An Easy Laboratory Method for Optimizing the Parameters for the Mechanical Densification Process: An Evaluation with an Extruder

G. Munoz-Hernandez[1], J. Domínguez-Dominguez[2] and O. Alvarado-Mancilla[3]

[1]CIATEQ, A.C. Research Division. Av. Retablo #150, Col. FOVISSSTE, Queretaro, Mexico. C. P. 76150. e-mail: guimuh@ciateq.mx

[2]CIMAT A.C. Dep. of Mathematics. Callejon de Jalisco s/n. Mineral de Valenciana.Guanajuato, Mexico. C. P. 36240. e-mail: jorge@cimat.mx

[3]I.T.Q. Dep. of Mechanical Engineering. Av. Tecnologico esq. Escobedo, Centro Historico. Queretaro, Mexico. C.P. 76000. e-mail: ricatti2001@yahoo.com.mx

ABSTRACT

Currently, Mexico and most developing countries have problems during dry seasons, due to shortage of forage which may cause economic losses to cattlemen. But, Mexico produces about 60 million tons of agricultural crop residues every year. An interesting use for these residues is to produce animal feed after harvesting as an efficient alternative to cattle feed. Some handling problems are associated with the low density of these materials, such as storage and transportation. In order to solve these problems, the densification process is proposed as a solution. However, before selecting or designing any commercial machine, it is necessary to know the mechanical behavior of the material and the processing conditions. The main objective of this work is to present an easy laboratory method to find optimal conditions of the densification process for producing animal feed.

The studied material was a sheep feed, which consisted mainly of alfalfa hay and corn crop residues. An open-end die was used to simulate the extrusion process. A Box Behnken design was run in the laboratory to find the best levels of the factors (moisture content, temperature and die length) on the responses (extrusion pressure, pellet density, and specific energy consumption). Afterwards, three runs were developed in the laboratory to confirm the optimum results. Also, same levels of the factors were used on real scale single-screw extruder to confirm the laboratory results.

Keywords: Densification, animal feed, crop residues, optimization, open end die, pellet, extrusion

G. Munoz-Hernandez, J. Dominguez-Dominguez, and O. Alvarado-Mancilla. "An Easy Laboratory Method for Optimizing the Parameters for the Mechanical Densification Process: An Evaluation with an Extruder". Agricultural Engineering International: the CIGR Ejournal. Manuscript PM 06 015. Vol. VIII. July, 2006.

1. INTRODUCTION

Biomass densification means the use of some form of mechanical pressure to reduce the volume of vegetable matter and the conversion of this material to a solid form, which is easier to handle and store than the original material (Erickson and Prior, 1990).

Mexico produces a lot of agricultural crop residues and by-products. For instance, the production of corn crop residues reached more than 44 million tons when considering just the harvest from 1994 to 1995 (Ponce, 1997). Other residues like those of sugarcane, sorghum, wheat straw and beans exist in smaller amounts. This kind of materials is very useful to reduce the problem of forage shortages in the dry season in most of the cattle-raising regions. Some by-products like soybean paste, corn gluten and poultry manure, have enormous potential as animal feed by mixing in a balanced way with crop residues. However, this potential depends on good handling procedures in order to avoid environmental or sanitary problems (Gomez, 1997). Also, molasses produced in the Mexican sugar mills is another ingredient with a great possibility for use in cattle feed. Nevertheless, the lack of options and established markets, the low density in natural state and the low nutrient content, lead to inefficient use of these materials.

Densification process is not a new idea. There are at least four methods of achieving densification using commercial machines: baling, cubing, pelleting, and briquetting, by means of piston presses, extrusion screws or by roll presses. The roll press has been used mainly for metallic and mineral dust compaction. Briquetting by means of piston presses and screw extruders has been used in preparing solid fuel materials. Cubing, pelleting and baling have been frequently used for animal feeds. One of the requirements to design, construct or improve designs in densification systems is based mainly of the knowledge on suitable levels of process variables (die geometry, relaxation time, die and material temperature and pressure) and of material variables (content and distribution of moisture, size and shape of particles, size distribution of particles, biochemical and mechanical characteristics) (Rehkugler and Buchele, 1969). These variables can then be adjusted to achieve the highest density, the largest output, the best consistency (density) and the lowest power consumption. In summary, an optimization process is required to obtain the greatest benefit with minimum costs of processing. Such information may even result in the proposal of new designs.

1.1 Background

Bhattacharya (1989) compared densification in hot and high-pressure conditions and densification in cold and low-pressure conditions in terms of quality of the product, and power consumption. Lodos and Cordoves (1987) concluded that the pelleting process still required more research aimed at trying to diminish the investment, reduce the power consumption and increase the productivity and density. Steverson et al. (1985) showed the necessity of experimental research in making densified fuels derived from trash and that the use of binders was not always economic. Tabil et al. (1997) and Steverson et al. (1985) mentioned that there is a little scientific information related to the effectiveness of binders.

