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ARTICLES

MODELLING AND OPTIMIZING THE TACTICAL PLANNING OF THE CORN SUPPLY CHAIN CONSIDERING DOMESTIC AND EXPORT MARKETS

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ABSTRACT. In this study, optimization models for the production and logistics tactical planning of the corn supply chain are presented and several outputs are explored. They consider the domestic market for animal consumption, ethanol production, and the international market. They are mainly oriented to support policies and decisions of public agents who have some interference in the supply chain. To evaluate the consistency and effectiveness of the models, they were applied to solve realistic problem instances of the Brazilian corn supply chain considering different scenarios and using data collected from several sources. The outcomes demonstrated that models can produce analysis considering aspects that have not been fully addressed in the literature before, such as some opportunities to use different modes of transport for corn distribution, to contract extra capacity for stocking and the impacts of some state taxes on its production and logistic systems. Other important aspects explored in the scenario analysis are the identification of capacity bottlenecks and investment opportunities. The conclusions and insights are converted into practical interpretations to support relevant supply chain decisions.

Keywords: production tactical planning, logistic planning, supply chain management, optimization model, corn agroindustry.

1 INTRODUCTION

Agribusiness has always played a relevant role in the world economic scenario, particularly in countries such as Brazil. However, its geographic dispersion and the interference of biological and climate factors imply complex production systems. Specifically, corn production involves a production chain whose agents must prioritize the offer of high-quality grains at low cost to remain competitive in the market. Corn is one of the most cultivated cereals on all continents.

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Some countries notably lead in corn production, including Brazil, which is one of the largest producers and consumers worldwide. Corn production is a complex agro-industrial and logistics chain comprising macro segments: agricultural production (seed and the grain to consumption), grain pre-processing, distribution to the consumers and eventually industrial processing to make manufactured products.

Figure 1 summarizes the corn agro-industrial chain. It involves some activities, operations and procedures related to the transformation, processing, and improvement of agricultural production, *in natura* or derivatives. These activities add value to the final product. In the "Before the farms" stage, preparation for planting corn takes place, involving cooperatives and resellers of agricultural inputs. The "Planting on the farms" stage includes planning and scheduling the harvest according to demand. The "After the farms" stage indicates the logistical distribution.

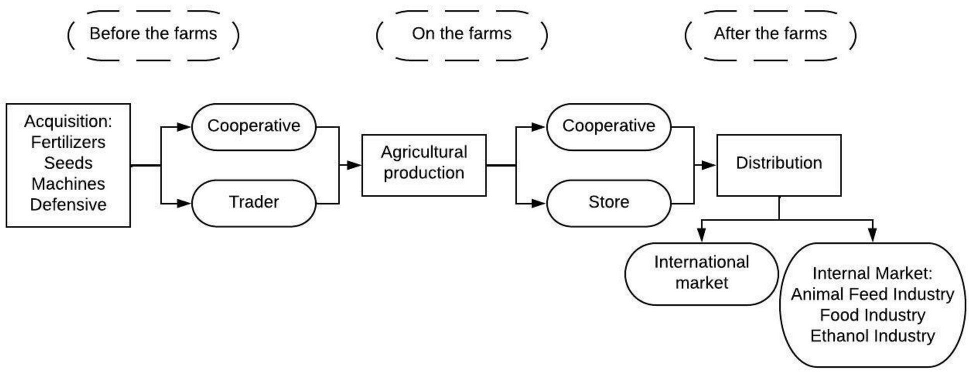

Figure 1 – Corn agro-industrial supply chain.

It is relevant to highlight that optimization models can be useful to indicate and quantify alternatives to reduce costs or maximize profit of agro-industrial chains, seeking the economical and operational efficiency of the stakeholders, considering flow restrictions, capacities, inventory balance and different types of demands. The main objective of this study is to present optimization models to support key tactical planning decisions in part of the corn grain agro-industrial chain aiming at to meet domestic and export demands. The focus was on the Brazilian context, but it can also be applied, with the necessary adjustments, to corn agro-industrial chains worldwide, or even to other products with similar characteristics to those of corn, such as soy, sorghum, or wheat.

Concerning the agricultural issue of the problem, the mathematical models consider the area availability, the productivity of the harvesting regions and the storage capacity, which are all factors of great impact on business profitability. In logistics, the models consider the distribution to meet the demand via different modes of transport. A linear optimization model and a variant of it are presented here. The first one (called Model 1) has the objective function of minimizing costs in the chain to meet domestic and export demands, including the cost of planting and harvesting, cost of drying grains, cost of corn transportation between silos and customers, cost of corn stocks, cost of contracting extra capacity in the silos (silo bag, i.e., a flexible polyethylene tube for temporary storage) and cost of importing corn whether necessary. The model also considers fiscal taxes (in the case of Brazil, mainly the Tax on Circulation of Goods and Services – *Imposto sobre Operaões relativas à Circulação de Mercadorias* - ICMS) and focuses on the importance of analyzing more than one mode of transport. For example, the model allows us to examine the competitiveness among Brazilian states due to different tax polices, logistic incentives etc.

The second model (Model 2) is a variant of Model 1, with the objective function of maximizing the profit margin (or economic/operational efficiency) obtained by meeting the demands of animal nutrition (beef, poultry, swine etc.), ethanol production and exports. It considers that the sale price of corn differs among those demands. In addition, Model 2 provides the possibility of not meeting the demands that are not economically viable. Through these models, we aim to help the decision-making process of public agents from governmental institutions, such as the Ministry of Agriculture and secretariats of municipalities, states, and countries, instead of isolated companies or private associations in the corn business that operate in only part of the whole chain. These agents can interfere in the supply chain, for example, through incentives and investments in different production, storage, and transportation capacities throughout the chain, by changing legislation and taxes that affect the chain, among other managerial actions.

In this study, we intend to contribute to supporting decisions in the management and tactical planning of corn supply chains. We address some research questions, such as: (i) Are there enough production, storage, and distribution capacities throughout the chain to ensure that all the demands of domestic and external markets will be met? (ii) Is it profitable to meet all these demands, considering the key costs involved and the current corn prices in the chain? To the best of our knowledge, no other studies have been found in the literature exploring this line of research for the corn supply chain. This article is organized in five more sections, besides this introduction. Section 2 presents a literature review related to optimization models in corn supply chains. Section 3 describes the problem with the dataset. In Section 4, the optimization models are detailed. Computational results are mainly described graphically in Section 5. The conclusions and insights from the computational outcomes are converted into practical interpretations supported by sensitivity analyses and alternative scenarios are discussed in Section 6. In this last section, we also discuss the possibilities of further investigations in this line of research.

2 LITERATURE REVIEW

The relevance of agro-industries to the economy leads to studies in several areas of optimization, mainly concerning the effective planning of agricultural and industrial production and logistics issues, or even in topics related to sustainable supply chains. Studies on the corn agroindustry have increased in recent years addressing different perspectives, from attention to the chemical composition of the raw material and derivatives to more agricultural and industrial concerns regarding production planning.

