An Easy Way to Determine the Working Parameters of the Mechanical Densification Process

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Abstract. Currently, México has problems related to dry seasons, which reduce the availability of forage and generate economic losses to cattlemen. But Mexico produces about 60 million tons of agricultural crop residues every year. A good alternative use for these residues is to produce cattle feed after the harvest season. Additional problems are associated with the low density of these materials, such as handling, storage and transportation. In order to solve these problems the densification process is proposed as a solution. Some current machines use the extrusion principle as a densification process. However, before selecting or designing these machines, it is necessary to know the mechanical behavior of the material and the processing conditions. Thus, the main objective of this work is to present an easy way to determine the optimal working parameters for the densification process for fibrous agricultural materials.

The material tested was feed for ruminants made up mainly of crop residues. The closed end die was used to simulate the densification process. Initially, a fractional factorial design, 2^{5-1}, was run to find the effects of the most important factors in this process on the response parameters of: density, durability and specific energy consumption. As a result of the statistical analysis, factor relaxation time was neglected because it was considered to be less significant. With the four remaining factors, a second order central composite experimental design was run to obtain the functions of the responses. Afterwards, an optimization method was used to coordinate the information represented by the response functions.

Keywords. Densification, Working parameters, Crop residues, Animal feed, Optimization, Closed End Die.

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, et al. 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. Others residues like those of sugarcane, sorghum, wheat and beans exist in smaller amounts. This kind of material is very useful to reduce the great problem of forage shortage in the dry season in most of the cattle-raising regions. Also, some by-products like soybean paste, corn gluten and poultry manure, have an enormous potential as animal feed, however, this potential depends on good handling procedures for avoiding any kind of environmental or sanitary problems (Gómez, 1997). In the same way, 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 these materials not being used efficiently.

In this way, mechanical densification is proposed to be a reliable solution for the beneficiation of materials of very low density by improving their transport, storage and use characteristics. The final use of such a process depends on technical evaluations and profitability evaluations. Despite, there being equipment in the market capable of carrying out the densification of bulk materials, it is necessary in a previous stage to know and/or determine the processing conditions and raw material conditions that lead either to a correct selection or design of machines for densification. Such information may even result in the proposal of new designs. In this sense, some authors point to the existing needs in the field of the mechanical densification.

The densification process however, is not new and 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 have been used in solid fuel. Cubing, pelleting and baling have been frequently used with feeds for animals. One of the requirements to design, construct and improve designs in densification systems, is based mainly on the knowledge of suitable levels of process variables (die geometry, relaxation time, die and material temperature and pressure) and 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 are adjusted to achieve the highest density, the biggest output, the best consistency (durability) and the lowest power consumption. In summary, process optimization is required to obtain the greatest benefit with minimum costs of processing.

Bhattacharya (1989) found that a detailed comparison between both densification in hot and high-pressure conditions and densification in cold and low-pressure conditions in terms of quality of the product, power consumption and financial aspects, did not exist. Lodos and Cordoves (1987) concluded that the pelleting process still required more research aimed at trying to diminish the investment price, diminish 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), agrees with Steverson et al. (1985), that there exists little scientific information related to the effectiveness of binders.

Background

Mechanics of agricultural materials, as a scientific discipline, presently is being developed and so far there are many process-material interactions that do not have exact methods of representation. Nevertheless, the experimental methods developed so far, can somehow be used successfully to select, design and optimize machines (Sitkey, 1986).

In this matter, some researchers have used mechanical elements of commercial machines as experimental prototypes, for example, Schwanghart 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 fed material were determined. In addition, it was found that the pelletization capacity was greatest, when the ratio of the radii of the rollers, r/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 in the bales. The densities obtained were in the range from 144 to 338 kg/m^3, with weights from 409 to 1516 kg. The maximum temperature registered was of 60ºC. The specific energy consumption was found in the range between 0.83 to 1.18 kWh/ton (2.99 to 4.25 J/g). Lindley and Vossoughy (1989) used a high-pressure briquettor 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.

Tabil et al. (1997) investigated the influence of binders added in the pelleting of alfalfa. He determined the durability and the hardness of the pellets. For the experiment a California Pellet Mill was used.