The mechanics of agricultural materials currently is being developed and so far there are many process-material interactions that do not have exact methods of representation (Sitkey, 1986). Faborode and O'Callaghan (1987) modeled the extrusion of fibrous agricultural residues by using an exponential equation. The pressure was modeled as a function of the geometry of the die. With a different approach, using only plasticity and viscoelastic material models, Munoz-Hernandez (2002) modeled the extrusion of corn crop residues in order to find the stress in the extrusion die and pressure in the material. Nevertheless, there are factors such as moisture content, temperature, size of particles and binder content, which affect the extrusion. It is difficult to include these factors in plasticity and viscoelastic models. But the experimental methods developed so far, can somehow be used successfully to select, design and optimize machines (Sitkey, 1986). In this manner, some researchers have used mechanical elements of commercial machines as experimental prototypes, for example, Schwanghart et al. (1969) cited by Sitkey (1986), obtained pressure distributions in an experimental prototype for pellets of forage flour based on the space between the die and the ring of the pelleting machine. In this study, efficiency curves relative to the thickness of the layer of feed material were determined. In addition, it was found that the pelletization capacity was greatest, when the ratio of the radius of the press roller r, to the radius of the die ring R, was in the range from 0.3 to 0.4. Fridley and Burkhardt (1984) modified a round baler for the collection and handling of forest biomass. The equipment was instrumented to measure the temperature of formation and the power consumption. The densities obtained were in the range from 144 to 338 kg/m^3, with bale weights from 409 to 1516 kg. The maximum temperature registered was 60 ºC. The specific energy consumption was found in the range between 0.83 to 1.18 kWh/metric ton (2.99 to 4.25 J/g). Lindley and Vossoughy (1989) used a high-pressure briquetting machine in order to characterize the densification process of materials such as flax straw, wheat straw and sunflower stalks. They tested factors such as size of particles, moisture content, pressure in the machine, temperature of the die and feeding rate for the machine. Tadtiyanant et al. (1993) performed the extrusion of dead poultry and residues with a single screw extruder. The specifications were: orifice size, 9 mm; screw speed, 550 rpm; and feed rate, 819 kg/h. The internal temperature of the barrel ranged from 148 to 160 ºC at the point of extrusion. Tabil et al. (1997) investigated the influence of binders added in the pelleting of alfalfa. They determined the durability and the hardness of the pellets made using a small California Pellet Mill.

Other authors have utilized a different approach to simulate the densification process. Bellinger and McColly (1961) used a cylinder of closed die form to calculate the compression and ejection energy of pellets of dry alfalfa and reported the compression plus ejection energy range as 2.7 to 8.2 hp-h/ton (13.03 to 39.57 J/g). Chancellor (1962) designed an apparatus to carry out the densification of hay wafers by applying impact loads. The experiment show the impact load was not as efficient as static load. Bilansky et al. (1985) carried out their experiments in a cylindrical closed die. Chen et al. (1989) designed a laboratory pelletizer operated with an Universal Testing Machine for compression tests. This pelletizer was also designed to control temperature and pressure, Zohns and Jenkins (1986), Esaki et al. (1986), Faborode and O´Callaghan (1986) also have carried out experiments with closed dies in the laboratory. In the same way, O´Doguerty and Wheeler (1984) used a closed die for testing the bulk compression of wheat straw. An interesting open-end die was used by Payne et al. (1973). The open-end die was designed to control temperature of the die, retention time and moisture content of chicken excreta.

Some authors used commercial prototypes and others simulated the stages of the densification process by using presses with lab-scale dies. The test with prototypes on real scale would result in better end results for the study of a specific process. However, the cost of the prototypes and the treatments can be limitations in initial steps of investment projects. Whereas use of lab-scale presses and densification dies, the cost is reduced. Also, it is possible to design dies of general purpose so that it simulates or it reproduces the common stages of the densification process and provided the technical information such as production costs and the final conditions of the product. For example, in a laboratory, the die temperature, pressure, moisture content, size of particles, time of residence and the use of binders can be controlled with high precision. This methodology was used by the authors in an initial study of densification factors (Dominguez et al., 2002; Munoz et al., 2004). The use of closed-end die showed interesting advantages but open-end die offers an opportunity to simulate real extrusion by including friction on the die walls.

2. MATERIALS AND METHODS

The factors and response variables can be studied according to the objectives of the experiment and the magnitude of the effect associated with each factor. The factors can be selected by using screening designs as proposed by Montgomery (2000) and the previous study (Dominguez-Dominguez et al., 2002).

The main objective of this study was to find the levels of factors that provide optimum responses (quality of the product and minimum cost) in the densification process to form a pellet. The pelleted material was a balanced mixture of agricultural ingredients which included 25% alfalfa, 25% corn crop residues, 24% ground corn, 12% soybean paste, 12% molasses and 2% minerals, on a dry-weight basis. In this study three response variables were selected to represent the cost and quality characteristics of product: Y_1 (extrusion pressure), Y_2 (pellet density) and Y_3 (specific energy consumption). Y_1 and Y_3 have to be as low as possible.

The methodology to reach a multi-response optimization is presented below:

Step 1. Selection and control of factors: X_1: Moisture content, X_2: Temperature and X_3: Die length. Selecting the response variables and target values (for minimization of the responses Y_1 , Y_2 and Y_3).

Step 2. Execution of the experiment, by means of Box-Behnken design (Myers and Montgomery, 2002). This design consists on 15 treatments. The experiment is carried out randomizing each treatment and the three responses Y_1 , Y_2, and Y_3 are measured.

