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Article

Optimizing corn trade routes in Mexico using linear programming

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Abstract

Corn is one of the most important foods in the diet of Mexicans; there was a sustained growth in imports since the trade opening of Mexico since 1994 with the entry into force of NAFTA; imports have grown to such a degree that, in 2021, Mexico was the world's second largest importer of corn with 17.4 million tons, only after China. This research aimed to determine the corn transport routes during 2020 through linear programming, minimizing their distances to meet the demands of each destination in two scenarios: a supposed closed economy and the current open economy with global exchanges. The optimal national distribution routes that together imply the shortest transport distances were determined for both scenarios. For the closed economy scenario, seven states of origin and 25 states demanding corn were identified. In the open economy, a total of 49 suppliers were proposed for the same 25 destinations. It was concluded that Mexico is commercially dependent on corn imports for 37% of its total consumption; due to the logistical challenge of minimizing the distances traveled for transportation, obtaining an optimal allocation implies an improvement in social welfare at the country level, easily tangible in the improvement of the final price of corn.

Keywords:

corn trade, corn transportation costs, efficient agricultural markets, national strategic corn reserve, storage capacity.

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Introduction

Corn in Mexico is a crop of great importance in the social, cultural, and economic spheres (ASERCA, 2018); during 2021, more than 27 million tonnes were produced in more than seven million hectares; in addition, it plays a fundamental role in the diet of the human population (Pérez-Solís, 2021), it is also used for livestock feed; white corn is intended for human consumption, while yellow corn is mainly used in the agricultural industry (ASERCA, 2018).

Making this distinction, in 2018, the production of white corn showed sufficiency to meet the demand; however, more than 80% of the yellow corn needed to meet demand was imported (CEDRSSA, 2019). This implies greater dependence on the foreign market, but it was since the agricultural crisis in the mid-sixties that Mexico ceased to be self-sufficient, to such an extent that, in 2021, Mexico was the second largest importer of corn with 17.4 million tons, only after China (FAOSTAT, 2024).

In addition, the growing urban population is increasingly demanding meat products and this implies that a significant part of this grain is destined for animal consumption (Rubio, 1987). Therefore, the import of this grain is the most relevant in terms of the agricultural industry (González-Estrada and Alferes-Varela, 2010); imports have grown since the opening of trade and, especially, since the entry into force of the North American Free Trade Agreement (Moreno-Sáenz *et al*., 2016).

In 2002, a significant deficit of corn was detected, leading to the destabilization of food security and the strengthening of the subjection to external market (Saad, 2004); this dependence was evidenced by the index of dependence on cereal imports (food security indicator) of the Food and Agriculture Organization of the United Nations (FAO), which shows that, during the year 2011, 35% of the corn consumed came from foreign territory (FAO, 2010).

Guiding to contribute to food security, the second Sustainable Development Goal of ONU (2015) and the 2019-2024 national development plan through Mexican food security (SEGALMEX, 2024), strategies have been established to increase the production of the agricultural sector and the marketing of products in the basic basket (SEGALMEX, 2020), which includes corn (SADER, 2024).

In 2020, the main white corn-growing states, according to the Agri-food and Fisheries Information Service (SIAP, 2024), were Sinaloa, Jalisco, Michoacán, and Guanajuato; the volume produced by these states corresponds to 51% of the total national production (SIAP, 2024). The national production is insufficient to meet the country's demand; the import of the grain is through different customs of the country.

Hence, both the location of the producing areas and the access points of the grain determine the distances to the centers of consumption. In this sense, linear programming (Moncayo-Martínez and Muñoz, 2018), applying the simplex method formulated by Dantzig (1947), turned out to be an option to determine the minimum distances between the different origins and destinations, considering that they represent, to a certain extent, the transport costs of the volumes demanded by the consumption centers (Dantzig and Thapa, 1997).

For this analysis, an objective function that maximizes or minimizes is proposed (Dantzig and Cottle, 2003), which will be subject to different restrictions of equality or inequality (Del Río-Gómez, 2021). Some authors have used it for its practicality to solve the transport problem (Díaz-Parra and Cruz-Chávez, 2006), for the minimization of prickly pear distribution costs in Mexico 2016.