Other authors have utilized dies to simulate the different densification processes. Bellinger and McColly (1961), used a cylinder of closed die form to calculate the compression and ejection energy of pellets of dry alfalfa, finding values from 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. Bilansky et al. (1985) carried out their experiments in a cylindrical closed die with a internal diameter of 76 mm. Chen, et.al. (1989), designed a laboratory pelletizer to work together with a Universal Testing Machine for compression tests. This apparatus was used to compact fine wood and coal residues. A pelletizer was designed with a control for temperature and pressure of the system. Zohns and Jenkins (1986), Esaki, et. al. (1986) and 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. The authors simulated the extrusion of corn crop residues in order to find the reached pressure in the extrusion die and save time during the design process. Plasticity and viscoelastic materials models were tested (Munoz-Hernandez, 2002).

Some authors have worked experimentally using commercial prototypes and others have simulated the stages of the processes by using presses with experimental dies for densification. The test with prototypes on a real scale surely is likely to produce more realistic results; nevertheless, the costs can constitute a problem in these kinds of projects. The costs include instrumentation of the systems (sometimes this is not possible on commercial equipment) and includes the large quantities of raw materials. For example cubing systems typically use 2000 kg as minimum amount of material for only one treatment. Thus, experimental tests by means of presses and laboratory dies for densification offer an easy and less expensive way to make experimental tests under controlled conditions. Laboratory equipment can simulate the common stages of the densification process and thus, obtain the technical information needed for economic and technical decisions. For example in a closed-end die the 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 using 6 factors (Domínguez et. al., 2002). The statistical analysis included the homogeneity of variance due to dispersion effects.

Materials and methods

The main objective of this work was to find the levels of factors that provide optimum responses (quality of the product and cost) in the densification of a cattle feed diet based on corn crop residues (62%).

This experimental study was made prior to the design of an extruder to process feed for ruminants. Firstly a literature review was made, and it showed which factors (independent variables) affected the densification process of many kinds of biomass. The factors and their range of feasible experimental levels for the densification of corn-residue-based material are X_1: Moisture content (8% to 20%), X_2: Temperature (80^{o}C to 100^{o}C), X_3: Pressure (20 MPa to 90 MPa), X_4: Size of particles (3/16 to ¾ inches, which are the diameter of the screen holes of the hammer mill) and X_5: Relaxation time (0s to 20s). In previous experimental tests, we found that the factor of relaxation time was not significant. Thus, in the optimization experiment this factor was controlled at a constant level. The responses (dependent variables) defined according to the application were density and durability, as those variables represent quality of product, and specific energy consumption as a cost parameter. Durability is a feature of a densified product, which represents the handling characteristics. In order to be considered as a suitable feed for livestock, the pellets ought to have a density ranging from 640 to 800 kg/m^3 (Bruhn, 1957), and a minimum durability of 90% to assure good handling (Macarthur, 1981). The material studied was a feed for maintenance of ruminants. It consisted of 62% corn crop residues, 15% poultry manure, 8% alfalfa, 8% molasses, 6% soybean paste and 1% minerals, all on a dry-weight basis. In addition, most biological materials behave as viscoelastic materials, and the densification process can be separated into stages such as: compression, stress relaxation and expansion (or recovering). The equipment required was a press (Figure. 1) and densification die (Figure. 2). The press was instrumented with a system for recording displacement, force and time. The dies could be designed according to the factors and the application.