Step 3. The quadratic regression model for each response was:

$$Y_j = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum\sum_{i<j} \beta_{ij} X_i X_j + \varepsilon_j, \tag{1}$$

where X_i represents to each factor, β_0 is the constant, β are the linear parameters and β_{ij} $i, j = 1, 2, 3$ are parameters of second order, ε_j is the random error, which is assumed to be normally distributed with zero mean and constant variance σ_j^2, $j=1,2,3$. Estimation by method least square for individual response for Y_1, Y_2, and Y_3 ($j=1,2,3$) is:

$$Y_j = \hat{\beta}_0 + \sum_{i=1}^{3} \hat{\beta}_i X_i + \sum_{i=1}^{3} \hat{\beta}_{ii} X_i^2 + \sum\sum_{i<j} \hat{\beta}_{ij} X_i X_j.$$

Step 4. Definition of the optimization criterion based on the desirability function (DF). The minimum and maximum levels of responses have to be defined just by technical or economical constraints.

The simultaneous response optimization is approximated by the desirability function approach (DF), as proposed by Derringer and Suich (1980). In this method, each response is converted into an individual desirability function $d_i = h(\hat{Y}_i)$, where $d_i = 0$ if the response is in an unacceptable range; $d_i = 1$ if the response is at the optimum value; and $0 < d_i < 1$ other value. The desirability function for maximum response is given by:

$$d_2(x) = \begin{cases} 0 & \text{if} \quad \hat{y}_i(x) < y_{\min} \\ \left(\dfrac{\hat{y}_i(x) - y_{\min}}{y_{\max} - y_{\min}} \right)^r & \text{if} \quad y_{\min} \le \hat{y}_i(x) \le y_{\max} \\ 1 & \text{if} \quad \hat{y}_i(x) > y_{\max} \end{cases} \tag{2}$$

where $y_{\min}$ and $y_{\max}$ denotes the acceptable minimum and maximum levels of responses respectively. In equation (2), the exponent ***r*,** is used to determine the desirability function, controlling the response in the final optimal solution. The desirability function for minimum response is given by:

$$d_{j=1,3}(x) = \begin{cases} 1 & \text{if} \quad \hat{Y}_{j=1,3}(x) < Y_{\min} \\ \left(\dfrac{Y_{\max} - \hat{Y}_{j=1,3}(x)}{Y_{\max} - Y_{\min}} \right)^r & \text{if} \quad Y_{\min} \le \hat{Y}_{j=1,3}(x) \le Y_{\max} \\ 0 & \text{if} \quad \hat{Y}_{j=1,3}(x) > Y_{\max} \end{cases} \tag{3}$$

Then the optimum solution (X_i) is found such that it maximizes the geometric mean of the individual response desirability.

$$D = \left(\prod_{j=1}^{3} d_j \right)^{1/3} \tag{4}$$

If all the responses attain their ideal values, the desirability is 1 for *i=1,2* and *3;* therefore, *D* is 1.

Step 5. The optimization scheme is as follow:

$$\begin{aligned} &\text{Min } Y_3(X) \\ &\text{Subject to} \\ &\qquad Y_1(X) \le 75 \\ &\qquad Y_2(X) \ge 1100 \\ &\qquad X \in R, \quad R \text{ the experimental region,} \end{aligned}$$

where $R: (-1 \le X_1 \le 1,\ -1 \le X_2 \le 1 \text{ and } -1 \le X_3 \le 1)$. The previous procedure is applied to obtain the coding factors (**-1**, **0**, **1**), $x_k = \dfrac{2(X_k - \bar{X}_k)}{X_{\max} - X_{\min}}$, $k = 1, 2, 3$. The coding factors are presented in Table 1. Another option is to find the optimal response using graphical method (Dominguez and Rocha, 2005), which was used along with the desirability function to obtain the optimum solution. Table 1 shows the experimental regions of the factors.

Table 1. Factors and levels (real and coded) for the Box Behnken design.

Factors	Levels		
	-1	0	1
Moisture content (X_1)	8 %	11 %	14 %
Temperature (X_2)	70 °C	90 °C	110 °C
Die length (X_3)	12.7 mm (½ inch)	19.05 mm (¾ inch)	25.4 mm (1 inch)

The laboratory equipment included a hydraulic press (Figure 1), and an open-end die (Figure 2). This die offers a better way to reproduce the extrusion process than closed dies. The pellet was obtained by using a die hole of diameter 6.35 mm. Typical pelleting systems includes multiple extrusion holes arranged on a ring die. The laboratory die is trying to simulate the extrusion by using only one hole (6.35 mm) in real scale. So, similar conditions of extrusion process have to be reached in order to reproduce the extrusion process.

The hydraulic press was adapted with a data recording system for displacement, force and time. The response Y_3, specific energy consumption, is determined as the internal product of displacement and force. The force is determined by the product of the hydraulic cylinder area (Bore diameter of hydraulic cylinder was 152.4 mm) and the pressure of the hydraulic system. The velocity of the hydraulic cylinder was 1.7 mm/s. A certified Sensotek pressure transducer was used to measure the pressure with 0.25% of repeatability. Y_1 is the maximum pressure of the curve pressure-displacement. Extruded pellet density Y_2 was determined from the ratio of the mass to the volume of the sample 24 hours after the experiment. The mass was obtained using an analytic scale with accuracy of ±0.01 g. To calculate the volume, the dimensions were taken using a vernier caliper. In order to measure the responses a data acquisition system and a computer were used. Three signals were recorded (one for the pressure of the system by using a pressure transducer, a displacement sensor and the time). The displacement sensor was a MLO linear Festo potentiometer with +/- 0.07% maximum error of full scale (300mm).

