Revista Facultad de Ingeniería (Rev. Fac. Ing.) Vol. 33, No. 69.
L-ISSN: 0121-1129, e-ISSN: 2357-5328.

DOI: 10.19503/01211129.v33.n69.2024.17119

MATHEMATICAL MODEL FOR THE DESIGN OF A BROILER CHICKEN SUPPLY CHAIN

Modelo matemático para el diseño de una cadena de suministro de pollos de engorde

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Fecha de recibido: 23-01-2024
Fecha de aceptado: 25-09-2024

ABSTRACT

Research on the design of agrifood supply chains has grown in recent years; however, there are still some sectors, such as the poultry industry, that have not been specifically considered and whose characteristics affect the network configuration decision. This research employed a three-phase methodology: first, characterizing the broiler chicken supply chain; second, developing a linear programming model for designing a supply chain that produces and markets broiler chickens in a Colombian city; and third, conducting a detailed analysis of the solution. As one of the main results, a network that minimizes transportation costs was established by determination of product flows between stakeholders during a year. The processing capacities of hatcheries, broiler farms, and processing plants were also considered. As future research, we intend to include the mortality rate during the transport derived from inadequate practices in the distribution operation of chicks and broiler chickens.

Keywords: broiler chickens; configuration; optimization: supply chain.

Esta edición se financió con recursos del Patrimonio Autónomo Fondo Nacional de Financiamiento para la Ciencia, la Tecnología y la Innovación, Francisco José de Caldas, Minciencias

Cómo citar este artículo: A-M. Paredes-Rodríguez, R-K. Duque-Zúñiga, J-B. Valencia-Potes, J-D. Melo-Vallejo, D-L. Peña-Orozco, "Mathematical model for the design of a broiler chicken supply chain", *Revista Facultad de Ingeniería*, vol. 33, no. 69, e17119, 2024. https://doi.org/10.19053/01211129.v33.n69.2024.17119

RESUMEN
La investigación sobre el diseño de cadenas de suministro agroalimentarias ha crecido durante los últimos años, sin embargo, algunos sectores como el avícola, cuyas características afectan la decisión de configuración de la red, aún no han sido considerados específicamente. Esta investigación empleó una metodología de tres fases: en primer lugar, la caracterización de la cadena de suministro de pollos de engorde; en segundo lugar, el desarrollo de un modelo de programación lineal para diseñar una cadena de suministro que produzca y comercialice pollos de engorde en una ciudad colombiana; y en tercer lugar, la realización de un análisis detallado de la solución. Uno de los principales resultados es la definición de una red que minimiza el costo de transporte a través de flujos de producto establecidos entre los *stakeholders* durante un año. Las capacidades de procesamiento de las plantas de incubación, granjas de engorde y plantas de beneficio también fueron consideradas. Como futura investigación se pretende incluir la tasa de mortalidad en el eslabón de transporte derivado a las inadecuadas prácticas en la operación de distribución de pollos recién nacidos y pollos de engorde.

Palabras clave: cadena de suministro; configuración; optimización; pollos de engorde.

1. INTRODUCTION

Agrifood supply chains are fundamental for countries because of their contribution in terms of food security [1], as well as to economic indicators such as gross domestic product (GDP) and employment [2]. Agri-food supply chains distribute various products such as fruits, vegetables, dairy products, beef, poultry, fish, and eggs. The configuration of this type of supply chain is influenced by the type of product, as each food presents a particular structure and characteristics that influence the strategic, tactical, and operational decisions of the network [3].

The poultry sector is one of the most important to produce basic food products for mass consumption worldwide. In Colombia, it plays an important role in food security and economic growth due to increased production and increased purchasing power of the population [4]. Broiler chickens are among the most demanded products in the poultry sector; the supply chain is mainly made up of hatcheries, farms, feed-manufacturing plants, processing plants, wholesalers, and retailers [5]. Broiler supply chain management is complex due to product losses resulting from bird diseases [6], poor transport route planning [7], and inadequate chicken feed [8], which makes decisions associated with network configuration key to manage the product, information, and money flows within the supply chain efficiently.

Agri-food supply chains involve the circulation of products, money, and information in a short life cycle [9] through various stakeholders like institutions, farmers, producers, cooperatives, industries, transporters, intermediaries, traders, retailers, wholesalers, and customers [10]. To identify research related to the design of food supply chains, especially broiler chickens or similar products, a literature review was conducted in the Scopus database using keywords such as “supply chain”, “meat or chicken”, “design.” Some relevant studies found during this process are presented below.