Studies related to the chemical composition of corn appear in Johnston and Singh (2004), who presented an optimization of enzymatic milling to minimize the quantity of enzymes compared to conventional milling. Busato et al. (2019) present a decision support system for a given corn silage production system that determines the configuration of the ideal number of transport units in each field of an area to be harvested. The authors minimize the total operating cost of the production under time constraints to complete the operation. Soto et al. (2013) aim to develop a model based on system dynamics that allows the simulation of the effect of knowledge management on the supply chain in the corn industry. Oliveira and Silveira (2014) analyzed the effects of corn segregation on Brazilian transport and storage logistics and how this affects its competitiveness worldwide.

Zuo, Kuo, and McRoberts (1991) combined linear optimization and mixed integer linear optimization through a heuristic procedure aiming to solve the production planning problem for a corn-seed production company, thus reducing costs. Jones et al. (2003) built a model for Syngenta's corn seed plan in two stages (corresponding to the company's facilities in North and South America) aiming to maximize the expected gross margin, through linear optimization using discrete approximations for demand and yield distributions. Junqueira and Morabito (2006, 2008, 2012) developed mathematical models to assist tactical production, storage and transport planning decisions considering the corn seed chain. Later, they analyzed the application of these models to generate optimized aggregate planning in a case study of a company in the corn seed sector. Table 1 summarizes the literature review directly related to the line of the present research for the corn agro-industrial chain.

3 PROBLEM DEFINITION

To better understand of the corn supply chain discussed here and the related decision problems for which the models in the next section serve, we consider the service of the domestic market (animal consumption and production of ethanol) and exports to other countries. Despite the distinction between the agricultural and industrial sectors, the activities throughout the chain are strongly connected, and the decisions of one sector directly influence the decisions of the other.

Agricultural operations are named as the first stage, in which the activities are the production and harvesting of corn in the producing states, and transport of grains to the Processing Units (*Unidades de Beneficiamento* - UB). The arrival of the corn grains at the UB indicates the beginning of the industrial stage, in which the grains are dried and sent to the storage silos. The main activity is the inventory management to ensure that demand is met. Transport logistics for domestic demand locations (here identified by centroids) and for export through seaports implies a challenge in logistics optimization. A schematic model representing the problem is presented in Figure 2 and shows the phases throughout the corn supply chain, from production planning and harvesting to meeting demand.

Table 1 – Studies on corn supply chain optimization.

Author	Problem	Optimization approach
Zuo, Kuo, and McRoberts (1991)	Production planning of a seed corn company and cost reduction.	Linear optimization and mixed integer linear optimization combined by the heuristic method.
Jones et al. (2003)	Modeling Syngenta's two-stage corn seed plan to maximize expected gross margin.	Linear optimization using discrete approximations for demand and throughput distributions.
Johnston and Singh (2004)	Minimization of the quantity of enzymes compared to conventional milling.	Optimization of the first grinding, immersion time and enzyme incubation time.
Junqueira and Morabito (2006)	Minimization of the total cost of production and logistics, including transportation, corn seed processing and ICMS costs.	Linear optimization model.
Junqueira and Morabito (2008)	Optimization in aggregate crop planning in a corn seed company.	Application of a linear optimization model in a case study.
Junqueira and Morabito (2012)	Tactical planning of production, storage, and transport of corn seeds in an entire crop.	Application of a linear optimization model to support decisions of a Brazilian company in the corn seed sector.
Soto et al. (2013)	Knowledge management in the supply chain in the corn industry.	Modeling in information technology that enables simulation.
Oliveira and Silveira (2014)	Measurement of how biotechnology regulatory issues directly affect infrastructure logistics.	Partial equilibrium model as a mixed complementarity problem and application of simulation.
Busato et al. (2019)	Decision support system to minimize the total operating cost of a production system under time constraints.	Combination of a simulation model and an optimization model based on linear optimization.

Models and decisions to be optimized

The aim of the problem is to support some key decisions of the tactical planning in the corn supply chain, to minimize the total cost of the chain (Model 1) or maximize the total profit of the chain (Model 2). To do this, the production capacity must be considered, and the need for imports should be verified. Regarding transportation, the purpose is to determine the most economical routes of distribution that are capable of meeting internal and external demands, considering different modes of transport. In addition, the objective function aims to minimize the amount stored at the end of the annual planning period and the contracting of extra storage capacity. The decisions to be supported by the models and which are directly related to the mentioned objectives are:

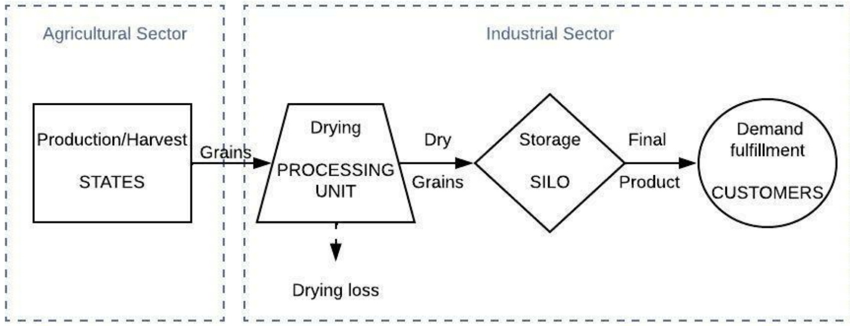

Figure 2 – Schematic model of the corn supply chain.

- How much cultivated area will be needed to meet the demands?
- How much corn will be dried and shipped from the coop's silos to demand points?
- Which modes of transport will be used in distribution?
- How much corn will be stored over the periods?
- How much extra storage capacity (silo-bag) will be contracted?
- How much corn will be imported to meet domestic demands?
- How much corn will be exported to meet external demand?

Main constraints of the problem

Several constraints must be considered in the production and logistics planning problem, such as:

- Demand constraints: the model solution must fully meet the customer demand (Model 1), or it can only partially meet the customer demand (Model 2). One constraint is dedicated to meeting internal customer demand and the other meets the external customer demand by sending the available quantity from the silos and importing corn grains, whether necessary.
- Continuity constraints: the input material flow must be the same as the output from the silos, that is, the amount of harvested corn is sent in full to the storage silos, before being transported to the final customers. For the sake of simplicity, the losses in the processes (pre-harvest, harvest, transportation and storage) are not explicitly considered in the tactical planning, but only implicitly considered in some parameters of the model, such as productivity.

- Capacity constraints: corn-producing states, storage silos, railroads and international distribution seaports have limited and known capacities.

- Inventory constraints: to control demand fulfillment, inventory must be balanced at the end of each period. The sum of the existing stock is considered at the end of the previous period and the corn production of the current period. The resulting value represents the total amount of corn available for this period and, after subtracting the amount allocated to meet the internal and external demand of the period, the remainder represents the stock at the end of the current period.

Features of the problem and its parameters

The analytical study of the parameters used in the optimization models of this work shows that the data collection process is one of the most relevant parts of tactical planning. The first parameters are related to corn planting. This is the area available for planting in each producing state in each period, measured in hectares, with two harvesting seasons per year. The average yield or area productivity of the producing states in each harvest is measured in tons per hectare. The values were collected from the Brazilian Geographic Information System of Automatic Recovery – SIDRA (IBGE 2022).

