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OPTIMAL DISTRIBUTION OF PORK IN MEXICO WITH ENDOGENOUS PRICES

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ABSTRACT

We aimed to elaborate a nonlinear programming model to provide strategic and viable alternatives for optimizing the distribution of meat in the Mexican market, applying 2022 data and a Karush-Kuhn-Tucker optimization approach. The study covered eight production and consumption areas, as well as import entry points. Findings revealed a 1.1% underestimation of national and regional production, equivalent to 16,921 tons, a figure close to that observed during that year, and a 0.4% overestimation of regional consumption, with a Net Social Value of 1,943.6 million pesos. This optimization indicated negative production and positive consumption, with marketing profits exceeding transportation costs, thus enabling the establishment of optimal distribution routes. The fit between the 2022 values and those of the model was 0.02%, confirming the robustness and consistency of the proposed mathematical model. We conclude that the model represents a reliable alternative with potential for application in future planning and evaluation scenarios, related to public policy in pig farming.

Key words: Net Social Value, nonlinear programming, pork meat, optimization, optimal prices.

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INTRODUCTION

In spatial models that employ nonlinear programming, endogenous prices—those determined within the model itself—form an essential part of supply and demand functions. Concerning this approach, both consumer and producer prices are considered dependent variables, whereas quantities are treated as independent variables (Vázquez and Martínez, 2015). To explain these types of models, Karush-Kuhn-Tucker (KKT) conditions are applied; these are essential for identifying optimal solutions (Satoshi, 2021; Andreani *et al.*, 2022a). When estimating the objective function, whether this is to maximize profits or minimize costs, the goal is always to ensure that the optimal prices obtained with the model coincide with the actual prices observed in the market during the period of analysis (Rebollar *et al.*, 2019a; Rebollar, 2021; Rebollar and Hernández, 2023).

In Mexico, pork ranks second in total meat consumption, only behind poultry; it also ranks second in production value, after beef. In 2022, the year for which data is available, the nation produced 1.73 million tons (Mt) of pork, led by Jalisco and Sonora, which together accounted for almost 50% of the national total.

Of the total pork produced in 2022, 225,000 tons (t) were exported, leaving 1.51 Mt in the country. Meanwhile, Mexico's imports totaled 1.41 Mt, with the United States accounting for 83.10% of these imports. As a result, Mexico's total apparent pork consumption in 2022 was 2.92 million t (COMECARNE, 2022a). Thus, Mexico ranked sixth globally among the world's leading pork importers, after the United States, Brazil, China, Argentina, and Australia. Mexico also ranked tenth in exports, allocating 10.2% of its available supply to these exports (COMECARNE, 2022a).

By 2022, Mexicans consumed approximately 22.1 kilograms (kg) per person, with just over 40% derived from imports, primarily from the United States of America (USA) (COMECARNE, 2022a). The spatial distribution of pork production and consumption was uneven, as some regions had a production-consumption surplus. Consequently, a portion of this product was sent to deficit regions to meet their consumption demand.

According to Bassols (1995), during the same year, the producing regions of central-western (CW) (40.90%), northwestern (NW) (16.13%), and eastern (EA) (11.32%) in Mexico were the most prolific in the national total, whereas in terms of consumption, the central-eastern (CE) (33%), central-western (CW) (17%), and southern (SO) (10.49%) regions were the most prominent. Furthermore, the CW region consumed 80.40% of its production and distributed the remainder to other areas of the country, whereas the CE region's production contributed only 15.41% to total consumption, thus requiring it to source from other regions, as well as by means of imports (COMECARNE, 2022a).

Karush-Kuhn-Tucker (KKT) optimization or first-order conditions are considered essential and ideal requirements to reach the optimal solution to a nonlinear programming problem (Morales *et al*., 2012; Fletcher, 2017); besides this, imposing inequality constraints implies that the KKT approach generalizes the method of Lagrange multipliers (Andreani *et al*., 2022b) and serves as a procedure to maximize or minimize equations containing many variables and constraints that represent factors, which in themselves are multipliers (Gu *et al*., 2021).