Figure. 1. Press and hydraulic unit

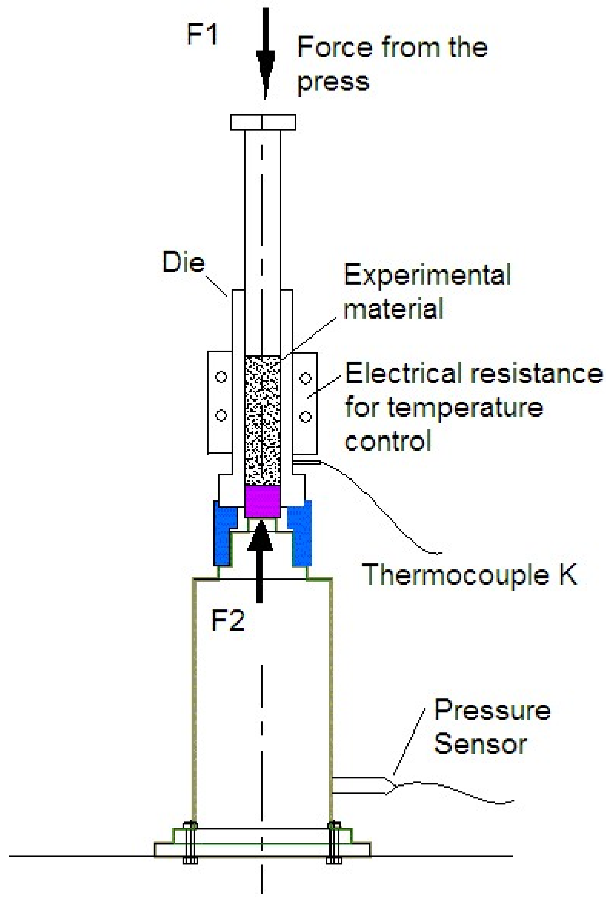


Figure 2. Densification die

The size of particles and the moisture content were controlled during material preparation. The crop residues were chopped in a hammer mill by using screen diameters of 4.8 mm (3/16 inches) to 19 mm (¾ inches), with which three levels of particle size were obtained. In order to determine the moisture content of the samples the ASAE S358.2 standard was used (ASAE, 1998). An oven for drying was used. It had temperature sensitivity and uniformity specifications better than ±2ºC, in the range of 50 to 150ºC. In order to control the pressure and the relaxation time, a data acquisition system and a computer were used. For this, three signals were obtained two pressure sensors (one for the total pressure F1 of the system and another to register the effective pressure F2, Figure 2) and one displacement sensor. This way we also obtained friction loses on the die wall. The relaxation time was a period of time measured after the maximum pressure was reached and the plunger was held in a fixed position. This period represented the residence time used in the cubing system. The temperature was controlled through use of an electrical resistance heater fitted around the die. A type-K thermocouple was placed in a hole made in the die (Figure 2) and used to control the die temperature. After the controlled die temperature had been maintained for five minutes, the experimental run was made. If an extrusion process was to be simulated, were the friction on the walls was to be included, a different die was used. Figure 3 shows an open-end die for extrusion of cornstarch. This may be a good option for a future project.

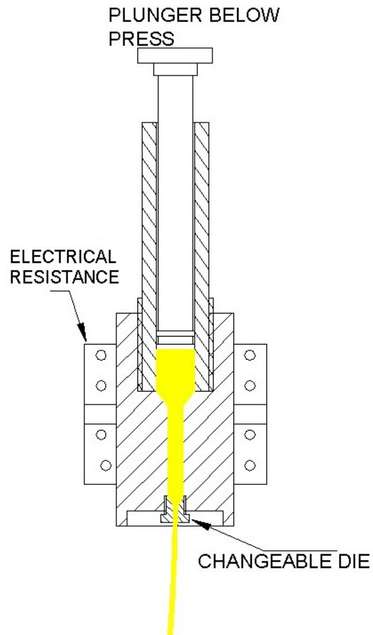


Figure 3. Temperature control

Briquette density was determined from the ratio of the mass to the volume of the briquette. The mass was obtained using a scale with an accuracy of 0.1 g. To calculate the volume, the dimensions were taken by means of a vernier caliper. In order to determine the durability the ASAE S269.4 standard was used (ASAE, 1998). It recommends a device, which rotated at 40 rpm for three minutes for tumbling. The specific energy consumption was calculated using data from both pressure and displacement signals. The area under the force-displacement curve was the energy consumption. This consumption divided by the mass of the sample yielded the specific energy consumption.

In order to find the best operating conditions the following sequence was used: the various levels of the factors were varied in order to minimize the specific energy consumption, while keeping the quality of the product (density and durability) within suitable levels. To attain this goal, an optimization procedure for multiple-response problems was used. This procedure uses the response surface methodology (RSM) and the desirability function. The RSM is popular in the study of the food-extrusion processes (Mercier and Harper, 1989).