In the corn supply chain considered here, the problem involves several producing states, i.e., 26 states are considered (25 federative units and 1 federal district), all of which present the area available for planting and the yield crop in the determined period. The state of Amapá was not analyzed in this study because there is still no land or route connection between Amapá and the rest of the country. The macro logistics of grain exports in this study mainly uses the road and rail modes. According to the study "Harvest Paths of Grain Production and Exports" (EMBRAPA TERRITORIAL 2022), the 2015 harvest included the export of 99 million tons of grain in its varieties (soybean and corn - bran and oil). The railway mode had a 47% share and the road mode had 42%. The waterway mode presented just over 10% and, due to its low percentage in relation to the others, for the sake of simplicity it is not considered in this study.

After drying, the corn is transported to multiple silos for the storage. Storage can take place in private and public silos; the latter from Conab (National Supply Company), where there are around 67 depots distributed throughout the country (Conab, 2022). Multiple customers are considered represented by 26 centroids of internal demand for animal consumption and ethanol production (one in each state), and 2 external customers (China and the Netherlands), representing the demand in Asia and Europe. The product consists of dry grains for three main sources of demand: animal feed, ethanol production and exports. It is noteworthy that the dried corn supply chain is independent from the sweet corn or corn seed chains. Dried corn chain independence can be exemplified through the different processing for feed and bran, wet and dry milling products (Figure 3).

Regarding data aggregation, the states with the highest production (Mato Grosso and Paraná) were divided into five macro-regions. The tactical planning horizon considered is one year. For

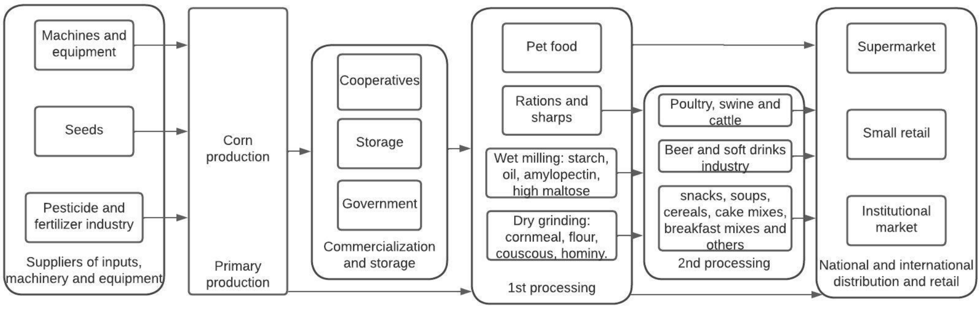

Figure 3 – Dried corn agribusiness in Brazil.

better detailing and to make it more coherent with reality, the data in relation to time are disaggregated into two harvesting periods with different durations and yields, known as main harvest (*safra*) and off-season harvesting (*safrinha*). The term off-season harvesting is used for cultivation of rainfed corn sown from January to April, after the usual harvesting of the summer crop.

The road transportation is responsible for more than half of the cargo transport in Brazil. In 2019, before the Covid-19 pandemic, it accounted for 61.1% of movements, compared to 20.7% for rail and 13.6% for waterways (CNT, 2022). The transportation mode considered to meet the domestic demand is exclusively by road. To meet the external demand, the modes considered are highways and railways, as they have almost 90% of the share in the transport for exports (EMBRAPA TERRITORIAL, 2022). The routes may have only one of the transportation modes or both. The railway mode is considered so that the model can explore the most economical routes according to the existing capacity.

For external customer service, multiple seaports designated for corn export are considered, according to the Strategic Territorial Intelligence System of Brazilian Agricultural Macrologistics (EMBRAPA TERRITORIAL, 2022). The ports are: Port of Santos (SP), Port of Paranaguá (PR), Port of Rio Grande (RS), Port of São Francisco do Sul (SC), Port of Itaqui / São Luís (MA), Port of Vitória (ES), Port of Itacoatiara (AM), Port of Santarém (PA), Port of Barcarena/Vila do Conde (PA), Port of Imbituba (SC) and Port of Itajaí (SC).

Problem capacity parameters are measured in tons per year. For silos, they indicate the maximum quantity of dried grains that can be stored in warehouses in a period, measured by Conab (2022). The capacity of seaports indicates the limit of port movement of corn grains that were collected at EMBRAPA TERRITORIAL (2022). The railway capacity reflects the amount available for grain transportation (ANTF, 2022). The internal demand parameter was measured in tons per year, considering the specific consumption of corn in poultry and swine production. According to the monitoring of the Brazilian grain harvest carried out by Conab (2022), these two categories of animals are the largest consumers of corn as the basis of their diet from birth to slaughter in all Brazilian states. To calculate this parameter the number of heads per herd type per state is multiplied by the specific corn consumption per animal type. The demand for corn grains to produce ethanol is gaining ground in the Brazilian industry and is indicated in tons per year. The domestic demand for corn for human and industrial consumption represents a small share compared to animal feed and ethanol. The demand for animal nutrition represents 78% of the total, 16% for industrial consumption and 6% for non-commercial consumption (for producers' own consumption) (IEA, 2021). The external demand parameter was measured in tons per year and represents the amount of corn grains that Brazil exports to foreign countries in a period. The parameters related to financial costs are of six types: planting, drying, stocking, transport, imports and contracting of extra storage capacity.

The cost of planting and drying grains are the main production costs and are measured in the Brazilian currency real (BRL) per ton. Inventory cost is also listed among production costs and represents storage expenses (BRL/ton). These costs were collected from Conab (2022). The transportation cost represents the distribution of corn from the silo where it is stored to the demand centroid, whether the customer is internal, or to the seaport, whether the customer is external. The calculation of this cost involves the multiplication of the distance, in kilometers, and the moment of freight, in BRL per ton per kilometer. Distance data were taken from the Google Maps (2022). Freight momentum varies whether the transport mode is road or railway, and the data were collected in Sifreca (2021) and ANTF (2022) added the ICMS tax when the flow was among states. The import cost represents the average cost of purchasing corn in grains from foreign-producing countries (in BRL/ton). The sale price of corn in grain represents the amount paid according to the different types of demand: animal nutrition, ethanol production and export Cepea (2021). The cost of hiring extra storage was obtained for silo bags (in BRL/ton) and the data came from Conab (2022).

4 MATHEMATICAL MODELLING

To mathematically represent the problem, a linear optimization model (Model 1) and a simple variation of it (Model 2) are developed, which are presented next. Figure 4 displays a temporal scheme of problem with the decision variables and their relationship centered in period t.

Definition of sets and indexes

$e \in E$ Producing states.

$j \in J$ Storage silos.

$p \in P$ Seaports.

$r \in R$ Route of transport (road and railways).

$k \in K$ Customers (internal and external).

$s \in S$ Harvest season (main and off season).

$t \in T$ Time periods (years).

Parameters

α_{est} crop yield of state e in harvest s in period t [ton/ha].

β_{est} Area available for planting in state e in harvest s in period t [ha].

δ_{jt} Storage capacity of silo j in period t [ton].

ε_{pt} Capacity of seaport p in period t [ton].

θ_t Railway capacity in period t [ton].

σ_{kt} Corn demand of internal customer k in period t [ton].

Ψ_{kt} Ethanol demand of internal customer k in period t [ton].

λ_{kt} Corn demand of external customer k in period t [ton].

γ_{kt} Price paid by customer k in period t [\$/ton].

ρ_{est} Planting cost in state e at harvesting season s in period t [\$/ton].

ω_{jt} Corn drying cost sent to silo j in period t [\$/ton].