Based on the above, this research aimed to determine the corn transport routes during 2020 through linear programing, minimizing their distances to meet the demands of each destination in two scenarios: a supposed closed economy and the current open economy with global exchanges. And, with this, contribute to food security because optimization would imply a reduction in prices. The hypothesis proposed is that if the optimal transport routes are determined, both suppliers and buyers of corn will perceive a reduction in costs and with it, the profit rate of corn grain rises.

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Materials and methods

The collection of the import figure of 15 953 291 t of corn during 2020 (FAOSTAT, 2024) considered tariff classification 100 590, which included all varieties of grain corn, which, added to the national production of 27 424 528 t, yields the total national consumption of 47 377 819 t, corresponding to total demand.

The solution was through the software called linear generalize optimizer 18.0 (Lingo), a mathematical tool that solves optimization problems (Dorta-González *et al*., 2001); establishing the model requires the following basic variables: objective function, established with the distances that exist between each of the origins to each destination and the constraints of supply and demand.

The optimal solution of the transport routes was determined based on a matrix of distances where the columns represent the origins and rows represent the destinations of the grain through the simplex method of linear programming, which minimizes transport costs through the optimal assignment of routes according to the distances between each location of the supplier and demander.

In the assumption of a closed economy, considering the 31 states and Mexico City, a deficit or surplus in production was determined in order to determine the states of origin and destinations, using the national and state production obtained from the 2020 agricultural closure, the national and state population extracted from the 2020 population and housing census (INEGI, 2020) and finally, the quantities imported and exported obtained from (FAOSTAT, 2024).

The preliminary calculation of apparent national consumption (ANC), which estimates what is consumed in a country over a period (Bustamante-Muñoz, 2015), is obtained by adding domestic production and imports minus exports. The ANC per capita is the quotient of dividing the ANC by the population of the country; the state ANC was then determined, resulting from the multiplication of ANC by the state population.

Finally, the consumption of each state is subtracted from the production of each state to identify if the state satisfies its demand; in the face of a positive result, the state will be a supplier, otherwise it is a demanding state (Martínez-Jiménez *et al*., 2023).

In the scenario of a closed market, without imports. Once the origins, the quantity offered, the destinations, the quantity demanded, and the distances were identified, the objective function was proposed by considering exclusively national origins (m) and destinations (n), the quantity supplied in origin (i)= Em, the demand in destination (j)= Dn, the distance between origin (i) and destination (j)= Cij; finally, Xij= the quantity transported from the origin to the destination. The objective function of the closed model is as follows:

$$Y=\sum_{i}^{m}\sum_{j}^{n} C_{ij}X_{ij}$$

Where: the producing regions (i)= 1, 2, ... m; and the consuming regions (j)= 1, 2, ... n, thus constructing the minimization function: Min Y= $C_{11}X_{11}+C_{12}X_{12}+ \dots C_{mn}X_{mn}$. Where: C_{11} represents the distance from origin 1 to destination 1; C_{12} represents the distance from origin 1 to destination 2 and so on until all national origins and destinations are included; X_{11}, X_{12} to X_{mn} will be the quantities of corn that must be sent according to the optimal allocation proposed.

Consequently, the constraints that condition the objective function, denoting the quantity available from each supplier and the quantity needed by each demander, were as follows: supply. $X_{11}+X_{12}+X_{13}.. .+ X_{1n}= E_1$. $X_{21}+X_{22}+X_{23}.. .+X_{2n}= E_2$. $X_{m1}+X_{m2}+X_{m3}.. .+ X_{mn}=E_m$. $X_{m1}+X_{m2}+X_{m3}.. .+ X_{mn}= E_m$. These restrictions show that the production of each origin exceeds its demand, so it has a surplus to send to the consumption centers an amount equal to its supply.