RSM (Myers and Mongomery, 1995) is a collection of statistical techniques that are useful for modeling and analysis of processes. The objective was to find the relationships between the responses and factors by means of an experimental design, and to then optimize the responses. We carried out an experiment of second order using what is known as central composite design, which consists of three parts. The first part included sixteen points from a factorial design 2^4. The second included eight points, which are called star points. The last seven runs were located at the center of the design region.

In model analysis it is convenient and computationally efficient to transform factors X_k ($k=1,2,3,4$) to coded variables x_1, x_2, x_3 and x_4, which are dimensionless. Then the usual coding scheme is:

$$x_k = [X_k - X_{km}]/C_m ,$$

where X_k represents the k-factors, X_{km} is the center point design and C_m is a constant. For example, each factor in the experiment has five symmetrically spaced levels on the original scale, as $X_{km} - \alpha C_m,\ X_{km} - C_m,\ X_{km},\ X_{km} + C_m,\ X_{km} + \alpha C_m,\ \alpha > 1$. Applying the transformation above, the coding factors x has five levels: -2, -1, 0, 1 and 2. In Table 1 are shown the levels and factors for this experiment.

Table 1. Factors and levels (real and coded) in the central composite design.

Factor	Levels				
	-2	**-1**	**0**	**1**	**2**
X_1 Moisture content (%)	8	11	14	17	20
X_2 Temperature (ºC)	80	115	150	185	220
X_3 Pressure (MPa)	20	32.5	45	57.5	70
X_4 Size of Particle (in)	3/16	3/8	1/2	5/8	3/4

A regression model was established for each one of the three responses, so y_1: density, y_2: durability and y_3: specific energy consumption can be respectively fitted as a quadratic model as follows:

$$y_p = \beta_{p0} + \sum_{i=1}^{k} \beta_{ip} x_i + \sum_{i=1}^{k} \beta_{pi} x_i^2 + \sum_{i<j}^{k} \sum \beta_{\beta ijp} x_i x_j + \varepsilon_p ,$$

where $p=1,2,3$ (every model), $\beta_p^{'}s$ represent the unknown coefficient, ε_p denotes the random errors. The random errors are assumed to possess a normal distribution with mean 0 and variance σ^2.

Using the statistical method called regression analysis, the statistical analysis was carried out from the data collected. A diagnostic checking of the error residuals needed to be applied to check that the assumption of independence of the errors had not been violated.

The best regression model for each response y_p was fitted. With the estimated values of these models the desirability function (DF) was built. The DF was developed by Derringer and Suich (1980). However, any other multiresponse optimization technique can be used, just as is the case for linear programming. Solver, available within Microsoft Excel, can produce such an optimization. The DF approach is one of the most frequently used multiresponse optimization techniques in practice. The desirability values are in interval [0,1], if the value is equal to 1, this represents the highest degree of closeness of a response to its ideal value. Thus, the desirability will indicate in a global mode the best condition for the three responses.

The three models fitted were evaluated in each one of the combinations of the levels of the various factors. Therefore, there were three predicted values for each model, that is to say: $\hat{y}_1(x), \hat{y}_2(x), \hat{y}_3(x)$. Every $\hat{y}_i(x)$ was transformed to one value $d_i(x)$. The $d_i(x)$ fell in the interval [0,1], and it measured the degree of desirability that was required so that the best response value was obtained. In our case, a larger response was desired for the first two responses and a smaller response for the third. Then the transformations are:

$$d_{j=1,2}(x) = \begin{cases} \dfrac{\hat{y}_i(x) - y_{\min}}{y_{\text{nominal}} - y_{\min}} & \text{if} \quad y_{\min} \le \hat{y}_i(x) \le y_{\text{nominal}} \\ \dfrac{\hat{y}_i(x) - y_{\max}}{y_{\text{nominal}} - y_{\max}} & \text{if} \quad y_{\text{nominal}} \le \hat{y}_i(x) \le y_{\max} \\ 0 & \text{if} \quad y_{\min} < \hat{y}_i(x) \text{ or } \hat{y}_i(x) > y_{\max} \end{cases}$$

where y_{nominal} denotes the nominal value between the minimum and maximum, $y_{\min}$ and $y_{\max}$ denotes the acceptable minimum and maximum levels respectively.