ϑ_{esjt} Shipping cost from state e to silo j at harvesting season s in period t [\$/ton].

τ_{jkt} Transportation cost from silo j to internal customer k in period t [\$/ton].

μ_{jkprt} Transportation cost from silo j to external customer k via seaport p using the mode r in period t [\$/ton].

π_{jt} Cost of extra storage contracted for silo j in period t [\$/ton].

φ_{jt} Storage cost in silo j in period t [\$/ton].

υ_t Purchase cost of the imported corn in period t [\$/ton].

Decision variables

P_{est} Area harvested in state e at season s and period t [ha].

W_{ejt} Quantity of corn in state e dried and sent to silo j in period t [ton].

X_{esjt} Quantity of corn shipped from state e to silo j at harvest season s and period t [ton].

Y_{jkt} Quantity transported from silo j to internal customer k in period t [ton].

E_{jkprt} Quantity transported from silo j to external customer k via seaport p through transport mode r in period t [ton].

I_{jt} Quantity of corn storage in silo j in period t [ton].

S_{kt} Imports destined to internal customer k in period t [ton].

C_{jt} Extra storage capacity for silo j contracted in period t [ton].

Z Objective function value.

Auxiliary variables (slack)

A_{kt} Variable to allow partial fulfillment of animal demand [ton].

L_{kt} Variable to allow partial fulfillment of ethanol demand [ton].

D_{kt} Variable to allow partial fulfillment of external demand [ton].

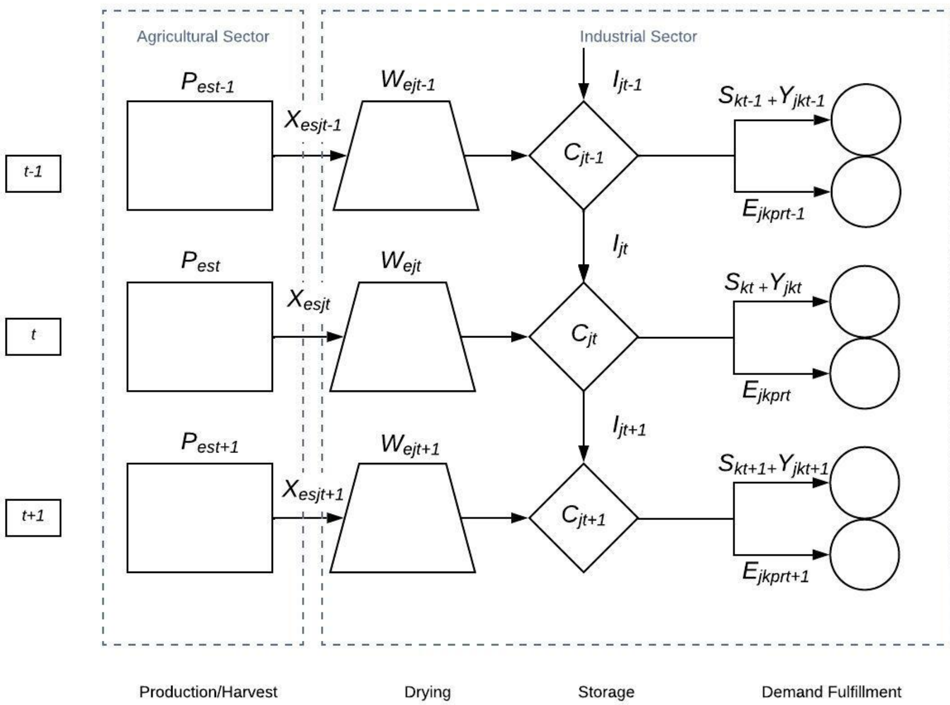

Figure 4 – Time clipping indicating the variables of the problem at period *t*.

Objective function

The objective function (1.1) of Model 1 aims to minimize the total cost of the supply chain and comprises eight parcels. The first one represents the cost of planting corn in each state and the second represents the cost of drying corn before it arrives in the silos. The third, fourth and fifth parcels represent transportation costs. The third corresponds to the cost from the producers to the silos, the fourth corresponds to the cost from the silos to the internal customers via roads and the fifth one from the silos to the external customers via seaports considering different modes of transport, including a combination of road and railway. The sixth minimizes the hiring of extra storage capacity. This storage takes place by silo bags to reduce costs. The seventh parcel corresponds to the inventory cost along the periods. Finally, the eighth is the cost of importing corn grain, when necessary.

$$Z1 = \sum_e \sum_s \sum_t \rho_{est} P_{est} + \sum_e \sum_j \sum_t \omega_{jt} W_{ejt} + \sum_e \sum_s \sum_j \sum_t \vartheta_{esjt} X_{esjt} + \sum_j \sum_k \sum_t \tau_{jkt} Y_{jkt} + \sum_j \sum_k \sum_p \sum_r \sum_t \mu_{jkprt} E_{jkprt} + \sum_j \sum_t \pi_{jt} C_{jt} + \sum_j \sum_t \varphi_{jt} I_{jt} + \sum_k \sum_t \upsilon_t S_{kt} \tag{1.1}$$

The minimization of the total cost along the supply chain is important to the business aiming to offer a high-quality product at a competitive price in the domestic and foreign markets. The objective function (1.2) refers to Model 2 and aims to maximize the total profit of the chain. It comprises three invoicing components and eight other cost parcels from the objective function (1.1). These first three parcels of (1.2) represent the revenue obtained from meeting (total or partially) internal and external demands. We use auxiliary variables in these three parcels.

$$Z2 = \sum_k \sum_t \gamma_{kt} (\sigma_{kt} - A_{kt}) + \sum_k \sum_t \gamma_{kt} (\psi_{kt} - L_{kt}) + \sum_k \sum_t \gamma_{kt} (\lambda_{kt} - D_{kt}) - \sum_e \sum_s \sum_t \rho_{est} P_{est} - \sum_e \sum_j \sum_t \omega_{jt} W_{ejt} - \sum_e \sum_s \sum_j \sum_t \vartheta_{esjt} X_{esjt} - \sum_j \sum_k \sum_t \tau_{jkt} Y_{jkt} - \sum_j \sum_k \sum_p \sum_r \sum_t \mu_{jkprt} E_{jkprt} - \sum_j \sum_t \pi_{jt} C_{jt} - \sum_j \sum_t \varphi_{jt} I_{jt} - \sum_k \sum_t \upsilon_t S_{kt} \tag{1.2}$$

Constraints

- Production and flow continuity: constraints (2) transform corn crop in grain storage in all silos for each state, season, and period. Constraints (3) ensure that the quantity storage is equal to the production of the two harvesting season s in period t. In this study, $t=1$ (one year) and $s=2$ (two harvesting seasons), but it was decided to maintain the t index to have a model that could be applied to multiple years.

$$\alpha_{est} P_{est} = \sum_j W_{ejt} \qquad \forall\, e,s,t \tag{2}$$

$$W_{ejt} = \sum_s X_{esjt} \qquad \forall e,j,t \tag{3}$$

- Capacity limit: constraints (4) indicate the limit of available area to harvest corn in each state and season. In constraints (5), the amount of corn sent from producing state e to silo j in period t must be less than the storage capacity of this silo in this period, added to the contracted amount of extra storage in silo bags. Constraints (6) and (7) ensure, respectively, that the amount of corn sent from silo j to external customer k by port p through mode of transport r in period t must be smaller than the port handling capacity for corn grains in this port p in period t (6) and the transport capacity by rail in this period t (7).