Demand. $X_{11}+X_{21}+X_{31}+...+ X_{m1}=D_1$. $X_{12}+ X_{22}+X_{32}+...+ X_{m2}=D_2$ … $X_{1n}+ X_{2n}+X_{3n}+...+ X_{mn}=D_n$. These restrictions indicate that the quantities sent from the different suppliers must coincide with the demand of each consumer center. The second scenario, which is an open market such as Mexico’s, unlike the closed one, does consider imports.

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In addition to the national suppliers, 38 foreign suppliers were included, corresponding to the 38 customs as entry points for corn imports, due to the limited capacity that Mexico has to be self-sufficient in food and due to the fact that the phenomenon of the demand for corn for livestock use has caused the country to need to import it to supply its consumption (Schwentesius and Ayala-Garay, 2014).

Of the 38 customs, 21 are bordering the United States, which has facilitated imports from our main corn supplier in addition to the fact that in the last decade (2010-2020), the United States have become the largest producer and exporter of corn in the world (FAOSTAT, 2024) and since the entry into force of the USMCA, the total imports of corn from that country increased 14 times (García-Salazar and Santiago-Cruz, 2004); besides the 21 border customs mentioned, 17 maritime customs were analyzed, which facilitate distribution to national consumption centers in the center and south of the country.

Based on the above, the objective function considered the basis of the national market, incorporated the restrictions represented by customs, which were symbolized by the literal 'w' within the objective function, and kept the same national destinations, as shown below: Min $Y= C_{11}X_{11} + C_{12}X_{12}+ \ldots C_{mn}X_{mn}+C_{wn}X_{wn}$.

Where: C_{wn}= the distance from customs to domestic destinations and X_{wn}= the amount of corn that must enter customs to meet the domestic demand shortfall. Supply. $X_{w1}+X_{w2}+X_{w3}.. .+ X_{wn} < 0$. These restrictions show that the supply of each custom will be greater than 0 since it will be subject to the quantity necessary to fully supply national demanders.

Demand. $X_{1wn}+ X_{2wn}+X_{3wn}+...+ X_{wn}=Dn$. These constraints carry the numerical sequence 1w, 2w, 3w, ... (for demonstration purposes), which indicates the count only of the customs; in the finished function, they will follow the numerical sequence of the national suppliers and indicate that the quantities sent from the different customs must coincide with the demand of each consumer center.

Results and discussion

Mexico's total corn consumption in 2020 was 43 065 437 t, of which only 63% comes from domestic production, and the missing 37% comes from imports, with the main supplier being the United States of America, a country that provides 92% of total imports. The ANC was used to calculate the ANC per capita, which results from dividing consumption by the population of the same year (126 014 024 inhabitants), obtaining a per capita consumption of 34.175 kg.

From the ANC per capita, it is possible to determine, with the population of each state of the republic, the total of each state and then decide if they are suppliers or demanders; two scenarios are obtained from these results, one with a closed economy and the other with commercial openness; they are analyzed individually below.

Scenario one: closed economy

It was identified that only seven states of the republic satisfied their local demand (Table 1). That is, only 22% of Mexican states were able to be self-sufficient and provide corn to other states dependent on corn grain; these contributed 64% of the total production in Mexico and covered the demand of 39% of the national population. These states (Sinaloa, Jalisco, Guanajuato, Michoacán, Veracruz, Mexico, and Zacatecas) are the ones that were recognized as origins or suppliers in the optimization of the distribution of corn in the remaining 78% of the territory, offering a total of 13 196 001 t.

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Table 1. Optimal distribution of national origins and destinations in a closed market.

Origin (i)	Destination (j)
Veracruz	Tabasco
Sinaloa	Nayarit, Baja California Sur, Durango, Chihuahua, and Sonora
Jalisco	Nayarit, Aguascalientes, San Luis Potosí, Colima, and Tlaxcala
Michoacán	Morelos, Mexico City, and Hidalgo
Mexico	Morelos
Guanajuato	Querétaro, Hidalgo, and Tlaxcala
Zacatecas	Coahuila

INEGI, SIAP, FAOSTAT, LINGO (2020).