Applying an amplified function within a mathematical model enables the integration of multiple interrelated variables, such as production volume, regional consumption and optimal prices, into a single analytical framework. This structure facilitates the generation of Lagrange multipliers, which are necessary to identify active constraints and evaluate the efficiency of the meat marketing system. Comparing the optimal prices obtained with actual price differentials between regions not only validates the model but also identifies supply routes that might improve regional distribution. Therefore, the proposed approach not only adds technical rigor but also provides a useful tool for making agri-food policy decisions, while having direct impact on logistical efficiency and equitable access to the product.

Our intention was therefore to estimate a nonlinear programming model that would provide viable alternatives, aimed at increasing the allocation of this meat product; that is to redistribute the available volume more efficiently in Mexico using 2022 data; optimizing routes, prices, and regional coverage to achieve a supply level exceeding that observed in the actual market. The model allows the use of demand-supply-price elasticity and consequently maximizes the Net Social Value (NSV), thus achieving an optimal supply of this meat product that exceeds the current level.

THEORETICAL FRAMEWORK

KKT conditions constitute the fundamental theoretical basis for solving optimization problems in nonlinear programming, especially when inequality constraints are incorporated. These conditions, which use first-order derivatives under assumptions of regularity, allow for the identification of optimal solutions in complex models with multiple variables. Their origin dates back to 1939, when William Karush proposed the concept of the saddle point in his thesis, formalized in 1950 by Kuhn and Tucker, who generalized the previous linear methods developed by Dantzig (Martínez, 2019).

This theoretical framework has been widely adopted in mathematical programming applied to economic problems, particularly in the spatial analysis of markets. Enke (1951) and Samuelson (1952) introduced the concept of social welfare to represent the area under the supply and demand curves, which made it possible to link mathematical optimization with the efficiency of resource allocation. In this study, these principles are integrated to model the distribution of pork in Mexico under KKT conditions, in order to maximize Net Social Value (NSV) and propose optimal regional supply routes.

Mathematical programming, linked to the aspect of solving market problems from a spatial perspective, began with Enke and Samuelson, who proposed the method for quantifying the economic surplus, generated by the interaction between supply and demand. This was mathematically represented as the calculation of the area between the supply and demand curves. This representation was called the social welfare function, as it enabled the evaluation of the total benefit obtained by economic agents in a given market (Enke, 1951; Samuelson, 1952).

By 1964, Takayama and Judge had added an analysis of transport costs and an estimate of implicit (inverse) supply and demand equations to the model. This helped define optimal prices and quantities of the product in question, subject to distribution. This therefore revealed the mathematical foundations that could be applied to all cases and in different geographical areas, where production and consumption occur (Takayama and Judge, 1964).

Consequently, once the model's solution is known, it provides results relating to optimal supply and spatial distribution matrices for the product, provided that the product's price exceeds the marketing margin, understood as the difference between the optimal consumer and producer prices. Therefore, spatial equilibrium models have been used to study problems related to interregional trade. These models can be expanded to include countries that import and export multiple products, as well as various types of merchandise. Furthermore, they are useful for simulating the impact of various international trade regulations on markets, such as quotas, import restrictions, subsidies, taxes, tariffs, and embargoes, among others (McCarl and Spreen, 1997).

Indeed, it is argued that the main difference between spatial equilibrium models and partial or general equilibrium models lies in the fact that the former distribute resources according to regions or areas and locations, where this economic activity is found. In contrast, the latter typically represent a single market, without considering any effects on other markets, while seeking to establish equilibrium for all markets (McCarl and Spreen, 1997). Spatial equilibrium models are applied to analyze both intraregional competition (interaction between consumers and producers within the same geographic region) and interregional competition (i.e., rivalry between economic agents from different regions seeking to introduce their products into markets that may be outside their production area) for example agricultural products, such as milk in the United States (Chavas *et al*., 1993) and in the Japanese market, by region (Yavuz *et al*., 1996).

Finally, by referencing Guajardo and Elizondo (2003), the spatial equilibrium model facilitates the use of supply and demand that depends functionally on price (inverse supply and demand functions) and permits different degrees of market structures.

METHODOLOGY

Citing Vázquez and Martínez (2015), Hernández *et al*. (2020), Rebollar *et al*. (2020), and Rebollar and Hernández (2023), the spatial equilibrium model, where the price of meat acted as an endogenous variable, required the application of demand and supply equations, known as inverse functions (Guajardo and Elizondo, 2003). The inverse demand function (1) attached to consumer region i was expressed as:

$$P_{di} = \alpha_{di} + \beta_{di} Q_{di};\ \beta < 0 \tag{1}$$

where P_{di}: endogenous consumer price of pork in region *i*, expressed in Mexican currency per *t*; Q_{di}: quantity of demand for the product in region *i*, expressed in *t*; α_{di}: intercept of the meat demand equation in region *i*; β_{di}: slope of the meat demand equation in region *i*.