$$d_3(x) = \begin{cases} 1 & \text{if} \quad \hat{y}_i(x) < y_{\min} \\ \dfrac{\hat{y}_i(x) - y_{\max}}{y_{\max} - y_{\min}} & \text{if} \quad y_{\min} \le \hat{y}_i(x) \le y_{\max} \\ 0 & \text{if} \quad \hat{y}_i(x) > y_{\max} \end{cases}$$

where $y_{\max}$ denotes the acceptable maximum levels, $y_{\min}$ represents the minimum value attainable. The total desirability is defined as a geometric mean of the individual desirability values:

$$D = (d_1 d_2 d_3)^{1/3},$$

Where D is the total desirability and d_i is any of the three desirability values. If all of the responses attain their ideal values, the desirability is 1 for $i=1,2$ and 3. Therefore, D is 1. An acceptable value for D can be between 0.7 and 0.9

The regression models obtained for y_1 density; y_2 durability and y_3 specific energy consumption were optimized according to restrictions in y_1: (650 < y_1 < 800 kg/m^3)), y_2: (90<y_2 <98%) and minimum in y_3. The whole process of computation was carried out with the program, Design-Expert (2000).

Results and Discussion

Table 2 displays the central composite design and experimental results. The number inside the parenthesis in the column one indicates the run order.

Table 2: Factors, levels and responses: x_1: Moisture content, x_2: Temperature, x_3: Pressure, x_4: Size of particles, y_1: density, y_2: durability and y_3: specific energy consumption

Run	x_1 (%)	x_2 (ºC)	x_3 (MPa)	x_4 (pulg)	y_1 (kg/m³)	y_2 (%)	y_3 (J/g)
1 (26)	14	150	45	½	630	91.2	9.85
2 (3)	11	185	32.5	3/8	629	91.5	7.69
3 (30)	14	150	45	½	602	94.1	9.45
4 (8)	17	185	57.5	3/8	534	88.3	7.26
5 (2)	17	115	32.5	3/8	567	92.9	5.92
6 (22)	14	150	70	½	595	89.1	11.31
7 (14)	17	115	57.5	5/8	483	82.1	10.22
8 (24)	14	150	45	¾	524	91.2	8.67
9 (11)	11	185	32.5	5/8	655	91.7	8.90
10 (12)	17	185	32.5	5/8	541	88.2	6.03
11 (10)	17	115	32.5	5/8	499	88.0	6.56
12 (18)	20	150	45	½	462	84.8	6.54
13 (13)	11	115	57.5	5/8	678	96.2	13.53
14 (31)	14	150	45	½	613	93.3	8.54
15 (19)	14	80	45	½	704	95.7	11.12
16 (16)	17	185	57.5	5/8	528	86.5	6.72
17 (17)	8	150	45	½	823	96.1	11.44
18 (29)	14	150	45	½	597	94.1	9.60
19 (1)	11	115	32.5	3/8	722	97.0	7.41
20 (9)	11	115	32.5	5/8	749	97.0	8.09
21 (27)	14	150	45	½	648	86.8	9.51
22 (7)	11	185	57.5	3/8	650	93.8	9.68
23 (4)	17	185	32.5	3/8	601	93.4	4.86
24 (20)	14	220	45	½	731	96.2	6.45
25 (6)	17	115	57.5	3/8	578	91.4	8.20
26 (21)	14	150	20	½	608	89.6	6.71
27 (25)	14	150	45	½	620	93.3	10.46
28 (5)	11	115	57.5	3/8	777	96.9	10.37
29 (23)	14	150	45	3/16	766	94.2	6.32
30 (15)	11	185	57.5	5/8	723	96.2	12.27
31 (28)	14	150	45	½	619	94.1	9.86

A full quadratic model was fitted using these factors. Regression analyses of these data are shown in Table 3. The columns two, three and fourth exhibit the estimated coefficients for the three responses respectively. Where (*) and (#) represent significance levels with $p<0.05$ and $p<0.01$ respectively.