Figure. 1. Hydraulic press

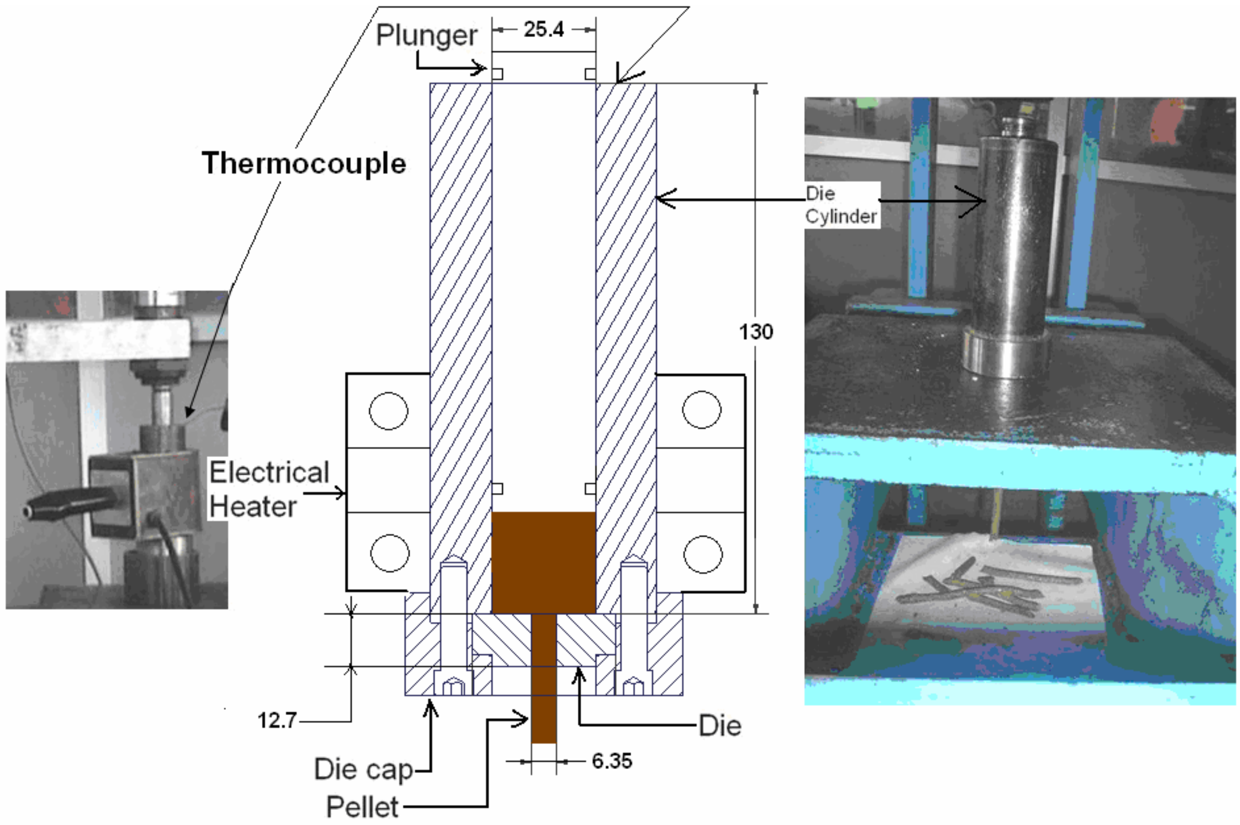

Figure 2. Densification open-end die (all dimensions in mm)

The moisture content (*X_1*) is a factor and was controlled during material preparation according Table 1. In order to determine the moisture content of the samples, the ASAE S358.2 standard was used (ASAE, 1998). An oven for drying with temperature sensitivity of ±2ºC in the range of 50 to 150ºC was used for the moisture content determination at wet basis (w.b.). The moisture content levels were obtained by adding water on the sample and leaving rest by 24 hours in close bag. The die temperature was controlled through use of an electrical heater fitted around the die. A type-K thermocouple was placed in a hole made in the die (Figure 2) and it was used to control the die temperature. After the die temperature was reached, ten minutes were allowed before the experimental run. The die length was the thickness of the die shown in figure 2. The different levels of die length were obtained by changing the die.

There are noisy factors which are kept as constant as possible for example velocity on the pellet (coming from the die) was constant about 27.2 mm/s, which was estimated from the press velocity after maximum compression of the material was reached. Typical velocities of the pellet in the extruder (real scale) were estimated from 5 mm/s to 70 mm/s. The size of particles of corn crop residues and alfalfa was not a factor and they were controlled to keep constant in the experiment. A 12.7 mm screen was used in a hammer mill. No binder was included in the feed.

3. RESULTS AND DISCUSSION

Table 2 displays the Box Behnken design and experimental results. The 15 treatments were randomized and each one was measured. The number inside the parenthesis is the treatment number.