$$P_{est} \leq \beta_{est} \quad \forall\, e,s,t \tag{4}$$

$$W_{ejt} \leq \delta_{jt} + C_{jt} \quad \forall e,j,t \tag{5}$$

$$\sum_j \sum_k \sum_r E_{jkprt} \leq \varepsilon_{pt} \quad \forall p,t \tag{6}$$

$$\sum_j \sum_k \sum_p \sum_r E_{jkprt} \leq \theta_t \quad \forall t \tag{7}$$

- Demand: Model 1 must meet all internal and external customer demands, while Model 2 can only partially meet these demands if doing so is more profitable. Constraints (8.1) refer to Model 1 and indicate the fulfillment of the internal demand, where the amount of corn sent to the internal customer k in period t from silos is equal to the internal demand of corn for animal consumption and for ethanol production. Meanwhile, constraints (8.2) refer to Model 2 and indicate that the fulfillment of customer demand k in period t may be partially met, depending on the values of the auxiliary variables A_{kt} and L_{kt}.

$$\sum_j Y_{jkt} + S_{kt} = \sigma_{kt} + \psi_{kt} \quad \forall k,t \tag{8.1}$$

$$\sum_j Y_{jkt} + S_{kt} = (\sigma_{kt} - A_{kt}) + (\psi_{kt} - L_{kt}) \;\; \forall\, k,t \tag{8.2}$$

- Similarly, constraints (9.1) refer to Model 1 and guarantee the fulfillment of all external demand, in which the sum of the amount of corn sent from the silos to the external customer k by port p through mode of transport r in period t should be equal to the demand of this external customer in this period. Constraints (9.2) refer to Model 2 and allow the fulfillment of these demands to be partially met, according to the values of auxiliary variables D_{kt}.

$$\sum_j \sum_p \sum_r E_{jkprt} = \lambda_{kt} \quad \forall k,t \tag{9.1}$$

$$\sum_j \sum_p \sum_r E_{jkprt} = \lambda_{kt} - D_{kt} \quad \forall k,t \tag{9.2}$$

- Inventory: stock balancing constraints (10) state the stock in silo j in period t is equal to the sum of the stock in this silo in the previous period $(t-1)$ summed with the corn production sent from the states to this silo in this period, subtracted by the quantities transported from this silo for internal and external customers.

$$I_{jt} = I_{j(t-1)} + \sum_e W_{ejt} - \sum_k Y_{jkt} - \sum_k \sum_p \sum_r E_{jkprt} \quad \forall\, j,t \tag{10}$$

5 COMPUTATIONAL RESULTS

The data collection process for the model parameters was done by contacting government institutions, private companies, and organizations in the agricultural sector, accessing several databases,

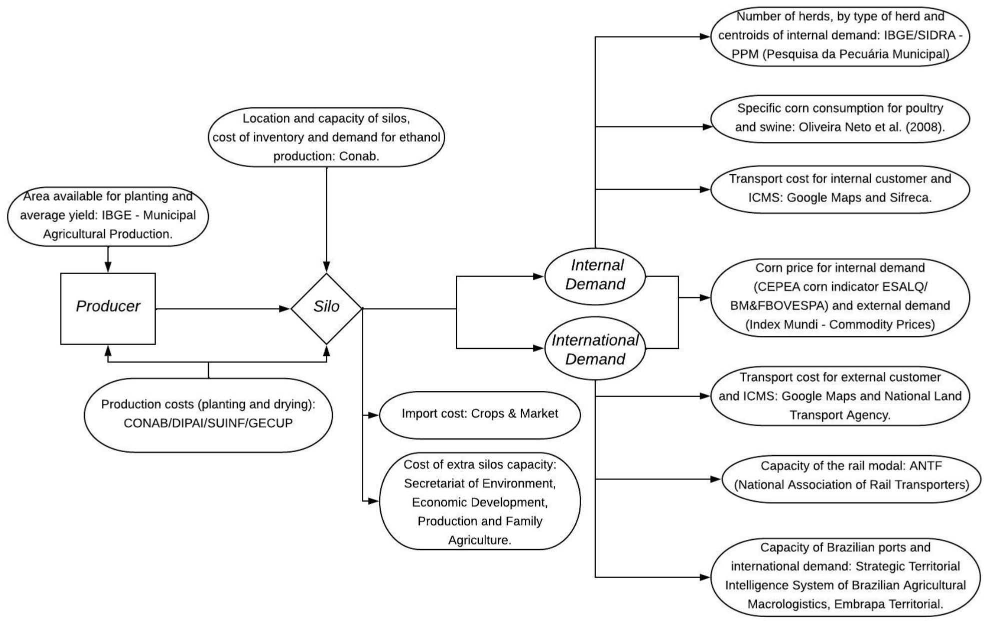

Figure 5 – Scheme of collecting data from different sources.

in addition to other internet searches. These data aim to represent the scenario of the corn supply chain studied. Figure 5 provides an outline of data collection from different sources in this research.

Models 1 and 2 can consider multiple periods and are able to produce solutions for tactical or even strategic planning, according to the granulometry of the data (monthly, semi-annual, annual etc.). Despite this, in the present study a single-period planning horizon was considered, that is, of one year and involving two consecutive harvestings that do not overlap in the year, as mentioned in Section 3. This scenario was called the baseline scenario and other alternative scenarios were also considered to investigate the impacts of changes in the parameters, such as in corn productivity (Scenario 1), changes in the seaport capacities (Scenarios 2 and 4), changes in railway capacities (Scenarios 3 and 4), changes in tax rates (Scenario 5) and changes in corn prices and in the corn demand from domestic and foreign markets (Scenarios 6, 7, 8 and 9), among others. These scenarios are in line with the objectives of this study, and other scenarios could still have been created to analyze the supply chain.

Analysis of alternative scenarios helps to validate hypotheses and evaluate more robust tactical production and logistics plans. Briefly, the baseline scenario involves $|E| = 34$ producers (24 states + 10 macro-regions of the two large producing states), distributing corn to $|J| = 67$ silos and meeting 3 types of corn demands from $|K| = 26+1 = 27$ internal and external customers: corn for animal consumption, corn for ethanol production and corn for exports. Each state can cultivate up to crops ($|S| = 2$) in the one-year period ($|T| = 1$). The transport of corn grains can be performed by road or rail, or a combination of both along the route (i.e., $|R| = 3$). External customers can be served through eleven seaports $|P| = 11$. Imports of corn are also allowed to meet some internal demands. There may be stock at the end of the period and extra storage in the form of silo bags is available in the chain for contracting.

To solve the models, the algebraic programming language GAMS 24.1.3 and the solver CPLEX 12.5 were used on a computer with 8 GB of RAM, Intel® Core® CPU i5-7200U and 2.5 GHz processor, and Windows 10 operating system. The models in the different scenarios analyzed involve more than 20 thousand variables and more than 5 thousand constraints. They could be solved until finding the optimal solution in computational times of a few seconds. Throughout this section, the results of the models for the baseline scenario and the others are presented mainly in the form of figures, graphs, and tables, to simplify the presentation and analysis of the solutions. For reasons of space saving, the solutions for each scenario are not presented here in detail, but they can be consulted in Marins (2021).