Table 3. Estimated coefficients of the three regression models.

coefficients	y_1	y_2	y_3	Factor
$\hat{\beta}_0$	618.43	91.98	9.09	
$\hat{\beta}_1$	-82.25*	-3.00*	-1.33*	x_1
$\hat{\beta}_2$	-5.75	-0.45	-0.68*	x_2
$\hat{\beta}_3$	-1.58	-0.38	1.33*	x_3
$\hat{\beta}_4$	-28.58*	1.05*	0.65*	x_4
$\hat{\beta}_{22}$	19.43*	0.90*	-----	x_2^2
$\hat{\beta}_{33}$	-----	0.75#	-----	x_3^2
$\hat{\beta}_{44}$	-----	-----	-0.51*	x_4^2
$\hat{\beta}_{12}$	21.63#	0.99#	-----	x_1x_2
$\hat{\beta}_{13}$	-----	-1.26*	-----	x_1x_3
$\hat{\beta}_{14}$	-----	-1.44*	-----	x_1x_4
$\hat{\beta}_{23}$	-----	-----	-0.37#	x_2x_3
CM_{error}	1721.19	3.90	0.70	
R^2	0.825	0.819	0.874	

Thus, the optimization problem is to minimize the objective function y_3**,** which involves the following restrictions in the experimental region and responses:

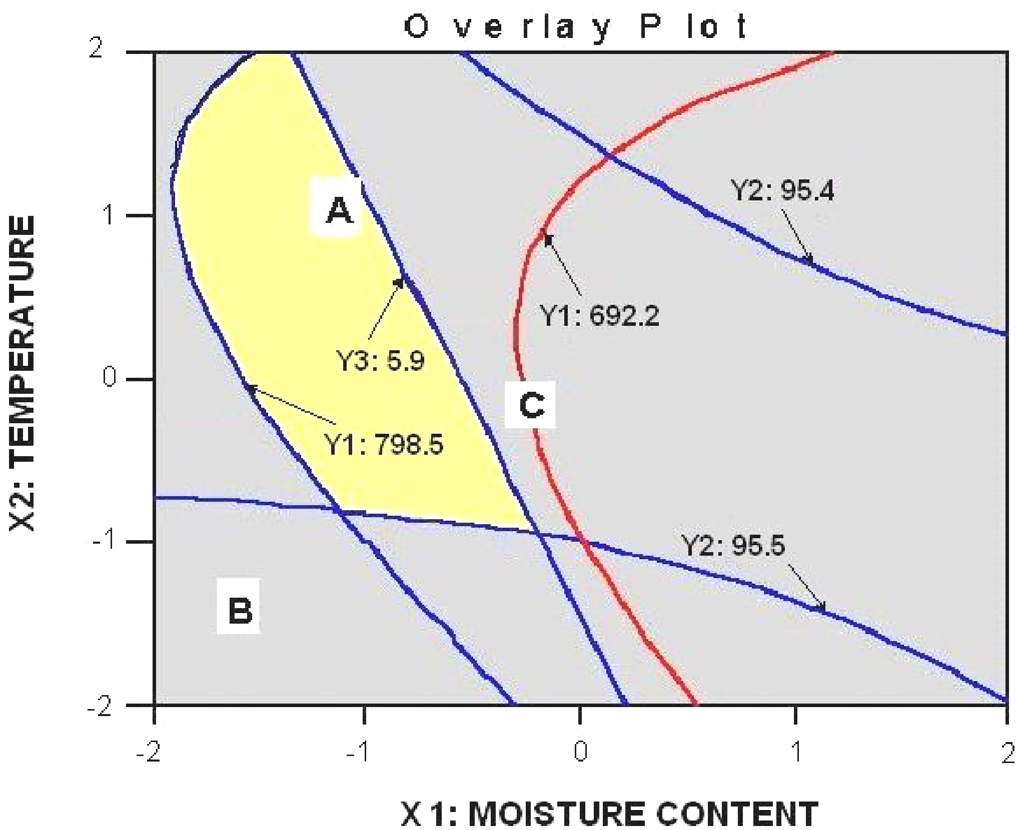
$$-2 \le x_1, x_2, x_3, x_4 \le 2,\ 650 \le y_1 \le 800 \text{ and } 90 \le y_2 \le 98.$$

Figure 4 shows the graphic solution of the optimization process, calculated by DF. This description is useful because it allows generating several possible optimum solutions for the process. These solutions are of interest to experimenters or users of the results.