Table 2: Factors, levels and responses: X_1: Moisture content, X_2: Temperature, X_3: Die length, Y_1: extrusion pressure, Y_2: pellet density and Y_3: specific energy consumption

Run	X_1 (%)	X_2 (°C)	X_3, mm (inches)	Y_1 (MPa)	Y_2 (kg/m^3)	Y_3 (J/g)
1 (14)	8	70	19.05 (¾)	181	1215.65	81.68
2 (4)	8	110	19.05 (¾)	78	1171.60	43.18
3 (7)	14	70	19.05 (¾)	107	1056.63	51.39
4 (10)	14	110	19.05 (¾)	42	1059.12	26.36
5 (5)	8	90	12.7 (½)	181	1173.59	81.54
6 (9)	8	90	25.4 (1)	106	1170.19	60.65
7 (13)	14	90	12.7 (½)	54	835.66	29.33
8 (6)	14	90	25.4 (1)	82	1024.80	43.29
9 (11)	11	70	12.7 (½)	125	922.27	57.45
10 (8)	11	70	25.4 (1)	142	1229.36	67.13
11 (1)	11	110	12.7 (½)	44	882.28	30.06
12 (2)	11	110	25.4 (1)	77	1222.90	44.13
13 (15)	11	90	19.05 (¾)	102	1180.00	47.98
14 (3)	11	90	19.05 (¾)	72	1102.57	41.48
15 (12)	11	90	19.05 (¾)	79	1094.49	46.00

The responses, Y_1 and Y_3, were found to be highly correlated. So, the optimization process included two responses: density Y_2 and specific energy consumption Y_3.

The least-squares method for fitting the model for the density, Y_2, resulted in:

$$\hat{Y}_2 = 1129.7 + 18.0X_1 + 161.9X_2 - 11.6X_3 + 48X_1X_3 - 68X_3^2 - 229.8X_1^2X_2 - 109.2X_1^2X_3$$

(R^2=0.95 CM_{error} =1726.3) (5)

For fitting the model for the energy consumption, Y_3 :

$$\hat{Y}_3 = 47.8 - 15.9X_1 + 5.9X_2 - 15X_3 + 8.7X_1X_3 - 17.7X_1^2X_2 - 15.2X_1X_3^2$$

(R^2=0.96, CM_{error} = 24.61) (6)

Both models are statistically significant (p<0.001), and no significant lack of fit was detected for either Y_2 or Y_3.

By applying the desirability function it was possible to attain the optimal solution. A better clarity of the optimum solution was obtained by using the graphical method. Minitab (2003) has a dynamic option of graphs to find a global optimal solution. Figure 3 displays one optimal solution. The solution is $X_{01} = (0.5, 1.0, 0)$ (Figure 3). The response Y_2 and Y_3 are evaluated in the optimum value, therefore the desirability function is one in both cases (Figure 3). Y_1 was not included in the graph because it is correlated with the response Y_2.

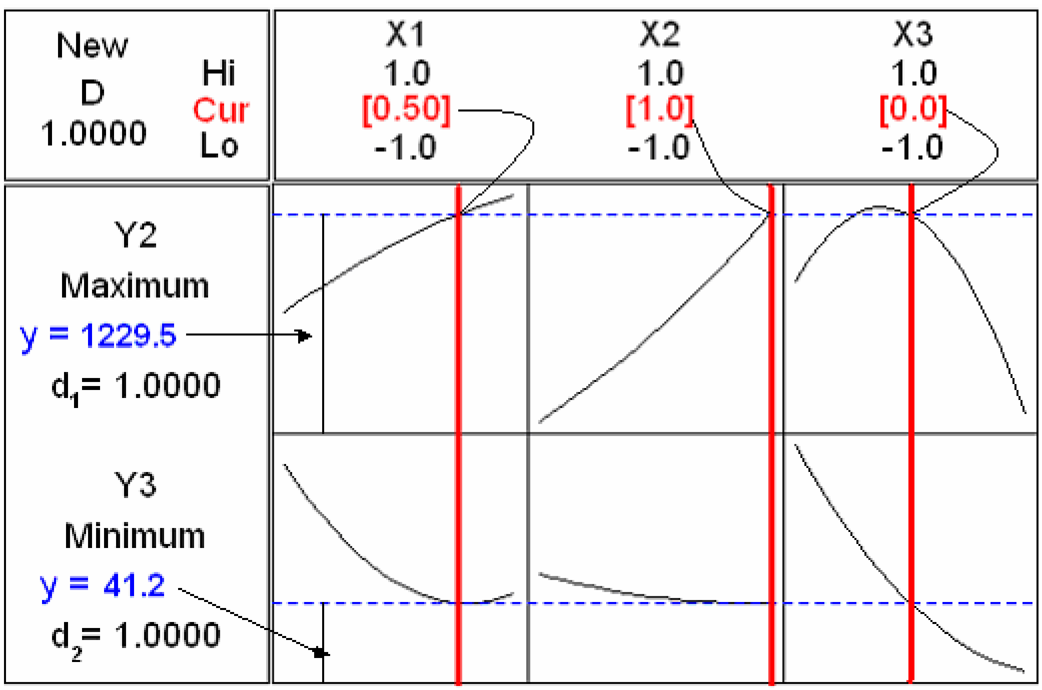

Figure 3. $X_1 = 0.5, X_2 = 1, X_3 = 0$ Optimal solution (indicated in horizontal axis), for the two responses $Y_2 = 1229.5, Y_3 = 41.2$. The vertical axis displays the value 1 for desirability function d_1 and d_2.

The best densification process conditions would be selected such that the energy consumption is minimum because it helps to reduce the operation cost. If we move the thick vertical line to the right or left in Figure 3, the optimal process conditions change. This option of obtaining the optimum levels in a dynamic way allows generating a region of optimum solutions for each of the cases. The same optimal conditions are illustrated in contour plots (Figure 4). In particular, the solution given by the desirability function is marked with the symbol # in Figure 4. Figure 4 was developed using the design expert software (Design-Expert, 2000).