Whereas, the inverse function corresponding to the supply (2) of meat was:

$$P_{si} = \lambda_{si} + v_{si} Qs_{di} \tag{2}$$

where P_{si}: endogenous price to the meat producer for supplying region *i*, in \$/t; Q_{si}: quantity of pork product for each *i* region, in *t*; λsi: intercept of the pork carcass supply equation in region *i*; v_{si}: coefficient that precedes the quantity of meat offered in region *i*.

Thus, in the partial derivatives of equations (3) and (4) it must be true that:

$$\frac{\partial P_{di}}{\partial Q_{di}} \leq 0 \tag{3}$$

$$\frac{\partial P_{si}}{\partial Q_{ds}} \leq 0 \tag{4}$$

Thus, the expression of the NSV (5) for Mexico, regionally, was structured by the difference in areas derived from the supply and demand curves of the meat, expressed as:

$$W_i\left(Q_{si}^*, Q_{di}^*\right) = \int_0^{Q_{di}^*} \alpha_{di} + \beta_{di} Q_{di} dQ_{di} - \int_0^{Q_{si}^*} \lambda_{si} + v_{si} Qs_{di} dQ_{si} \tag{5}$$

While adding the payments for moving the meat between the eight regions, was expressed mathematically as follows (6):

$$NW = \sum_{i=1}^{n} W_i\left(Q_{si}^*, Q_{di}^*\right) - \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} T_{ij} \tag{6}$$

where C_{ij}: Cost of transporting meat from zone *i* to zone *j*, in \$/t, related to difference between *i* and *j*. T_{ij}: Quantity of tons of pork transported from region *i* to region *j*.

This model was assembled from eight consumer regions, eight producer regions and two points of entry for meat imports. In order to produce this model, it was necessary to restrict both demand (7) and supply. In the case of demand, the sum of the quantity of pork transported to zone i had to be greater than or equal to consumption in that zone. That is:

$$Q_{di} \leq \sum_{j=1}^{n} T_{ij}, \text{ for all } i \tag{7}$$

With regard to supply restrictions (8) of pork, the total product transported outside of zone i had to be equal to or less than the total volume of meat from that region, therefore:

$$Q_{si} \leq \sum_{j=1}^{n} T_{ij}, \text{ for all } i \tag{8}$$

The model for the Mexican pork carcass market integrated supply and demand regions, trading a homogeneous product (pork carcass). Consequently, the regions represented distinct markets, primarily separated by transport costs (Rebollar and Hernández, 2023). These costs were specified per physical unit and independent of the volume produced.

The reported volume of production for each region, plus the volume of pork imported by that region, was classified by state using data from SIAP (2022). Then, the volume of pork exported by that region was subtracted from its production to estimate the total production for each region. Regarding imported volume, this information was obtained from Porcinocultores Mexicanos (PORCIMEX, 2022) and the Mexican Meat Council (COMECARNE, 2022b).

The equations for demand, supply and transport costs were estimated using secondary information available for 2022. Obtaining consumption (demand) by region, involved having the population data for each federal entity for the same year (2022), displayed on the website of the National Population Council (CONAPO, 2022); then, the number of inhabitants was multiplied by the amount of meat consumed per person, provided by COMECARNE (2022b) and added to the demand from each state, in the respective zones.

The regional producer price for meat was generated from the data reported by each state as part of the region and weighted by production. Weighting was as follows: once the average rural price or producer price for this meat was available for each state, along with the volume produced (in t), then the states were grouped to form each region, the producer price was multiplied by the volume reported by each state to generate the value of the state's production of that meat. Subsequently, the value of the total production for that region was calculated and divided by the total volume of meat produced or reported by the same region, thus obtaining the weighted producer price for that area. The consumer price was obtained from the SNIIM (2022), and the import price of meat was consulted on both the COMECARNE (2022b) and SENASICA (2021) websites. Thus, the international price of meat at import arrival points 1 and 2 was USD 2,098/t (FIRA, 2024) at an exchange rate of 20.12 pesos per US dollar (BANXICO, 2022). The national transportation cost of meat, expressed in Mexican monetary units per ton and per km, was obtained through an electronic consultation of multimodal land distribution companies, available from ACSAA (2024).