In the graph the three responses are observed at the same time. To represent these, the values of the factor x_3 and x_4 were fixed at the coded levels –0.43 and –2 respectively. The levels of the factor x_1 and x_2 varied freely between -2 and 2. The curves (known as the contour plot) in the graph represent the optimum values of the responses for the whole experimental region of x_1 and x_2. For example, y_3 (y_3 =5.92) characterizes a minimum possible response for specific energy consumption, and this includes a region: $-0.9<x_1<0.4$, $-2<x_2<2$, $-x_3=-0.43$ and $x_4=-2$. The constraints for y_1 density and y_2 durability are satisfied.

This way, the region shadowed by the contour plot represents a feasible solution for the three responses. The point A (see Figure 4) describes this. However, the response, specific energy consumption (y_3), increases in the shaded area up to an approximate value of 7. The point B shows an optimum solution with little desirability relative to the three responses.

Finally, the point C represents other acceptable solutions, with the advantage that the response y_3 (specific energy consumption) has smaller values.



Y1= Density	
Y2 =Durability	
Y3 = Specific energy consumption	

Figure 4. Contour plot for the three responses.

The Table 4 represents the solutions of the points A, B and C corresponding to the Figure 4.

Table 4. Solutions represented in the Figure 4. *Approximate value from the Table 1

Point	x_1	x_2	x_3	x_4	y_1	y_2	y_3
A coded	-1.19	1.03	-0.43	-2.0	755.8	92.9	6.2
Real value*	10	186	40	3/16			
B coded	-1.56	-1.44	-0.43	-2.0	896.0	98.2	8.0
Real value*	9	100	40	3/16			
C coded	-0.27	-0.18	-0.43	-2.0	694.1	94.1	5.6
Real value*	13	144	40	1/16			

The values of the DF are shown in the Figure 5 and which correspond to the numeric solutions obtained with process optimization. The values near to 1 for the DF are the most desirable. This graph corresponds to the same experimental region that is represented by the data in Figure 4, that is: $-2.0<x_1$, $x_2<2.0$, $-x_3=-0.43$ and $x_4=-2$. Three solutions between several possible solutions are shown in the Table 5. Where the desirability function has values equal to, or very close to, 1.