The shady region in Figure 4 represents a set of possible optimum solutions. This method has the advantage that multiple trade-off solutions can be found. Upon careful examination it can be seen that each trade-off solution corresponds to a specific order of importance of the objectives and operation costs. The point 3 characterize the solution in the central point of the experiment, that is to say $X_1 = 0, X_2 = 0, X_3 = 0$ and the corresponding responses in that point are: $Y_1 = 89.3$, $Y_2 = 1129.7$ and $Y_3 = 45.5$. This solution is not suitable for the process.

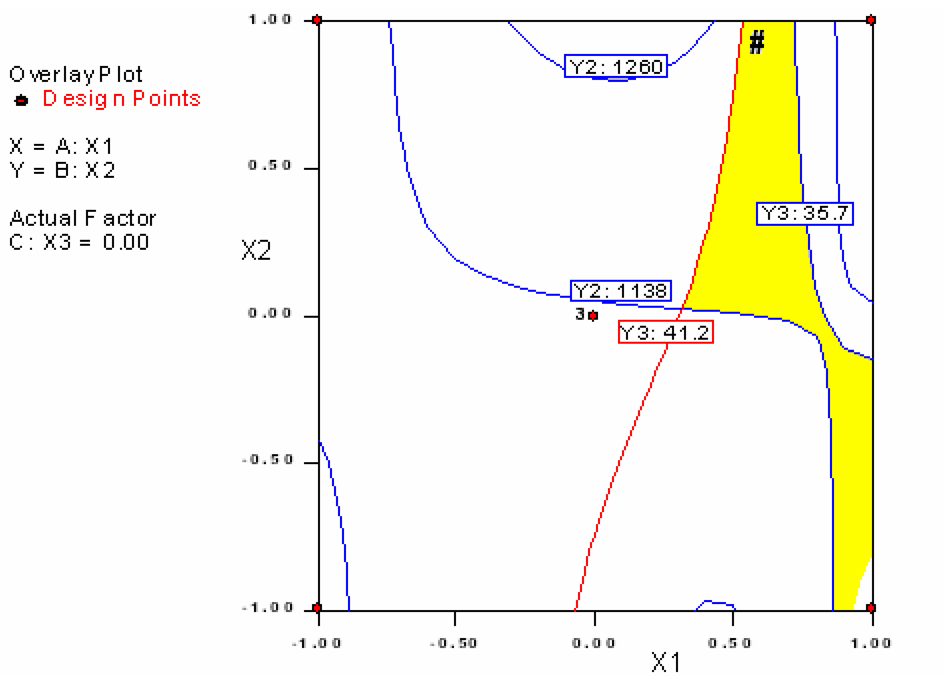

Figure 4. Contour plot superimposed for the variables Y_2 and Y_3, the shady area describes a set of possible solutions with $X_3 = 0$.

Two optimal solutions are reported in Table 3. In order to confirm optimization results, Table 4 shows three confirmation runs at the optimum conditions X_{01}. The confidence intervals are also presented and should contain the optimum solution. Table 5 shows the confirmation test at the optimal point X_{01} and the features of the pellet extruded from an extruder of local manufacture.

Table 3. Two optimal solutions from application of the DF method.

	Optimal	X_1	X_2	X_3	Y_1^*	Y_2	Y_3
Coded	X_{01}	0.50	1.0	0	80.3	1229.5	41.2
Real		12.5%	110^0C	$3/4$			
Coded	X_{02}	0.9	0.20	0	85.2	1138.8	35.7
Real		13.7%	94^0C	$3/4$			

* Obtained from the response models

Table.4. Results of confirmation tests of the optimum point, X_{01} = (0.5, 1, 0)

	Optimum results	test 1	test 2	test 3	Interval of Confidence (with $\alpha = 0.05$)
Extrusion pressure (MPa)	80.3	58	80	60	(38, 84)
Density (kg/m^3)	1229.5	1172	1190	1117	(1100,1207)
Specific energy consumption (J/g)	41.2	41.2	42.6	35.6	(30,46)

The main objective of this study was to obtain the best levels of the factors in order to reach the minimum power consumption (41.2 J/g) and the maximum pellet density (higher than 1100 kg/m^3). By using the optimum levels, densification in low-cost extruder (capacity of 550 kg/h, compression ratio of 8.3, tapered single-screw, and length of 0.712 m (28 inches)) was conducted (Figure 5). The extruder was locally manufactured and was designed to process mainly agricultural crop residues. The best levels of the factors were set in the extruder (die temperature of 110°C, moisture content of 12.5 % and, die length of ¾ inches). Pellet density were determined and compared with the laboratory results of confirmation (Table 5). Extrusion pressure and specific energy consumption were not determined in extruder because there were not instruments on the extruder. But shatter resistance (Lindley and Vossoughy, 1989) and final diameter of pellet were used for comparison (Table 5). Diameter of pellet was measured after 24 hours. Shatter resistance was measured as the percentage losses of the weight from shattering. Each pellet was subjected to 10 repeated drops from one meter height onto a concrete surface.

The percent weight loss of pellets was used to calculate the shatter resistance as one hundred minus the percent weight loss of pellets.

