AGRO PRODUCTIVIDAD

Optimization of a production unit of the dairy agroindustry: Chapingo dairy technology unit case

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ABSTRACT

Objective: To evaluate the optimization level of a dairy production unit (DPU) through a mathematical programming model (MP). It is expected that by maximizing net income by at least 10%, the DPU will be more profitable than without optimized management.

Design/Methodology/Approach: The analysis was carried out under the economic approach of agricultural production, taking into consideration 11 decision variables in the objective function (OF), which was subject to 20 constraints. The variables were based on the requirements of the demand for dairy by-products, using technical coefficients (input-output coefficient). Excel® Solver® was used to develop the sensitivity report and to analyze the shadow prices and reduced costs.

Results: Three scenarios were modeled. Between the first and third scenario, the income increased to \$58,000.00 (41.02%). Between the second and third scenario, the income increased to \$63,840.00 (46.16%).

Study Limitations/Implications: Dairy food processing is an important industry in the economies of the world.

Findings/Conclusions: Panela cheese recorded the highest shadow price (\$72.85), which indicates that the DPU should concentrate on this type of dairy product. In conclusion, the optimization of the DPU guarantees the efficient use of scarce resources and therefore generates a higher profit.

Keywords: Mathematical programming, optimization, constraints, reduced cost, shadow prices.

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INTRODUCTION

Dairy food processing is an important industry in the developed and developing economies of the world. A wide range of dairy products meets the diverse consumer tastes and trends. Production planning in the dairy industry is usually a challenging task (Bilgen and Çelebi, 2013).

In times of food crisis, global economic crisis, and increased poverty, improving the performance of dairy production units (DPUs) is an essential strategic instrument for

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development (Alvarado *et al*., 2020). Demand for dairy products is expected to double by 2050, as a result of increasing population, rising incomes, and nutritional concerns. Therefore, DPUs will have to increase their production, in order to meet the growing demand, without sacrificing their profitability versus the competition (Salinas *et al*., 2020). Guevara and Guevara (2015) affirm that the dimensionality of milk production systems makes milk production one of the major contributors to food security. SADER (2020) defines production units as the set of land, infrastructure, machinery, equipment, animals, and other goods used in agricultural activities. SADER (2020) also recognizes the contribution of production units to the reversion of productivity and competitiveness problems in the agricultural sector, given Mexico's high dependency on food imports. OECD/FAO (2019) points out that the increase in productivity within the DPUs will accelerate agricultural growth, since it is an effective factor for both economic development and poverty reduction. Rueda and Rueda (2017) and Alvarado *et al*. (2020) agree on the advantages of the DPUs for the welfare in rural areas through the development of the economic-productive factors to generate jobs and income, which directly contribute to the increase in GDP. In Mexico, there are more than 300,000 DPUs that represent more than 78% of dairy farms (SAGARPA, 2018).

With regard to the Mexican economy, DPUs play an important role in food security: since they contribute approximately 35% of the national milk production and generate permanent paid employment opportunities, they have been promoted to alleviate poverty (Salinas *et al*., 2020). The DPUs usually include teaching, service, and research activities; dairy production; milk pasteurization; and Oaxaca, panela and Chapingo cheeses production (Hernández, 2018). The objective of this research was to optimize the profitability of the DPU, through a mathematical programming model (MP). It is expected that by maximizing its net income, the DPU will be higher than the current situation without optimized management.

MATERIALS AND METHODS

The research was carried out in the dairy production unit of the Universidad Autónoma Chapingo (UACh), known as the Chapingo dairy technology unit (DTU), in Texcoco, State of Mexico (19° N, 98° W). The experimental fields were located at 2,252 m.a.s.l. The objective of the DTU is to contribute to the practical training of the students of the Departamento de Ingeniería Agroindustrial (DIA).

According to Terrazas (2012), in order to carry out an analysis under the economic approach of agricultural production through the construction of a MP model, the decision variables to be optimized in the objective function (OF), subject to production constraints, must be taken into consideration. First, the said variables were defined. The OF will determine the values of the technical coefficient of the decision variables (Jebelli *et al*., 2016). The general form of OF (Z) is expressed mathematically as follows:

$$Maximize\; Z = \sum_{j=1}^{n} a_j x_j \qquad \text{where: } j = 1 \text{ until } n \tag{1}$$