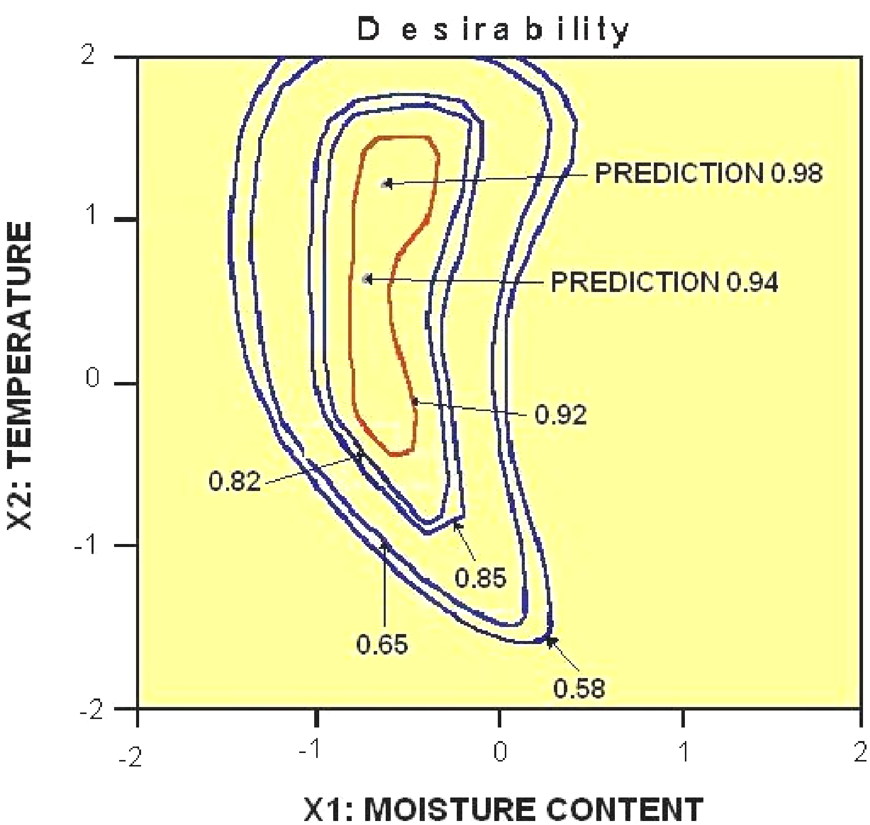


Figure 5. Each curve represents the total desirability D.

Table 5. Three solutions such that the constraints are satisfied. *Approximate value.

Solution	x_1	x_2	x_3	x_4	y_1	y_2	y_3	Desirability
1 coded	-0.59	1.29	-0.44	-1.93	725.0	94.0	5.46	1.000
Real value*	12	195	40	3/16				
2 coded	-0.34	-1.35	-1.35	-1.08	724.85	94.0	5.98	1.000
Real value*	13	103	28	3/8				
3 coded	-0.67	1.02	0.30	-2.00	725.0	94.1	6.25	0.986
Real value*	12	185	49	3/16				

With the desirability method used in this work, we can outline several scenarios. This allows selecting some favorable conditions for the process. For example, solution 2 indicates low levels for the four factors. In particular, the temperature and pressure levels ought to be as low as possible, while it would be advantageous for the size of particles to be as large as possible, since fine chopping is more expensive. However, in the other two solutions the temperature and the pressure are higher. But, all constrains on the responses are fulfilled. Thus, solution 2 is suitable: with a **13%** moisture content, **102ºC** die temperature, **28** MPa compressive pressure and a size of particle approximately 9.5 mm (**3/8** inches). Figure 6 shows the product densified under the best conditions. These optimized conditions are not greatly different from those reported in the literature. The optimum value of the moisture content was (13%), which is in the range recommended by Grover, et. al. (1996) for biomass. Likewise, O´Doguerty and Wheeler (1984), found maximum durability in wafers of wheat straw was possible within moisture contents between 10 and 20%. With regard to the level of temperature, 115^{o}C, Reece (1966) had found that a temperature of 60^{o}C was enough for increasing the durability from less than 10% up to an acceptable value 72%. In the same way Smith et al. (1977), found that the maximum level of compaction was reached at temperatures greater than 90^{o}C when compressing wheat straw. The findings relative to the size of particles confirm that the greater the size of particles, the better is the durability obtained (Faborode et al. 1987), (Lindley et al. 1989), (O´Doguerty et al. 1989). In addition, greater particle size was related to smaller energy consumption in the process.

Figure 6. Product densified in the best conditions

Conclusions

1. The results of the optimization process show good agreement with results obtained in earlier experimental work by the authors (Domínguez *et al*, 2002). Moreover, the selection of the most significant factors allowed simplifying the study of the densification process. Of course, experimental designs could be used efficiently if more factors were to be considered.

2. The second order central composite experiment allowed the obtaining of the functions for the density, durability and specific energy consumption in terms of the significant process factors. Then, through the use of an optimization process the optimum values were calculated. These optimum values are **13%** moisture content, **102^{o}C** die temperature, **28 MPa** compression pressure and particle size of approximately that obtained with a hammer mill screen having **9.5 mm** (3/8 inches**)** openings.

3. The methodology included: equipment items (Universal test machine, die, electrical resistance heater and thermocouple for temperature control, two pressure sensing cells, a displacement sensor and the data acquisition system), the experimental designs, regression analysis and an optimization process. Under these circumstances, the methodology of RSM (Response Surface Methodology) and DF (Desirability Factor) were found to be very useful tools in the process of optimizing a system having several objective parameters.

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