The programming model (9) was configured by an expression of order optimization and manifested the addition of surpluses on the consumption and production side, less the costs of mobilizing the product; subject to linear constraints related to regional demand (10) and supply (11) equilibria of the meat expressed as:

$$Max\sum_{i=1}^{n}\left[\int_{0}^{Q_{di}^{*}} P_{di}\left(Q_{di}\right)dQ_{di} - \int_{0}^{Q_{si}^{*}} P_{si}\left(Q_{si}\right)dQ_{si}\right] - \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}T_{ij} \tag{9}$$

Subject to:

$$Q_{di} - \sum_{j=1}^{n} T_{ij} \leq 0 \text{ for all } i \tag{10}$$

$$-Q_{si} - \sum_{j=1}^{n} T_{ij} \leq 0 \text{ for all } i \tag{11}$$

Q_{di}, Q_{si}, $T_{ij} \geq 0$ for all i and j (positive conditions of the model).

Bassols was used as a reference to regionalize the country (1995: 43), eight consumer zones were considered: Northwest (NW): that includes Baja California (BC), Baja California Sur (BCS), Sonora (Son), Sinaloa (Sin) and Nayarit (Nay); Northern (NR): Chihuahua (Chih), Coahuila (Coah), Durango (Dgo), San Luis Potosí (SLP) and Zacatecas (Zac); Northeast (NE): Nuevo León (NL), Tamaulipas (Tams); Central-Western (CW): Aguascalientes (Ags), Colima (Col), Guanajuato (Gto), Jalisco (Jal), Michoacán (Mich); Central-Eastern (CE): Mexico City (CDMX), Hidalgo (Hgo), State of Mexico (Mex), Morelos (Mor), Puebla (Pue), Querétaro (Qro), Tlaxcala (Tlax); Southern (SO): Chiapas (Chis), Guerrero (Gro), Oaxaca (Oax); Eastern (EA): Tabasco (Tab), Veracruz (Ver); Yucatán Península (YP): Campeche (Camp), Quintana Roo (QRoo), Yucatán (Yuc). In addition to 10 supply areas, eight of which were producers: NW, NR, NE, CW, CE, SO, EA, YP and the difference between two points of entry for pork imports, coming from the USA. The point of internment 1 (PI1), involved the borders of Colombia, which is part of the state of NL; those of Nuevo Laredo and Reynosa in Tams and Piedras Negras pertaining to the state of Coah. PI1, showed the importation of 91% of the meat, while entry point 2 (PI2), was at the borders of Mexicali and Tijuana located in BC; that of Nogales and San Luis Rio Colorado in the state of Son and that of Ciudad Juárez in the state of Chih (COMECARNE, 2022b; SENASICA, 2022), which also reported the entry of the remaining 9% of the meat import.

In order to solve the optimization problem, the respective demand equations (12) had to present a slope of less than zero and the supply equations (13) had to present a slope greater than zero. In this proposition, the Karush-Kuhn-Tucker requirements (Rebollar and Hernández, 2023) were expressed as follows, where the letter Z represents the model's objective function; that is the Net Social Value (NSV) function. In this study, Z was oriented towards maximizing the NSV by means of optimal allocation of meat in Mexico.

$$\frac{\partial Z}{\partial Q_{di}} = P_{di} - \lambda_{di} \leq 0 \tag{12}$$

$$\left(\frac{\partial Z}{\partial Q_{di}}\right) Q_{di} = 0,\ Q_{di} \geq 0 \tag{13}$$

These equations (12 and 13) require that the demand price of the pork by-product in region *i* be the same as the shaded price (λ_{di}), provided that the volume of meat consumed is positive. Equation (14) was expressed as:

$$\frac{\partial Z}{\partial Q_{si}} = P_{si} - \psi_{si} \leq 0,\ \left(\frac{\partial Z}{\partial Q_{si}}\right) Q_{si} = 0,\ Q_{si} \geq 0 \tag{14}$$

In (14) the market price to the producer of meat in zone i of Mexico, should behave in the same way as at its optimal price (ψ_{si}), provided that the volume produced is non-negative; likewise in (15):

$$\frac{\partial Z}{\partial T_{ij}} = -C_{ij} + \lambda_{di} - \psi_{si} \leq 0,\ \left(\frac{\partial Z}{\partial T_{ij}}\right) T_{ij} = 0, T_{ij} \geq 0 \tag{15}$$

Equation 15 implies that the market price on the consumption side (λ_{di}) in delimitation i, should not exceed the average of the optimal producer prices (ψ_{si}) of the meat in zone i and j delimitations, plus the transfer costs expressed as T_{ij}, provided that the volume of meat moved is not negative.