Baseline scenario

The baseline scenario performed with Model 1 aims to represent the status of the corn supply chain studied according to the parameters obtained. The main variables analyzed are the planted and harvested area of corn (P_{est}), the fulfillment of the demands of the internal (Y_{jkt}) and external markets (E_{jkprt}), the drying of the corn (W_{ejt}), the usage of extra capacity in the silos (C_{jt}), and the amount of corn imported (S_{kt}). Other variables analyzed are the corn transportation from the states to silos (X_{esjt}), generally located in the states, and the storage of corn in the silos (I_{jt}). The following results were obtained from the optimal solution of Model 1. The cultivated area generated by Model 1 is presented in Figure 6.

During the first season, the states in yellow use 100% of the available area. In the second harvest season ("*safrinha*"), the states in green also use 100% of the available area. The blue states had no cultivation in the solution of Model 1 (Figure 6). This result does not mean that these states do not produce corn in the real context; however, with the input data to this chain and, considering a slack in production, the solution indicates that some states are more competitive to meet the demands than others in a minimum cost solution for the chain.

Only two states cultivated two crop seasons in this solution: Mato Grosso (MT) and Paraná (PR) (yellow background with green stripes). Most of the states in the North region are more competitive in the second season, while the states in the Center-South cultivate mostly in the first one. Most states in the Northeast region do not have production in the solution, which indicates that, based on the cost data and other parameters used, these states are less competitive to meet the demands compared to the others.

Domestic demand is met exclusively by road. Figure 7 shows the ten largest quantities of corn transported to meet the internal demand. Once more, there is a concentration in the Center-South region, where transport comes mainly from the largest corn producers (Mato Grosso and Paraná). External demand is met by road, rail or, in some cases, both. Figure 8 shows the ten

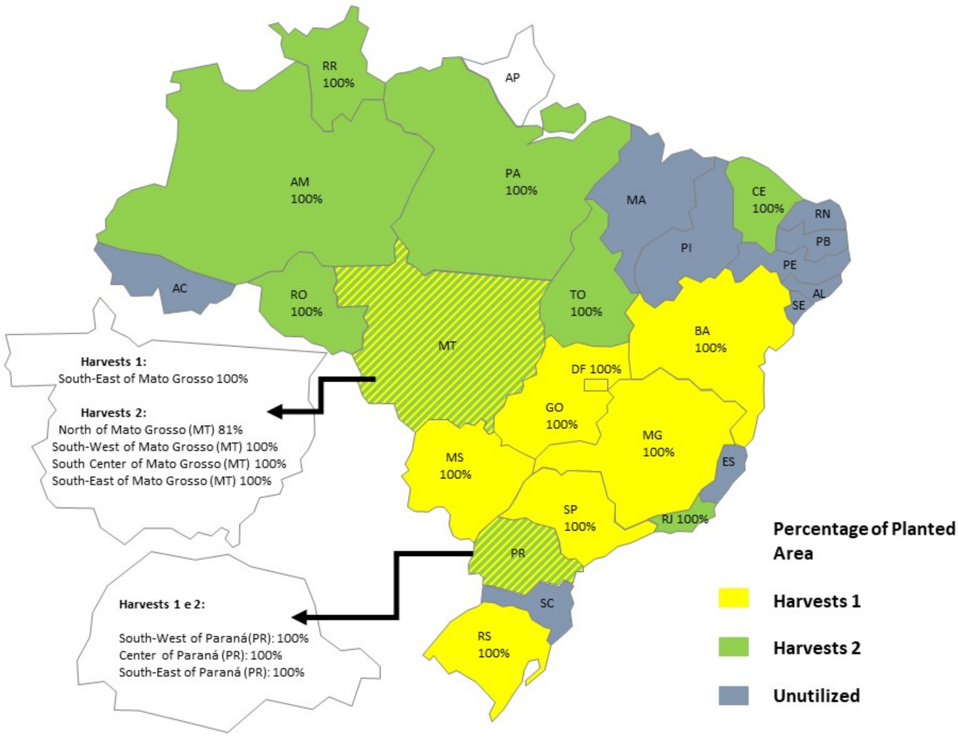

Figure 6 – Cultivated area (in percentage) of each state (and its macro-regions) in the solution of Model 1.

largest quantities of corn transported to seaports according to the mode of transport used. The importance of the Port of Santos as the main outlet and the ports in the Center-South region can be highlighted due to the high level of use in the export of corn grains. The state of Mato Grosso also stands out as the one that sends corn to the largest number of seaports, including the MT-SP route, in which grains are unloaded at the Rondonópolis (MT) terminal to proceed to the Port of Santos (SP) via railroad.

The current data from Embrapa Territorial (2022) indicate that the state of São Paulo (SP) has the largest quantities exported through the seaports of Imbituba (SC), Santos (SP) and Vitória (ES). The solution indicates that São Paulo exports mainly through the port of Vitória (ES). This does not mean that this result is incorrect or unrealistic, but that the Port of Santos receives corn from other states and, due to its limited capacity, part of the demand from São Paulo is sent to the Port of Vitória considering the distance and tax breaks. In the solution, the only import was made to meet the demand in Roraima due to high transportation costs.

Figure 9 shows the need of extra storage in silo bags generated in the baseline scenario. Again, the Center-South region is the one that needs the greatest storage capacity as it contains the main producing states. Highlights include the states of Mato Grosso (MT), Minas Gerais (MG), Paraná (PR) and Rio Grande do Sul (RS), which require a large amount of extra storage. Relative to the

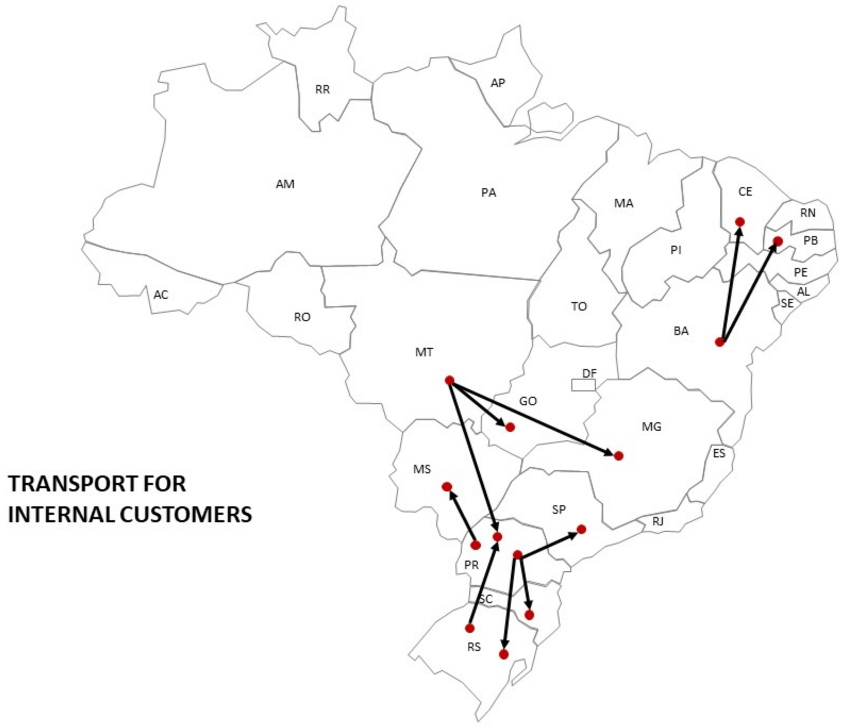

Figure 7 – Ten largest quantities of corn transported to meet domestic demand in the solution of Model 1.

objective function of the baseline scenario, the largest portions of cost refer to planting (58.64%), transportation to meet the internal (17.10%) and external (20.94%) customers. Then, the cost of drying the grains (2.28%), contracting extra storage (1.01%) and importing grains (0.03%).