The 25 demanding states or destinations were: Puebla, Chihuahua, Colima, Coahuila, Guerrero, Mexico City, Nayarit, Campeche, Aguascalientes, Hidalgo, Querétaro, Yucatán, Nuevo León, Tabasco, San Luis Potosí, Quintan Roo, Tamaulipas, Morelos, Sonora, Chiapas, Baja California Sur, Durango, Oaxaca, Baja California, and Tlaxcala; these states are recurrent as demanding states in other studies conducted, such as that by Gómez and García (2013).

The shortage of corn in these states is 28 836 910 t. According to the methodology used, the origins (i) and destinations (j) were identified by optimizing the distribution of corn taking the distance between suppliers and demanders as a variable; the results obtained for the closed market are presented below in Table 2.

Table 2. Optimal quantities of domestic suppliers in a closed market.

Origin (i)	Quantity distributed (t)
Veracruz	664 292
Sinaloa	5 811 166
Jalisco	2 654 942
Michoacán	1 789 731
Mexico	590 817
Guanajuato	1 450 275
Zacatecas	234 777

INEGI, SIAP, FAOSTAT, LINGO (2020).

According to the calculations made, national demand is only covered in 60% of the destinations with surpluses from the 7 offering states. Sinaloa is the state with the largest amount available, with 5 811 166 t, it was able to supply Nayarit, Baja California Sur, Durango, Chihuahua, and Sonora with 4%, 33%, 36%, 60% and 25% of its supply, respectively. The state with the lowest surplus was Zacatecas, with 234 777 t and offered 100% to Coahuila.

With respect to Jalisco, with a surplus of 2 654 942 t, it offered the highest percentage of that amount to San Luis Potosí and the lowest was for Nayarit, 32% and 11%, respectively. Michoacán supplied between 30% and 36% to each of the states of Morelos, Mexico City, and Hidalgo. The states of Veracruz and Mexico provided 100% of their surpluses to Tabasco and Morelos, respectively; finally, Guanajuato distributed its supply to Querétaro, Hidalgo, and Tlaxcala; the latter being the one that received the largest proportion (58%).

It was observed that the most recurrent destinations are Morelos, Hidalgo, Nayarit, and Tlaxcala; it was also found that with the amount offered by national origins, it is only possible to cover 46% of the total amount required in the 25 destinations. Figure 1, developed with the platform of (MapChart, 2020), shows the afore mentioned distribution and the rest has to be covered by international trade with imports, since, in research such as that by Tejeda-Villanueva et al. (2019), it is reaffirmed that when there is a shortage of a certain product, imports are used.

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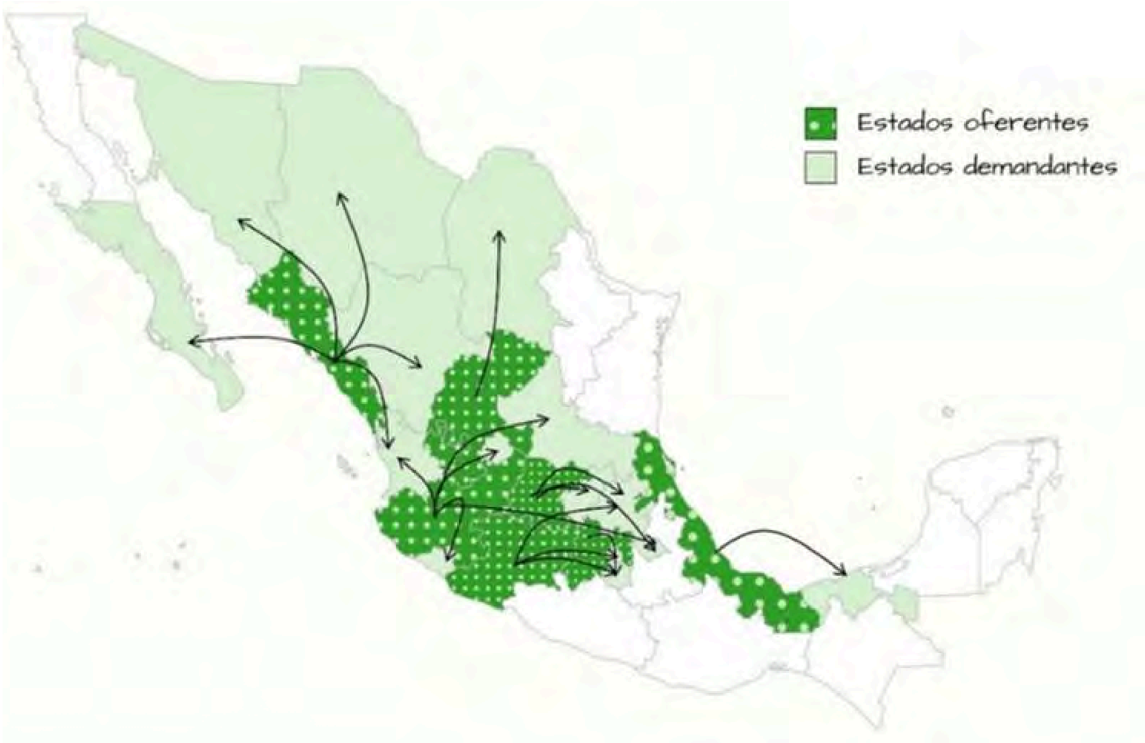
Figure 1. Optimal corn trade flows in a closed market. INEGI, SIAP, FAOSTAT, LINGO (2020).