Optimization of the problem enabled us to observe the quantity supplied (Q_{si}) and demanded (Q_{di}) per region, the supply and distribution between different regions (T_{ij} where i is different from j) and within the respective zone (i_{ij}, for i=j). The price of meat per zone was established at the shadow prices P_{di} and P_{si}. The resulting observations regarding equilibrium prices and regions are: a) if region i consumes the total demand it generates (T_{ii}=Q_{i}>0), then the price differential between demand and supply of meat is equal to the transportation cost (P_{di}=C_{ii}+P_{si}); b) if region i sends meat to region j (T_{ij}>0), then the transportation cost from region i plus the supply price from zone j equals the demand price in delimitation i, that is, P_{dj}=P_{sj}+C_{ji}.

If zone j does not send product to delimitation i, it is because the price to the producer of meat in zone j exceeds that of the consumer in delimitation i, therefore, trade between zone j and delimitation i is not instigated or that supply route was declared inactive in the results output (P_{di}<C_{ji}+P_{sj}).

In the context of equations for the consumer and the producer of meat, two estimators are observed: the intercept (α_{i}) and the slope (β_i), generated by considering elasticity, prices, volumes produced and demand for pork by-product, expressed as (16):

$$\varepsilon_{pi} = \left(\frac{\partial Q_i}{\partial P_i}\right)\left(\frac{P_i}{Q_i}\right) \qquad (16)$$

where εpi refers to the price elasticity of both demand and supply in delimitation i.

Contemplating supply and demand functions for pork by-products by region requires awareness of price elasticity of demand, which for this study was consulted in Rebollar *et al*. (2014). Regarding import entry boundaries, the values published in Pérez *et al*. (2010) and Vázquez and Martínez (2015) were used. Finally, the model output and validation were compared to the values observed during the study year, and analysis was then performed. The model was run using the MINOS-GAMS solver, version 24.4.2 p/w8, Office 2013 with reference to Rosenthal (2014:219).

RESULTS

Table 1 presents the results from the optimal model or base model in terms of production, imports and acquisition of Mexican pork, both by zones, as by the national amount, as well as in terms of Net Social Value (NSV) (objective function or Z function) and its contrast to official values observed in 2022.

Table 2 shows the results from the base model, focusing on production and prices; specifically, the optimal producer price and how it compares with the market price for pork. The difference between the market price and the optimal

Table 1. Mexico. Pork trade, 2022. Base model.

Delimitation	Levels 2022	Optimal model	Difference	Difference, %
Production (t)				
NW	242,797	241,922	-875	-0.36
NO	54,767	54,479	-288	-0.53
NE	30,156	30,058	-98	-0.32
CW	616,138	612,845	-3,293	-0.53
CE	148,103	147,822	-281	-0.19
SO	83,463	83,448	-15	-0.02
WE	170,386	159,397	-10,989	-6.45
YP	159,506	158,424	-1,082	-0.68
Subtotal	1’505,316	1’488,395	-16,921	-1.12
Imports (t)				
Detention zone 1	1’282,190	1’310,737	28,547	2.226
Detention zone 2	126,810	126,225	-585	-0.461
Subtotal	1’409,000	1’436,962	27,962	1.985
Consumption (t)				
NW	272,313	271,019	-1,294	-0.475
NO	304,482	307,114	2,632	0.865
NE	215,362	216,165	803	0.373
CW	495,400	502,739	7,339	1.481
CE	960,957	963,154	2,197	0.229
SO	305,661	304,964	-697	-0.228
WE	242,027	241,873	-154	-0.064
YP	118,115	118,329	214	0.181
Subtotal	2’914,316	2’925,357	11,041	0.379
NSV (MMDP)	1,943.6	1,944.0	0.4	0.021

Source: taken from the optimal model, 2022. NSV Net Social Value.