The sensitivity analysis of Model 1 for the baseline scenario offers some insights, for example: negative values of the dual variables associated with the capacity constraints (Eq. (4)) of Model 1 indicate opportunities to increase the available areas (β_{est}) in these states to reduce the total cost of the supply chain, whether in the first harvest, the second harvest, or both. These are the cases of crop 1 and 2 in the states of Paraná and Mato Grosso, crop 1 in the states of Goiás (GO) and Rio Grande do Sul, crop 2 in the state of Rondônia (RO), among others. These analyses partially anticipate the results obtained for Scenario 1, as discussed below. Other insights based on the sensitivity analysis of the Model 1 refer to the values of the dual variables associated, for example, to constraints (5), (6) and (7) related to the limitations of storage capacity in the silos (δ_{jt}), port export capacity (ε_{pt}) and rail transport capacity (θ_t), respectively. More details about these analyses are available in Marins (2021).

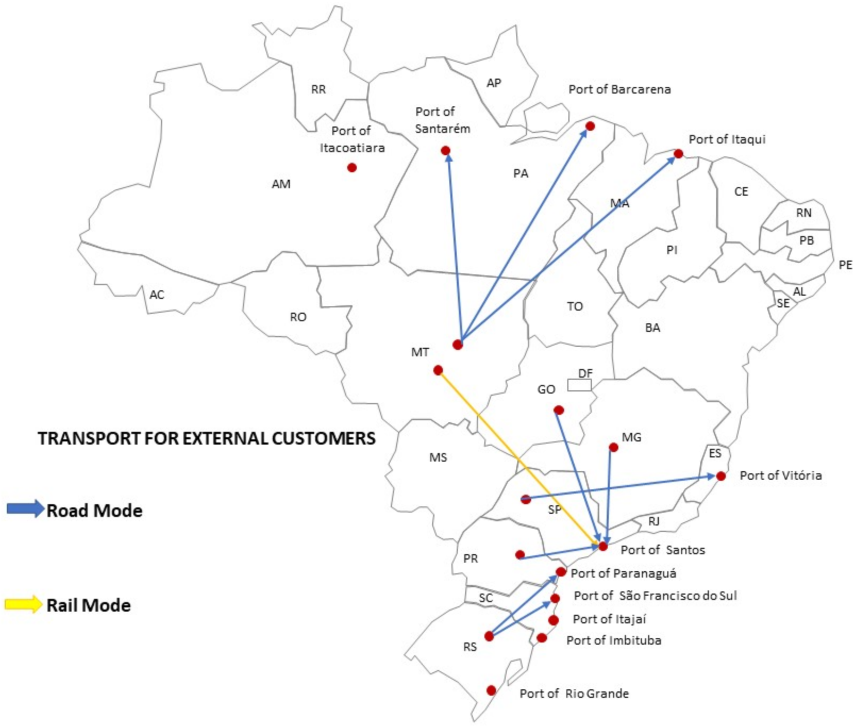

Figure 8 – Ten largest quantities of corn transported to seaports to meet the external demand in the solution of the model.

Scenario 1

Scenario 1 analyses the impact of the crop yield increase (α_{est}) in the areas. In recent years, corn productivity has been increasing with the advancement of agricultural technologies and increasing investment. To build Scenario 1, the average crop yields (tons per hectare) of the producing states over 10 years (2009-2019) were analyzed. The average yield increased in this period was 6%, and this was the value used in Scenario 1 to compare with the baseline.

When solving Model 1 for Scenario 1 with a yield increased by 6%, the optimal solution reduces the cost of the supply chain by 3.64% (Table 2, Figure 10). The cost reduction refers mainly to the lower cost of planting crops (5.65% lower than the baseline), followed by the lower costs of contracting extra capacity in the silos, transportation to external customers, transportation to internal customer, import and drying of grains.

Some producing states had their cultivated areas reduced in the solution of Scenario 1 compared to the baseline, which reinforces the potential of sensitivity analysis. For example, in the case of the North macro-region of the state of Mato Grosso (MT), the use of 81% of the available area for planting in crop season 2 of the baseline solution (Figure 6) is reduced to 61% in Scenario

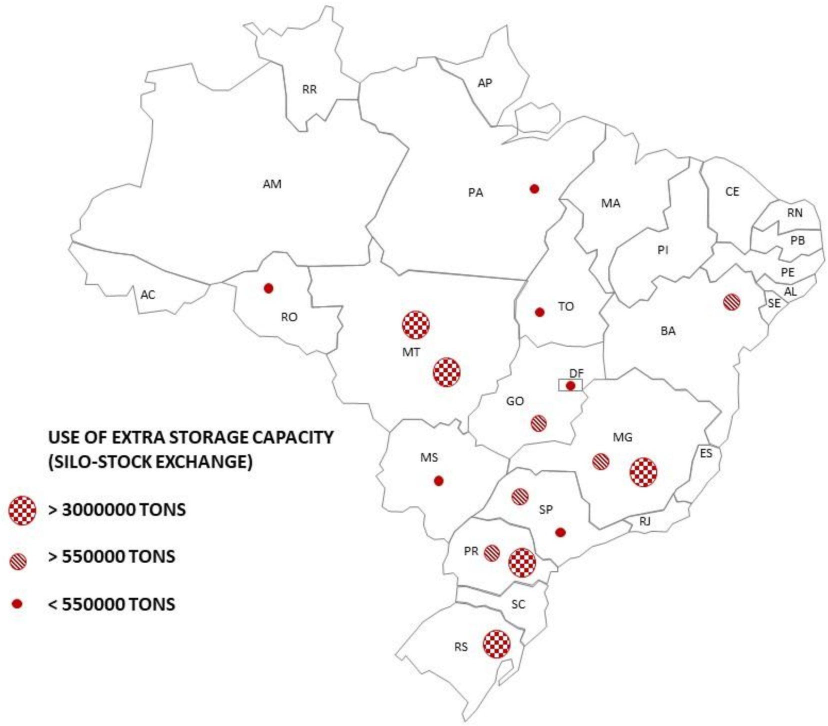

Figure 9 – Need for extra capacity in the silos in the solution of Model 1.

1 with increased yield. These analyses indicate and quantify opportunities for cost reduction in the chain through investments in agricultural technologies so that countries such as Brazil can maintain their positions among the largest corn producers. The results of Model 1 for Scenarios 2, 3, 4 and 5 are summarized below. Details of these scenarios can be found in Marins (2021).

Table 2 – Solution of baseline and Scenario 1 of the Model 1.