Figure 5. An extruder connected with rear power take-off of a tractor

Table.5. Confirmation of results from laboratory tests with field-scale extruder

	Optimum results	Laboratory confirmation test 1	Laboratory confirmation test 2	Laboratory confirmation test 3	Extruder
Extrusion pressure (MPa)	80.3	58	80	60	------
Density (kg/m^3)	1229.5	1172	1190	1117	1161
Specific energy consumption (J/g)	41.2	41.2	42.6	35.6	-----
Shatter resistance of pellet (%)		90.97	96.4	92.6	98.02
Final diameter of pellet (mm)		6.64	7.01	7.17	6.63

Figure 6 shows the picture of pellets produced from the extruder and the laboratory apparatus. The external surface of laboratory pellet is rough; the fibers are seen along the pellet. Extruder pellets show smooth surface. In the extruder the material is mixed and conveyed through the barrel and the die. Also, extruder may provide more friction on the material located on the external surface of the pellet.

Figure 6. Comparison of pellets from the full scale extruder and from the laboratory.

Similar studies with laboratory die were conducted by Payne et al. (1973). They studied the effects of different factors on the microbial analysis of chicken excreta extruded. However, they did not optimize the responses. Moisture content, temperature and pressure are factors studied in many experiments. O´Doguerty and Wheeler (1984) found about 15% of moisture content as optimum level in the compaction of wheat straw. Dominguez-Dominguez et al. (2002) found optimum responses on 11% of moisture content and 65 °C of die temperature for cattle feed with 62% of corn crop residues. Moisture content of 12.5% in the present study is in according with above levels.

Results from Reed, Trezek and Diaz (1980) showed that the specific power consumptions was decreased up to 50% by preheating the material from 100 °C to 225°C. But very high temperature could produce degradation on feed constituents. So, degradation of the feed nutriments has to be considered in future studies.

Die length is a factor with limited information in literature, but commercial information from California Pellet Mill (CPM), shows die length (die thickness) from 63.5 mm to 76.2 mm, for holes of 6.35 mm (1/4 inch) and light-bulk materials. Light-bulk materials are dairy feeds with low protein and low grain. It is about twice the value obtained in this work and no binder was used. More die length implies more specific power consumption (equation 6).

4. CONCLUSIONS

By applying the desirability function to least-squares adjusted regression models it is possible to build a scenario to optimize the densification process. The use of graphic techniques provides an option for finding multiple trade-off optimal solutions with a wide range of objective function values. Problems associated with this option are the high variability of the process and the decreases in precision.

Appearance of the laboratory pellet was different, but values for density, shatter resistance and final diameter for pellets from both laboratory and extruder were found to be within the same statistical range of confidence. It indicates that more materials can be easily tested in the laboratory for feasibility investigations of densification processes for agricultural materials, with confidence that the results will apply to real-scale operations.

5. ACKNOWLEDGEMENTS

Special acknowledgements for the valuable comments and suggestions provided by Dr. William J. Chancellor, at this and previous projects. Professor Emeritus. Biological & Agricultural Engineering Department. University of California, USA.

Dr. Guadalupe Bernal Santos by providing the balanced sheep feed. Escuela de Veterinaria y Zootecnia. Universidad Autonoma de Queretaro, Mexico.

6. REFERENCES

ASAE Standards S269.4. 1998. Cubes, Pellets and Crumbles-Definitions and Methods for Determining Density, Durability and Moisture Content. ASABE, 2950 Niles Rd., St. Joseph, MI 49085-9659, USA ph. 269-429-0300, fax 269-429-3852, hq@asae.org

ASAE Standard S358.2. 2003. Moisture Measurement-forages. ASABE, 2950 Niles Rd., St. Joseph, MI 49085-9659, USA ph. 269-429-0300, fax 269-429-3852, hq@asae.org

Bhattacharya, S.C. 1989. State of the Art of Biomass Densification. Division of Energy Technology. Energy Sources, N. Y., Taylor and Francis. 11 (3):161-186.

Bellinger, P. L. and McColly, H. 1961. Energy Requirements for Forming Hay Pellets. Agricultural Engineering. 42 (5,6):180-181.

Bilanski, W.K., Graham, V.A. and Hanusiak, J.A. 1985. Mechanics of Bulk Forage Deformation with Application to Wafering. Transactions of the ASAE. 28(3):697-702.

California Pellet Mill Company (CPM). Pelleting-Before and After the Die. P.O. Box 6806, San Francisco, CA 94101 U.S.A.

Chancellor, W.J. 1962. Formation of Hay Wafers with Impact Loads. Agricultural Engineering. 43 (3):pp136-138,139.

Chen, P., Haygreen, J.G. and Graham, M.A. 1989. An Evaluation of Wood/coal Pellets made in a Laboratory Pelletizer. Forest Products Journal. 39(7/8):53-58.

Derringer, G. and Suich, R. 1980. Simultaneous Optimization of Several Response Variables. J.Qual. Technol. 12(4):214-219.

Design-Expert, Stat Easy 2000. Version 6.0 Minneapolis, MN.

Domínguez-Domínguez, Jorge, González-Valadez, Miguel and Muñoz-Hernández, Guillermo. 2002. Una Estrategia para Optimizar el Proceso de Densificación Mecánica de Residuos Agrícolas y Agroindustriales. Agronciencia. Revista del Colegio de Posgraduados. Mexico. 36:593-604. ISSN 1405-3195

Dominguez D., J and Rocha M., R. M. 2005. Optimización multirrespuesta en procesos industriales: una propuesta gráfica. Memorias del XVIII Foro Nacional de Estadística. INEGI.