[11] developed a mathematical model for a multi-period, multi-product, multi-echelon configuration of a meat supply chain to optimize three objectives simultaneously, namely, minimization of total cost, minimization of CO2 emissions, and maximization of facility capacity utilization. The efficiency of the developed model was tested in a supply chain located in Ontario, Canada. Also, [12] established a resilient supply chain for the meat sector considering metrics of some sustainability lines (economic and environmental). The authors considered the effect of disruptions in the decision network associated with product flow, facility location, and inventory.

[7] developed a mathematical model for the design of a poultry supply chain in a pandemic context considering stochastic elements, multiple periods, and different modes of transportation. To validate the performance of the model, a case study on the broiler industry in the state of Mississippi, USA, was performed. [5] proposed an optimization-based methodology to integrate farms and processing plants and plan production under chicken growth uncertainty considering two models for inventory management and lot allocation.

[13] established a mixed integer linear programming model to design a supply chain for a Colombian multinational food company considering the maximization of the net present value (NPV) in different scenarios where the demand varies for each type of product. [14] proposed a model to design a food supply network with multiple objectives such as minimizing operating costs and maximizing end-customer satisfaction. This is directly related to product quality derived from network travel times and temperature conditions, which are uncertain in the network.

[15] developed a multi-objective mixed integer linear programming model for the strategic design of a perishable products network from a sustainability approach. Decisions associated with the flow within the chain, opening of nodes, and selection of transportation modes were considered. The metrics used by authors consist of cost minimization, carbon dioxide emissions, and product delivery time to the end customer.

[16] designed a supply chain for perishable products that considers disruptions in the network facilities and transportation between stakeholders. The authors proposed a mixed integer linear programming model and performed a scenario analysis considering the occurrence of different risks in the network, using total operating cost and value at risk (VaR) as main performance metrics.

[17] designed a supply chain for perishable foods, specifically dairy products, considering that the shelf life of the product varies depending on factors such as the temperature of the environment and the type of vehicle used. That mathematical model seeks to promote sustainability in the network by minimizing the net present value of network operating costs, while reducing energy consumption and traffic congestion as a social indicator.

[18] designed a broiler chicken supply chain to determine the centroid of retailer clusters and the location/allocation of processing plants in the network in such a way that total logistics costs are minimized while guaranteeing the use of vehicle and processing plant capacity. Mixed integer linear programming model was applied to a real case of a supply chain in the city of Tlemcen (Algeria) to test its validity, considering some data such as demand, costs, and capacity of the echelons. On the contrary, this research proposes a linear programming model to design a broiler supply chain in the department of Valle del Cauca - Colombia considering three echelons such as hatcheries, broiler farms, and processing plants.

2. METHODOLOGY

The methodology used for the study is shown in Figure 1. Initially, in Phase 1, a characterization of the broiler chicken supply chain was made; then, in Phase 2, the mathematical model for the network design was formulated; finally, in Phase 3, a detailed analysis of the results obtained after running the model with a real case study was carried out.

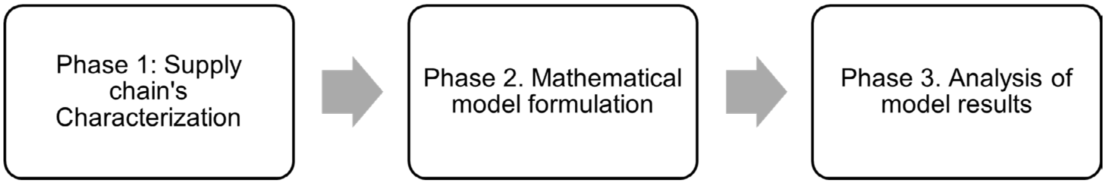

Figure 1. *Methodology used for broiler supply chain configuration.*

Phase 2. Mathematical model formulation

This phase involves the development of a mathematical model for the proposed design of a strategic supply network for broilers, considering the stakeholders and flows defined in Phase 1.

Phase 3. Analysis of model results

This phase includes the formulation of the model in AMPL language, running the model, and the analysis of the results derived from a case study in a Colombian city considering different decisions associated with the opening of facilities and flow within the network.

3. RESULTS

Phase 1. Supply Chain Characterization

From field work in the city under study, Figure 2 shows a general outline of the product flow in the broiler supply chain: hatcheries send day-old chicks to broiler farms; one month later, they are responsible for taking the chicks to the processing plants, which have contact with the final customer (retailers).

