872	420991	-23118	-0.058
33.8456	30.241	3.6038	0.1064	0.03388	0.03184	0.00204	0.0602	457650	459643	-1993	-0.004
38.7328	31.891	6.8416	0.17664	0.03388	0.03184	0.00204	0.060	519696	498296	21400	0.041

where M_n = mass number, P_{wn} = power consumption number, T_n = processing time number

Table A.2: Reference Value used for calculating the optimal values of the responses

Reference Value	Values
Dry matter (%)	34
Starch content (%)	18.3
Bulk density (kg/m ³)	1174.02
Viscosity (kg/ms)	23.383
screw conveyor pitch (m)	0.15
Mass of pre-conditioned cassava M_i (kg)	25
Mass of Pellets formed M_o (kg)	14.50
Processing time t (sec)	1345.2
Speed (RPM)	230