Erickson, S. and Prior, M. 1990. The Briquetting of Agricultural Wastes for Fuel. FAO Environment and energy paper 11. FAO, Via delle Terme di Caracalla, 00100 Rome, Italy.

Esaki, H., Satake, T. and Guo, K. 1986. Research on the Pelletization of Biomass (Part II). Compressive Characteristics on the Forming of the Pellet and Wafer. Journal of the Japanese Society of Agricultural Machinery. 48(1):83-90.

Faborode, M.O. and O´Callaghan, J.R. 1986. Optimizing the Compression/Briquetting of Fibrous Agricultural Materials. Journal of Agricultural Engineering Research. London Academic Press. 38(4):245-262.

Faborode, M.O. and O´Callaghan, J.R. 1987. Theoretical Analysis of the Compression briquetting of Fibrous Agricultural Materials. Journal of Agricultural Engineering Research. London Academic Press. 35(3):175-191.

Fridley, J.L. and Burkhardt, T.H. 1984. Densifying Forest Biomass into Large Round Bales. Transactions of the ASAE. Paper No. 81-1599. pp. 1277 – 1281.

Gómez, J.G. 1997. Subutilizados los Productos Agrícolas e Industriales. Revista: Carne y Leche. Septiembre-Octubre. México. pp. 11-12.

Lindley, J.A. and Vossoughy, M. 1989. Physical Properties of Biomass Briquettes. Transactions of the ASAE. 32(2):361-366.

Lodos, J. and Cordoves, M. 1987. La Caña de Azúcar: fuente de Combustible Almacenable y Electricidad, Uso alternativo de la caña de azúcar para energía y alimento. Colección GEPLACEA. Serie: Diversificación. México D.F. 195-213.

Minitab. 2003. Release 14 for Windows, by Minitab Inc. USA.

Montgomery, Douglas. 1997. Design and Analysis of Experiments. Fourth Edition, John Wiley & Sons, N.Y. USA.

Munoz-Hernandez, G. 2002. Modelación Mecánica de Materiales Agrícolas Fibrosos con Aplicación al Proceso de Densificación (Application of Mechanical Modeling of Fibrous Crop Residues on Densification Process). Ph. D. diss., Especialidad de Diseño Mecánico del Postgrado Interinstitucional en Ciencia y Tecnología (PICYT). Available at the library of CIDESI, http://www.cidesi.edu.mx/.

Munoz-Hernandez, G., Gonzalez V., M. and Domínguez D., J. 2004. An Easy Way to Determine the Working Parameters of the Mechanical Densification Process. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Manuscript FP 03 013. Vol. VI. August, 2004.

Myers, R. and Montgomery, D.C. 2002. Response Surface Methodology: Process and Product Optimization Using Designed Experiments, Wiley Series in Probability and Statistics. New York.

O´Doguerty, M.J. and Wheeler, J.A. 1984. Compression of Straw to High Densities in Closed Cylindrical Dies. The British Society for Research in Agricultural Engineering. UK. 29(29):61-72.

Payne, F. A., Ross, I. J., Hamilton, H. E. and Fox, J.D. 1973. Short Time, High Temperature Extrusion of Chicken Excreta. Transactions of the ASAE. Paper No. 72 – 450.

Ponce Román, 1997. Simposium Internacional de los Subproductos para la Alimentación Animal. Carne y Leche. Pp 11-12

Reed, T.B., G. Trezek, and L. Diaz. 1980. Biomass Densification Energy Requirements. In Thermal Conversion of Solid Wastes and Biomass, 189 – 177. Washington, D. C.: American Chemical Society.

Rehkugler, G.E. and Buchele, W. F. 1969. Biomechanics of Forage Wafering. Transactions of the ASAE. 12(1):1-8,12.

Schwanghart H. Messung und Berechnung von Druckverhaltnissen und Durchsatz in einer Ringkoller-Strangpresse. 1969. Aufbereit. Tech., 10 (1969) pp.713-722

Sitkey, G. 1986. Mechanics of Agricultural Materials. Budapest, Elsevier Science Publishers. Pp: 420- 438.

Steverson, E.M. Semler, T.T. and Goldsberry, J.A. 1985. An Evaluation of Densification Technologies. 1EG&G Idaho, Inc. Prepared by U.S. Department of Energy Washington, D.C. 20555. Under DOE Contract No. DE-AC07-76IDO1570. DE86 002326

Tabil, L.G., Sokhansanj, S. and Tyler, R.T. 1997. Performance of Different Binders during Alfalfa Pelleting. Canadian Agricultural Engineering. 39: 17-23.

Tadtiyanant, C., Lyons, J. J. and Vandepopulibre, J. M. 1993. Extrusion Processing Used to Convert Dead Poultry, Feathers, Eggshells, Hatchery Waste and Mechanically Deboned Residue into Feedstuffs for Poultry. Department of Animal Sciences, University of Missouri, Columbia, Missouri 65211.

Zohns, M.A. and Jenkins, B.M. 1986. An Automatic Laboratory Apparatus for Densification of Particulate Materials. ASAE paper No. 86-6578. 1986 Winter Meeting of ASAE. ASAE, St. Joseph, MI.