Subject to 20 constraints and 11 decision variables, as follows:

$$\begin{array}{c} a_{11}X_1 + a_{12}X_2 + a_{13}X_3 + \ldots + a_{1\,11}X_{11} \leq = \geq b_1 \\ a_{21}X_1 + a_{22}X_2 + a_{23}X_3 + \ldots + a_{2\,11}X_{11} \leq = \geq b_2 \\ a_{31}X_1 + a_{32}X_2 + a_{33}X_3 + \ldots + a_{3\,11}X_{11} \leq = \geq b_3 \\ \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ a_{20\,1}X_1 + a_{20\,2}X_2 + a_{20\,3}X_3 + \ldots + a_{20\,11}X_{11} \leq = \geq b_{20} \end{array} \tag{2}$$

And non-negativity constraint: $X_j \geq 0$ (3)

The constraints for the DPU are based on the requirements of the demand for dairy by-products and production restrictions (Anderson *et al.*, 2011). Subsequently, a sensitivity report was developed directly from Excel® Solver® for the analysis of the shadow prices and reduced costs. The dairy processes of the DPU that are considered are the decision variables whose level of production must be optimized and sold (Table 1).

The limits of the constraints were established based on field research at the DPU. These limitations included the technical coefficients, the minimum demand for each by-product, the amount of raw milk received weekly in the DPU, and the intensity of the labor requirements for scenario 1 (Table 2).

Three scenarios were proposed: 1) the model was calibrated to obtain results similar to the current production situation; 2) the optimal combination of production activities was determined; and 3) slack variables were introduced.

The objective function of the three scenarios was:

$$\begin{aligned} \mathit{Maximize}\, Z = &-7LB - 0.6LP + 16VLPC - 17.35PY + 32VY \\ &-47.15PQP + 120VQP - 84.73PQO + 140VQO \\ &-112.16PQCH + 160VQH \end{aligned} \tag{4}$$

Table 1. Decision variables for the objective function.

Variable	Abbreviation	Notation	Coefficient	Element in the OF
Raw milk	LB	X_1	c_1	$c_1 * X_1$
Pasteurized milk	LP	X_2	c_2	$c_2 * X_2$
Pasteurized milk for sale	VLPC	X_3	c_3	$c_3 * X_3$
Yogurt production	PY	X_4	c_4	$c_4 * X_4$
Yogurt sale	VY	X_5	c_5	$c_5 * X_5$
Panela cheese production	PQP	X_6	c_6	$c_6 * X_6$
Panela cheese sale	VQP	X_7	c_7	$c_7 * X_7$
Oaxaca cheese production	PQO	X_8	c_8	$c_8 * X_8$
Oaxaca cheese sale	VQO	X_9	c_9	$c_9 * X_9$
Chapingo cheese production	PQCH	X_{10}	c_{10}	$c_{10} * X_{10}$
Chapingo cheese sale	VQCH	X_{11}	c_{11}	$c_{11} * X_{11}$

Source: Dairy production unit (DPU) data for the year 2020. c_i = net price = product price$_j$ × quantity produced$_i$ − variable cost$_i$

Table 2. Technical coefficients for the restriction limitations, scenario 1.

Product	Sign	Quantity required	Unit	Yield	Price
LB	=	22,400	L	1	7
LP	≤	22,400	L	1	0.60
VLPC	≤	14,000	L	1	16
PY	≤	3,000	L	0.9	32
PQP	=	300	kg	6.67	120
PQO	=	200	kg	10	140
PQCH	=	160	kg	12.5	160
Mano de obra	≤	42	h		
Agua	≤	15	m^3		
Cultivo láctico	≤	60	g		
Cloruro de calcio	≤	160	ml		
Sal	≤	350	kg		
Cuajo	≤	100	ml		

Data directly provided by the DPU, 2020.

For the three scenarios, the signs were changed; as shown below, the first sign belonged to the first scenario and so on:

Subject to:

Raw milk received: $1LB == \leq 22{,}400$
LP Production: $1LP \leq = \leq 22{,}400$
Sale of LP for consumption: $1LP \leq = \leq 22{,}400$
Yogurt production: $1PY \leq = \leq 3{,}000$
Panela cheese production: $1PQP == \leq 3{,}000$
Oaxaca cheese production: $1PQO == \leq 200$
Chapingo cheese production: $1PQCH == \leq 160$
Transfer from LB to LP: $-1LB + 1LP \leq\leq\leq 0$
TransferfromLPtoby-products: $-1LP + 0.9PY + 6.67PQP + 10PQO + 12.5PQCH \leq\leq\leq 0$
Restaurant markets: $-1LP + 1VLP \leq\leq\leq 0$
Yogurt market: $-1LP + 1VLP \leq\leq\leq 0$
Panela cheese market: $-1PQP + 1VQP \leq\leq\leq 0$
Oaxaca cheese market: $-1PQO + 1VQO \leq\leq\leq 0$
Chapingo cheese market: $-1PQCH + 1VQCH \leq\leq\leq 0$
Labor: $0.000022VQCH + 0.00018LP + 0.00255PY + 0.01861PQP + 0.03708PQO + 0.054687PQCH \leq\leq\leq 42$
Water: $0.00022VQCH + 0.00022LP + 0.00033PY + 0.00333PQP + 0.005PQO + 0.00625PQCH \leq\leq\leq 15$
Lactic culture: $0.01PY + 0.18PQCH \leq\leq\leq 60$
Calcium chloride: $0.2PQP + 0.3PQO + 0.25PQCH \leq\leq\leq 160$