Table 2. Conditions for optimization Supply of pork meat.

Region	Production optimal	Market price to the producer ($/t) A	Optimal price to the producer ($/t) B	Difference (A-B)
NW	241,922	39,107	39,107	0
NO	54,479	44,953	44,950	3
NE	30,058	45,361	45,356	5
CW	612,845	47,033	47,032	1
CE	147,822	49,494	49,494	0
SO	83,448	49,835	49,818	17
WE	159,397	50,635	50,635	0
YP	158,424	47,728	47,727	1
PI1	1’310,737	43,244	43,245	-1
PI2	126,225	37,845	37,846	-1

Source: self-elaborated with optimal information.

producer price provided necessary and sufficient evidence for the model to optimize the quantity of pork supplied.

On the demand side, Table 3 shows the result from the optimization conditions, given by the output of the base model on the consumption side. The arithmetic difference between the market price to the consumer and the optimized value to the consumer was zero, indicating compliance with these conditions.

Optimization of trade flows

Table 4 presents the difference between the distribution or marketing margin of pork and the cost of transporting it. If this difference was positive, then it was considered an essential and sufficient requirement to implement the optimal distribution route for the meat between the different participating delimitations, helping to maximize the social welfare provided by the model.

DISCUSSION

In Mexico, pork is transported by road using specialized vehicles designed to move finished live animals at their commercial weight, although also under refrigerated conditions. These vehicles are double-axle semi-trailer trucks, four meters high, 2.5 m wide, and 12.2 m long. The transport company charges per ton of meat and per kilometer traveled, which already includes the return trip of the empty vehicle (Morales and de la Torre, 2006; Miranda, 2013).

Under optimal conditions and without considering market distortions in the Mexican pork sector in 2022, the model maximized the objective function, and its fit is known as the baseline or optimal model. The difference between the estimated Net Social Value (NSV) and the value observed for that year was 0.021%, which falls within the valid range of 0 to 10% (Rebollar and Posadas,

Table 3. Optimization conditions related to pork consumption.

Region	Optimal consumption	Market price to the consumer ($/t) A	Optimal price to the consumer ($/t) B	Difference (A-B)
NW	271,019	44,900	44,900	0
NO	307,114	47,457	47,460	-3
NE	216,165	45,634	45,630	4
CW	502,739	48,285	48,280	5
CE	963,154	49,930	49,930	0
SO	304,964	52,706	52,710	-4
WE	241,873	52,275	52,270	5
YP	118,329	48,784	48,800	-16

Source: self-elaborated with information from the optimized model.

Table 4. Pork meat. Optimal distribution routes by region, 2022.

Activated itinerary (X_{sd})	Beneficiary ($/t)	Transport costs ($/t)	Difference
$X_{1,1}$ (NW to NW)	5,793	5,792	1
$X_{2,5}$ (NO to CE)	4,979	4,979	0
$X_{3,7}$ (NE to WE)	6,914	6,912	2
$X_{4,4}$ (CW to CW)	1,252	1,252	0
$X_{4,5}$ (CW to CE)	2,898	2,897	1
$X_{5,6}$ (CE to SO)	3,216	3,216	0
$X_{6,6}$ (SO to SO)	2,892	2,892	0
$X_{7,7}$ (WE to WE)	1,635	1,635	0
$X_{8,7}$ (YP to WE)	4,547	4,547	0
$X_{8,8}$ (YP to YP)	1,073	1,070	3
$XP_{11'1}$ (P_{I1} to NR)	4,215	4,211	4
$XP_{I1'3}$ (P_{I1} to NE)	2,390	2,388	2
$XP_{I1,5}$ (P_{I1} a CE)	6,685	6,684	1
$XP_{I1,6}$ (P_{I1} to SU)	9,465	9,465	0
$XP_{I1,7}$ (P_{I1} to OR)	9,025	9,024	1
$P_{I2'1}$ (P_{I2} to NO)	7,054	7,053	1
$P_{I2'2}$ (P_{I2} to NR)	9,614	9,610	4

Source: taken from the optimization model, 2022.

2023). Therefore, the baseline model was deemed appropriate for evaluating the impacts of timely trade policy.