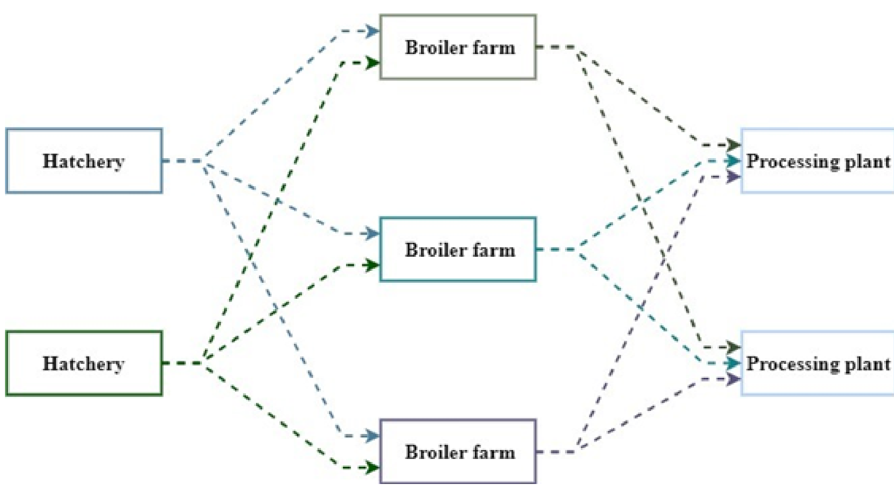

Figure 2. *Sketch of the supply chain under study.*

Phase 2. Mathematical model formulation

The mathematical model to be used in the design of the broiler supply chain considers all input parameters as deterministic. The model assumes that losses in the chain are depreciable; therefore, they are not considered in the model approach. The associated product flows between the stakeholders in the network, the number of trips, and the final inventory at broiler farm are some of the decisions considered in the model. The final model minimizes the logistical operating cost associated with poultry transportation. A detailed formulation is presented below:

Sets

Hatcheries i = P1, P2.

Broiler farms j = G1, G2, G3.

Processing plants k = B1, B2.

Months t = 1,2,3,4,5,6,7,8,9,10,11,12.

Parameters

Ioj = Initial inventory on broiler farms j.

VAN = Capacity of trucks transporting newborn chickens.

CAM = Capacity of trucks transporting broiler chickens.

INCUi = Capacity of hatcheries i.

GRANj = Capacity of broiler farms j.

CAPBEk = Capacity of processing plants k.

DEMk = Demand by processing plants k.

CT1 = Transportation cost of vans transporting newborn chickens ($/KM).

CT2 = Transportation cost of trucks transporting broilers chickens ($/KM)

DIST1j = Distance from hatcheries i to broiler farms j.

DIST2k = Distance from broiler farms j to processing plants k.

Variables

Xijk = Quantity of chickens to be shipped from hatcheries i to broiler farms j at time t.

Yjkt = Quantity of chickens to be shipped from broiler farms j to processing plants k at time t.

V1ijt= Number of trips made by the truck from hatcheries i to broiler farms j at time t.

V2jkt = Number of trips made by the truck from broiler farms j to processing plants k at time t.

Ijt = Final inventory of broiler farms j at time t.

Objective function

Equation (1) minimizes transportation costs between stakeholders considering the number of trips made according to the capacity of vehicles transporting hatchlings and broiler chickens, and the distance between stakeholders.

$$Minimize\ Z = \sum_{ijt} V1_{ijt} * CT1_{ij} * DIST1_{ij} + \sum_{jtk} V2_{jkt} * CT2_{jk} * DIST2_{jk} \tag{1}$$

Constraints

Hatchery capacity: Equation (2) shows that the number of chicks to be shipped from hatchery i to farm j at time t must be less than or equal to the capacity of hatchery i.

$$\sum_{j} x_{ijt} \leq INCU_i \ \ \forall i,t \tag{2}$$

Broiler farm capacity: in Equation (3), it is guaranteed that the number of chickens shipped from plant i to farm j at time t is less than or equal to the capacity of broiler farm j.

$$\sum_{i} x_{ijt} \leq GRAN_j \ \ \forall j,t \tag{3}$$

Capacity of the processing plants: Equation (4) shows that the quantity of chickens to be sent from farm j to processing plant k at time t be less than or equal to the capacity of processing plant k.

$$\sum_{j} y_{jtk} \leq \mathrm{CAPBE}_k \ \forall k,t \tag{4}$$

Calculation of the number of trips between hatcheries and broiler farms: Equation (5) shows that the number of trips made by the van from hatchery i to farm j must be greater than or equal to the number of chicks to be shipped from hatchery i to farm j at time t divided by the capacity of the vans transporting the hatchlings.

$$V1_{ijt} \geq \frac{X_{ijt}}{VAN} \ \forall i,j,t \tag{5}$$

Calculation of the number of trips between broiler farms and processing plants: Equation (6) guarantees that the number of trips made by the truck from broiler farms j to processing plants k be greater than or equal to the number of chickens to be shipped from broiler farms j to processing plants k at time t divided by the capacity of the trucks transporting fattened chickens.