Salt: $0.5PQP+0.5PQO+0.6PQCH \leq\leq\leq 350$
Rennet: $0.5PQP+0.5PQO+0.6PQCH \leq\leq\leq 350$

RESULTS AND DISCUSSION

When comparing the levels of production and sales in scenario three, a reduction of 8,400 L of the raw milk received weekly was observed; therefore, the pasteurization diminished to 37.5%. Other by-products remained at the same levels in the three scenarios (Table 3).

Between the first and third scenario, the net income had a difference of $58,800.00 and Z increased by 41.02%. Between the second and third scenario, a difference of $63,840.00 meant that the income increased by 46.16%.

The net income obtained in the scenarios was similar to the percentage used by Salinas *et al.* (2020) to optimize their economic benefit in stratum I (46%) and stratum III (73%). The results of Arauco and Arauco (2016) match those obtained in the model; they optimized the production of the Mantaro S. A. dairy plant, increasing its income from $3,030.00 to $93,000.00 biweekly soles, through the application of optimization techniques and the efficient use of available resources.

The third scenario obtained $202,113.00 per week, which means that the DPU must sent its entire production to the market, as a consequence of the reduction of 8,400 L of LB received per week. Likewise, the variable costs (with savings of $58,800.00) were optimized by 22.08% between the first and third scenario.

When contrasting the second and third scenario, the optimization was 23.52% and diminished weekly by $63,840.00. When comparing the second and third scenario, the pasteurization process decreased 23.52% and $5,040.00 were saved per week. Alvarado (2011) maximized his benefit by 5.40%, with an increase from $109,704.00 USD to

Table 3. Results of the optimized OF in the tree scenarios of the DPU (2020).

Scenarios	Optimized quantity			$ MX		
	1	2	3	1	2	3
LB	22,400	22,400	14,000	−156,800	−156,800	−98,000
LP	14,000	22,400	14,000	−8,400	−13,440	−8,400
PY	14,000	14,000	14,000	−52,050	−52,050	−52,050
PQP	3,000	3,000	3,000	−14,145	−14,145	−14,145
PQO	3,000	3,000	3,000	−16,946	−16,946	−16,946
PQCH	300	300	300	−17,946	−17,946	−17,946
VLP	300	300	300	224,000	224,000	224,000
VY	200	200	200	96,000	96,000	96,000
VQP	200	200	200	36,000	36,000	36,000
VQO	160	160	160	28,000	28,000	28,000
VQCH	160	160	160	25,600	25,600	25,600
Max Z				143,313	138,273	202,113

Data obtained directly from the MP model. The amounts with sign (−) correspond to variable cost.

$115,634.00 USD, obtaining similar results to those found in this research. Terrazas (2012) determined that the application of mathematical models to industrial and business problems makes the application of mathematical programming an imperative.

The optimal production of the three scenarios of the DPU is similar to that found by Arauco and Arauco (2016), who established that the optimal quantities for a biweekly production are the following: 202 kg of semi-integral fresh cheese, 506 kg of fresh cheese, 1,668 L of yogurt, and 498 kg of manjar blanco.

Processing 14,000 L of raw (unpasteurized) milk weekly, in the first and third scenario, provided similar results to those of Jablonsky and Skocdopolova (2017), when 56,810 L of raw milk were collected or bought each month to be processed.

The variable costs of by-products remain at the same levels in all three scenarios. The second part of the sensitivity report showed changes in the resources, which are the values to the right of the constraints (Right Hand Side-RHS-). These results represent the availability of resources of the DPU (LB, LP, Y, QP, QO, QCH, labor, water, inputs, raw materials, etc.). Changes in these values also affect the results of the feasible region and consequently the value of the optimal solution.

Among the results found, the final value obtained stands out, as well as the shadow prices generated (Table 4).