The Net Social Value (NSV) resulting from model optimization was 1.944 billion pesos, 0.02% higher than that observed in 2022. Output underestimated the volume of meat produced in all areas, at a value of -1.12%; this percentage indicates an estimate of lower production than the level actually observed. Likewise, the model overestimated imports by 1.98%, the volume of which increased from 1,409 thousand tons in 2022 to 1,437 thousand tons in terms of output, equivalent to a 2.22% increase in imports due to PI1 and a 0.46% decrease in imports entering through PI2.

Similarly, there was a 0.02% overestimation in the national consumption variable, increasing from 2.91 thousand tons observed in 2022 to 2.93 thousand tons predicted by the model. This increase occurred in five of the eight regions, notably CW, NO, and CE. In the remaining three regions, consumption was lower than observed that year. Notably in the YP region, the effect of NSV was barely perceptible due to its geographical location and because it is considered self-sufficient, as almost all of its production is consumed within the region, leaving a small surplus for redistribution.

Optimization of production

Once the mathematical condition is met—that is, the market price on the production side coincides with the ideal price (provided by the model) for pork—production is considered optimal. Table 2 shows that this condition is met in all pork-producing areas and only minor variations due to the use of decimals prevented some figures from reaching zero.

The model results provide the optimal price for the producer; conversely, the market price for the producer is estimated by considering the relevant equation (Rebollar and Hernández, 2023). Thus, notably in the case of the CW region (Central-West), the equation for the endogenous market price was CW=-1,302,875+2.202690965 (X_{CW}); where X_{CW} represents the optimal volume of meat for the CW zone assigned by the model, which was 612,845 t; therefore, the market price obtained was \$47,033/t and the optimal price was \$47,032/t. The difference between the two prices was one, generated by using decimals.

This mathematical condition was sufficient for the existence of positive optimal prices and consumption (Rebollar *et al*., 2019a) of pork meat; the estimates for the rest of the regions were established in a similar way.

Optimization of consumption

Regarding demand for pork, the endogenous price function estimate for the consumption side, in the case of the Central-Eastern (CE) region, was $P_{CE} = 567{,}376 - 0.537242\ Y_{CE}$; where the optimal consumption provided by P_{CE} was 963,154 t and the result was: $P_{CE} = 567{,}376 - 0.537242\ (963{,}154) = \$49{,}930$ \$/t (Table 3). This result is precisely the market price for the demand side; therefore, when compared with its optimal price (σ_d) for the area in question was \$49,930 \$/t; the difference between these two prices was zero, thus mathematically fulfilling the requirement of non-negative optimal consumption.

The CE (Central-East) region of the country acquired 32.97% and the YP (Yucatan Peninsula) only 4.01% in relation to the total consumed; thus, based on estimates of pork consumption per person published by COMECARNE (2022a), in which this variable has more to do with the number of consumers than with the price.

Optimization of market flows

In this investigation, the result of the marketing margin of pork between regions that marketed the meat in 2022 was both greater than and equal to zero, similar to the finding of Rebollar *et al*. (2019b), on the pork by-product for Mexico, to that of Rebollar (2021) in national chicken meat and of Rebollar and Hernández (2023) for beef cattle; when the margin is greater than or equal to the cost of transport per ton of the meat, then evidence is generated for the supply routes of the meat to be considered as optimal, which goes hand in hand with the mathematical requirement of KKTr, generated by the Lagrangian model.

In this regard, the distribution and supply route for the meat in question, stipulated as an example by $X_{2,5}$ (from the NO zone to the CE) (Table 4), was energized because the price optimized on the consumer side in CE, denoted by (σ_d) exceeded that of the producer (σ_s) observed in the NO region, while the cost per ton traded from the NO zone to the CE was less than the arithmetic difference between both prices (margin) (Table 4).
Other meat supply routes for the remaining regions are not presented in Table 4 because the cost of transporting the meat exceeded the margin.

CONCLUSIONS

In contrast to data observed in 2022, the model maximized the Net Social Value function in the variables of meat production, imports and consumption. The optimization conditions relating to optimal and market prices for both producers and consumers were met and the difference between transportation costs and the distribution margin for meat was a determining factor in ensuring that the supply and distribution routes between regions were optimal. Finally, the optimality criteria, viewed as constraints, were fulfilled, demonstrating that under the established conditions, the model's validation is useful for evaluating policy scenarios of interest to the government sector, in order to generate viable alternatives for meat distribution in the country.

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