Second scenario: open economy

In the open market model, as in most countries, such as Mexico, 38 points of entry were added to the supplying states. These customs are: Agua Prieta, Ciudad Acuña, Ciudad Camargo, Ciudad Juárez, Ciudad Miguel Alemán, Ciudad Reynosa, Colombia, Matamoros, Mexicali, Naco, Nogales, Ojinaga, Piedras Negras, Puerto Palomas, San Luis Río Colorado, Sonoyta, Tecate, Tijuana, Altamira, Tampico, Tuxpan, Veracruz, Coatzacoalcos, Dos Bocas, Ciudad del Carmen, Puerto Progreso, Cancún, Subteniente López, Ciudad Hidalgo, Salina Cruz, Acapulco, Lázaro Cárdenas, Manzanillo, Mazatlán, Guaymas, La Paz, and Ensenada, to supply the 15 640 909 t missing from the national demand.

The results for the open economy showed that imports cover 54% of national demand and come from 11 of the 38 customs considered. Table 3 shows the optimal distribution of the supplying and demanding customs through which the import of corn is viable, from the logistical point of view, which implies the optimization of costs and, therefore, an increase in welfare due to their reduction (Sánchez *et al*., 2017).

Table 3. Corn entry customs for optimal distribution to their destinations.

Origin (i)	Destination (j)
Ciudad Miguel Alemán	Coahuila and Nuevo León
Mexicali	Baja California
Altamira	Tamaulipas
Veracruz	Puebla and Tlaxcala

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Origin (i)	Destination (j)
Coatzacoalcos	Chiapas
Dos Bocas	Tabasco
Ciudad del Carmen	Campeche
Puerto Progreso	Yucatán
Subteniente López	Quintana Roo
Salina Cruz	Oaxaca
Acapulco	Guerrero

INEGI, SIAP, FAOSTAT, LINGO (2020).

Only 3 of the 11 optimal customs represent 57% of imports: Veracruz, Mexicali, and Salina Cruz, as shown in Table 4, due to the close geographical location with Baja California, Puebla, Oaxaca, and Tlaxcala, states to which they supply corn.

Table 4. Optimal volumes to import through the selected customs.

Customs of origin (i)	Quantity imported (t)
Ciudad Miguel Alemán	940 434
Mexicali	2 735 180
Altamira	1 033 534
Veracruz	4 053 897
Coatzacoalcos	1 889 626
Dos Bocas	150 479
Ciudad del Carmen	557 625
Puerto Progreso	721 149
Subteniente López	960 100
Salina Cruz	2 123 584
Acapulco	475 301

INEGI, FAOSTAT (2020).