The shadow price of the LB in the first and second scenario is −$7.00, which is equal to the market price of the product. In the first scenario, 12,880 L more can be received of LB, and in the second 4,480 L more; however, the first can receive 8,400 L less, but the second scenario cannot receive any less L. The shadow price of the VLPC was $15.40, $16.00 and $8.40, in the first, second, and third scenarios, respectively. The VLPC in the first scenario is 54.54% more profitable than the third scenario; the VLPC is 47.5% more efficient in the second scenario than in the third; and the VLPC can increase up to 8,400 L per week in the three scenarios. In the first and third scenario, the VLPC can diminish by 5,299 L, and in the second by 14,000 L, without affecting the optimal solution found by the model.

Producing an additional liter of fruit yogurt implies an increase in profit of $14.65 in the three scenarios and the weekly production can be increased by 120 L. According to the shadow prices, PQP is 50.5% more profitable in first and second scenario —since the optimal value increases $72.85 for each additional kilo of PQP (only $36.00 in the third scenario). Therefore, production in third scenario can increase up to 24 kg more without affecting the optimal value.

The PQO in scenarios 1 and 2 had a shadow price of $52.27.

Increasing an additional kilo of the PQCH increases income in first and second scenario by $47.84 and in third scenario by $1.74.

In the third scenario, transferring an additional liter from LB to LP has a shadow price of $7.00; therefore, for each liter transferred from LB to LP, the optimal value will increase by $7.00. The same phenomenon takes place when a liter of LP is transferred to VLPC, but in this case the income increases by $7.60.

According to the shadow prices calculated in the scenarios, selling an additional liter of yogurt or a kilo of panela, Oaxaca or Chapingo has a positive impact on the profit of $32.00, $120.00, $140.00, and $160.00, respectively (because these are the market prices

Table 4. Contrast between the final value and the shadow-price of the scenarios.

Scenarios	**Final Value**			**Slack Variable**	**Shadow Price**		
	1	**2**	**3**	**S1−S20**	**1**	**2**	**3**
LB	22,400	22,400	14,000	8,400	−7	−7	0
LP	14,000	22,400	14,000	8,400	0	−0.60	0
VLPC	14,000	14,000	14,000	0	15.40	16.00	8.40
PY	3,000	3,000	3,000	0	14.65	14.65	14.65
PQP	300	300	300	0	72.85	72.85	36
PQO	200	200	200	0	55.27	55.27	0
PQCH	160	160	160	0	47.84	47.84	1.78
Transfer LB to LP	−8,400	0	0	0	0	0	7
Transfer LP to By products	−5,299	−13,699	−5,299	5,299	0	0	0
Transfer LP to VLPC	0	−8,400	0	0	0.60	0	7.60
VY	0	0	0	0	32	32	32
VQP	0	0	0	0	120	120	120
VQP	0	0	0	0	140	140	140
VQCH	0	0	0	0	160	160	160
Labor	32.42	33.93	32.23	9.76	0	0	0
Water	12.13	14	10.25	4.75	0	0	0
Lactic culture	58.80	58.80	58.80	1.2	0	0	0
Calcium chloride	160	160	160	0	0	0	184.23
Salt	346	346	346	4	0	0	0
Rennet	92	92	92	8	0	0	0

Data obtained from the sensitivity analysis of the MP model.

of products). Despite the unlimited labor in the DPU, operating in the red is not convenient for the university (UACh); therefore, this resource should be constrained. Salinas *et al.* (2020) determined that, according to the producers (who agree with this argument), labor was the second most important element. However, when the DPUs are seen as companies, they generate work and self-employment positions, often with an above minimum payment (Posadas *et al.*, 2014).

Water does not have a shadow price, because it is used without restrictions. However, if it were constrained, it would effectively represent a problem for the DPU, since the dairy industry is one of the biggest spenders or consumers of this resource. The lactic culture, calcium chloride, salt, and rennet resources did not have a shadow price, because the DPU is subsidized by the University.

CONCLUSIONS

The optimization of the DPU with mathematical programming is a tool that improved the efficiency in its production. The following strategy was proposed: not receiving LB allowed an increase in the profit up to $58,800.00 per week. In its turn, this also increased the optimal value, since if no more liters of LB were received, they would not be pasteurized, which reduces variable costs.

By optimizing the income of the DPU, a benefit of $143,313.00 was obtained between the first and third scenario; the aim was to obtain the maximum value of Z per week (an increase of 41.02%).

On the production side, the cheese that should be produced more is panela (PS=72.85/kg) and the cheese that should be produced less is Chapingo. When deciding whether to use VLPC or PY, VLPC turned out to be a better choice, since it increases the optimum by $1.35; additionally, the variable costs of VLPC are 96.54% lower than those of PY. Another significant aspect is that selling fruit LPC or PY is not as profitable as the production of certain types of cheese.

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