$$V2_{jkt} \geq \frac{Y_{jkt}}{CAM} \ \ \forall j,k,t \tag{6}$$

Demand by processing plants: Equation (7) shows that the quantity of broilers to be shipped from broiler farms j to processing plants k at time t must be greater than or equal to the demand by processing plants k.

$$\sum_j y_{jtk} \geq \text{DEM}_k \ \forall k, t \quad (7)$$

Broiler Farm Inventory: Equation (8) and (9) represent the set of inventories in broiler farm j.

$$I_{j,1} = Io_j \ \ \forall j \quad (8)$$

$$I_{jt} = \sum_i I_{jt-1} + X_{ijt-1} - \sum_k Y_{jkt} \quad \forall j, t > 1 \quad (9)$$

Phase 3. Analysis of model results

The model is programmed in AMPL language and was run on an Intel Core i5 10TH generation computer with 4GB RAM. The model was tested for a small instance consisting of 2 hatcheries, 3 broiler farms, 2 processing plants, and 12 months. The main results are presented below.

The estimated annual cost of optimal distribution for the network is USD$31,230,800. For presentation purposes, only the results of the first five months of the model will be shown. Tables 1 and 2 show that hatchery 1 controls distribution only to farm 3, which has a capacity of 89,000 birds and partially fulfills its capacity, since 70,000 birds are shipped. Therefore, it benefits from the transportation costs and the fulfillment of the client's demand. Similarly, hatchery 2 controls transporting the total capacity of farms 1 and 2, that is 9,500 and 14,000 chicks, respectively, and also sends the amount necessary to complete the capacity of the plant to farm 3, which is equivalent to 89,000 hatchlings.

Table 1. *Route from hatchery 1 to broiler farm 3*

Hatchery 1					
Months	**1**	**2**	**3**	**4**	**5**
Quantity of birds	70,000	70,000	70,000	70,000	70,000
Trips number	7	7	7	7	7

Table 2. *Route from hatchery 2 to broiler farms 1, 2, and 3.*

Hatchery 2					
Months	**1**	**2**	**3**	**4**	**5**
Quantity of birds farm 1	9,500	9,500	9,500	9,500	9,500
Number of trips farm 1	1	1	1	1	1
Quantity of birds farm 2	7,000	10,000	10,000	10,000	10,000
Number of trips farm 2	1	1	1	1	1
Quantity of birds farm 3	16,500	13,500	13,500	13,500	13,500
Number of trips farm 3	2	2	2	2	2

Tables 3 and 4 show that farms 2 and 3 are responsible for sending broiler chickens to processing plant 1, thus meeting its demand for 70,000 chickens. Farms 1 and 3 send the chickens to processing plant 2, farm 2 sends all its production and farm 3 transports what is required to complete the demand for 33,000 chickens by processing plant 2.

Table 3. *Route from broiler farms to processing plant 1*

Processing plant 1					
Months	**1**	**2**	**3**	**4**	**5**
Quantity of birds farm 2	0	10,000	10,000	10,000	10,000
Number of trips farm 2	0	1	1	1	1
Quantity of birds farm 3	0	60,000	60,000	60,000	60,000
Number of trips farm 3	0	6	6	6	6

Table 4. *Route from broiler farms to processing plant 2*

Processing plant 2					
Months	**1**	**2**	**3**	**4**	**5**
Quantity of birds farm 1	0	4,500	13,000	13,500	13,000
Number of trips farm 1	0	1	2	2	1
Quantity of birds farm 3	0	28,000	20,000	19,500	30,000
Number of trips farm 3	0	3	2	2	3

4. CONCLUSIONS

A linear programming model was developed to design a broiler supply chain that considers flow decisions between hatcheries, broiler farms, and processing plants over time. The model minimizes the total transportation cost of the network.

The designed model includes a particular constraint of the broiler supply chain: chicks must be one month at the broiler farm before being marketed. For future research it is expected to include a bird mortality factor within the broiler rearing and transport activities.

Due to the environmental and social impact of broiler supply chains, future research is expected to include other economic indicators in addition to transportation costs, while involving social and environmental metrics that lead to defining a sustainable network configuration.

AUTHORS' CONTRIBUTION

Andrés Mauricio Paredes-Rodríguez: Investigation; Methodology; Writing-review & editing; Formal Analysis. **Ruth Karina Duque-Zuñiga:** Investigation; Methodology. **Jhon Bairon Valencia-Potes:** Investigation; Methodology. **Juan David Melo-Vallejo:** Investigation; Methodology. **Diego León Peña-Orozco:** Investigation; Validation.

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