According to the optimal distribution, 81% of the customs are feasible and must supply the demand of their own state, as shown in Figure 2, but they could not be considered as a viable option to supply the other states; it was identified that only the customs of Ciudad Miguel Alemán and Altamira are viable options to supply other states since they diversify their destinations.

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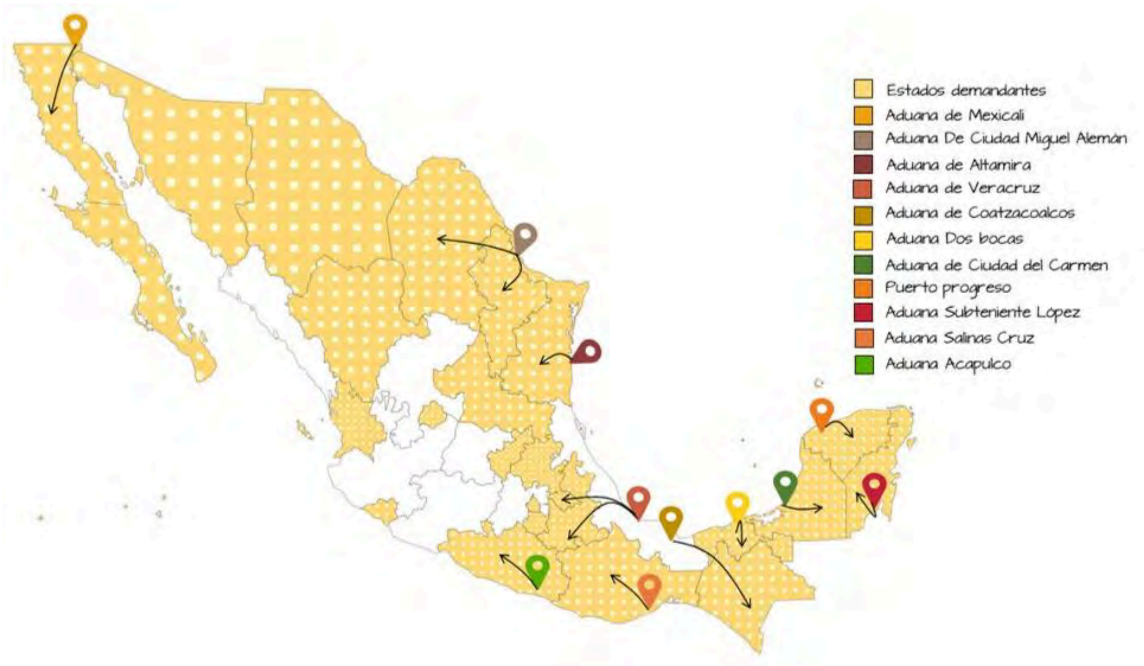
Figure 2. Selection of corn entry customs for optimal distribution. INEGI, SIAP, FAOSTAT, LINGO (2020).



Conclusions

The independent variable used to model the problem was the distance between the supplying and demanding locations; although there are other variables that are more precise to determine transportation costs, the main reason why a monetary variable was not used is because it was not possible to homogenize the means or routes of transportation; therefore, determining a homogeneous cost per tonne transported is not possible, this was the main limitation of this approach. The best routes for the transportation of corn with the shortest distances were identified by quantifying the national demand for corn grain distributed in the different states, differentiating producers and demanders, highlighting the usefulness of linear programming.

Nevertheless, there is an important gap to strengthen its valuable findings and it lays the foundations for future research that considers the variable of the seasonal supply of producing states, such as Sinaloa, Jalisco, and Michoacán, and the needs of consumption centers over time. In addition to the seasonal supply, it will be necessary to analyze storage capacity, storage and transportation costs, even threats to transportation such as insecurity, important variables for the linear programming model to have a representation more attached to the national reality in space and time.

To have the necessary elements for the design of a national strategy that guides production and storage with communication infrastructure, such as rail transport, that makes national exchanges more efficient in order to strengthen food security. Once the current national situation has been strengthened, it will be necessary to think about expanding the afore mentioned strategy to another that will guarantee that Mexico can have a strategic reserve of corn in the event of any global eventuality that threatens global supply chains.

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