Objective function cost parcels	Baseline	Scenario 1	Difference between absolute values*
Planting and harvesting crops	58.64%	57.42%	-5.65%
Transport for external customer	20.94%	21.55%	-0.85%
Transport for internal customer	17.10%	17.61%	-0.79%
Grain drying	2.28%	2.36%	0.00%
Extra capacity contracting	1.01%	1.04%	-1.26%
Grain import	0.03%	0.03%	-0.51%
Total	100.00%	100.00%	-3.64%

Scenarios 2, 3, 4 and 5

In Scenario 2, the impact of increasing port capacity for exports is analyzed. For creating Scenario 2, an expansion project described in the report *Demand and Capacity Assessment of the Container Port Segment in Brazil* was taken as a basis (ILOS, 2021). Only data from the ports considered in this study were collected, resulting in an average growth of 33% in port capacity. The first comparison deals with the total cost of the chain and each cost share of the objective function (1.1). With the increase in port capacity, the cost of the chain was reduced by around 2%. The reduction in this cost refers mainly to the lower cost of transport to external customers (almost 11% lower than the previous value in baseline). On the other hand, the cost of contracting capacity in the silos, transportation to internal customers, planting crops and drying grains increased by less than 1% in relation to the previous values.

Regarding exports, the seaports of Imbituba (SC), Vitória (ES), Itajaí (SC), São Francisco do Sul (SC) and Santos (SP) show an increase in the amount of corn exported. The ports of Paranaguá (PR) and Itacoatiara (AM) showed a decrease in exports. Meanwhile, the other seaports that exported in the baseline scenario do not have exports in Scenario 2. As discussed in the results of Scenario 1, part of the outcomes for Scenario 2 could also be anticipated through the sensitivity analysis of the baseline solution, analyzing the shadow prices values associated with the constraints (6) of Model 1.

In Scenario 3, the impact of increases in agricultural bulk transportation capacity on the rail mode is analyzed. For creating Scenario 3, the report "Cargo railways and the future of Brazil: ANTF proposals for the new government" were considered (ANTF, 2018). The report indicates the value of 31% increase in rail transport, and this was the rate used in this scenario. When solving Model 1, this increase in the capacity of the rail mode reduces the cost of the chain by only 0.4%. The portions that were reduced were, in descending order: planting cost, transport cost for external and internal customers, and cost of contracting extra capacity in the silos. As discussed in the results of Scenario 1, part of the results for Scenario 3 could also be anticipated through the sensitivity analysis of the baseline solution, analyzing the shadow price values associated with constraints (7) of Model 1.

In Scenario 4, the impact of increases in seaport export capacity (Scenario 2) and increases in rail transport capacity (Scenario 3) are analyzed simultaneously. Export limits are directly linked to the capacity of seaports and railroads. One motivation for analyzing this scenario is the concern of the Brazilian government to improve the seaport and rail structure to support the service to the foreign market. Some investments and incentives are foreseen in projects by government agencies to increase seaport and rail capacities and improve the performance of the logistics network of this chain over the next five years. When solving Model 1 for Scenario 4, the cost reduction in the chain is almost 2.5% (Figure 10), that is, greater than the cost reductions in Scenarios 2 and 3 when considered separately, as would be expected due to increased supply chain capacity. To calculate the ICMS unit cost, the ICMS rate (%) and the tax base (%) are multiplied by the product price. For example, a tax rate of 12% and a tax base of 40% results in 4.8%. As the price of a 20-kilo package is 100 BRL, the unit cost of ICMS is 4.80 BRL.

In Scenario 5, the impact of the same tax of the ICMS for all states is analyzed. In this case, transportation costs would be modified and there would be no more tax incentives for moving goods between states. The motivation for this scenario is the possibility of this tax change in Brazilian legislation, in which states currently have different ICMS rates. By solving Model 1 using a single ICMS rate (equal to 12%), the solution obtained reduces the cost of the chain by almost 1%. As expected, the parts of the objective function (1.1) with the greatest differences are the transport costs for internal and external customers. These costs are reduced because products travel shorter distances in the absence of tax incentives from other states. The states of São Paulo and Paraná increase the amount of cultivated area and, on the other hand, the state of Mato Grosso decreases. It can be inferred, then, that the current ICMS system (baseline and Scenario 1) encourages the flow of production from Mato Grosso, emphasizing that Mato Grosso is the state that produces the most corn in the whole country.

Figure 10 compares the baseline scenario and Scenarios 1, 2, 3, 4 and 5. Note that throughout the chain, cost is reduced related to the baseline. For example, the chain cost in Model 1 for Scenario 2 is 1.87% lower than the chain cost in the baseline scenario.

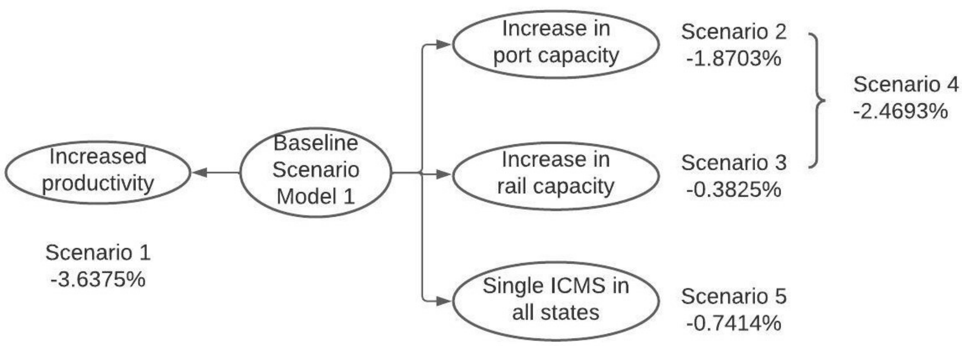

Figure 10 – Outcomes comparison of baseline scenario with Scenarios 1, 2, 3, 4, 5.

Model 2 results with Scenarios 6, 7, 8 and 9

Model 2 maximizes the chain's profit by allowing part of the demand to not be met if it is not profitable for the system, in this case, if costs exceed revenues. When solving Model 2 for the baseline scenario of the chain and comparing the solution obtained with the solution of Model 1 for this same baseline scenario, the difference between the costs of the two solutions is 44%. That is, Model 2 solution fails to meet several demands due to its non-compensatory profit contribution margins in the baseline scenario of the chain. The Model 2 solution presents cost reductions in all cost parcels of the objective function (1.2) (or (1.1)), which suggests that the values obtained from the prices used in the baseline scenario may not be well adjusted to the reality of this chain (i.e. these values may be underestimated), or that the values raised from the costs used in the baseline scenario may not be properly considering the incentives and negotiations that occur between the agro-industries in this chain (i.e. these values may be overestimated). Costs, especially those related to planting and harvesting in the states and transporting products from silos to markets, are the most relevant in this baseline scenario. These results bring some limitations to the analysis of Model 2 results in this scenario. Four other alternative scenarios in addition to the baseline scenario (Scenarios 6, 7, 8 and 9) are also investigated here, all related to increases in prices paid by different types of demand in relation to the baseline scenario and/or with increases in quantities demanded.

In Scenario 6, the impact of the price increase on consumers in the animal nutrition sector is analyzed. The price consulted in the historical data informed by CEPEA (Economic Research Center at Esalq, USP), through its ESALQ/BM&FBOVESPA corn indicator, paid by the internal demands, indicates an average increase of 9.2%, a value used in Scenario 6. When solving Model 2 with this increase, the chain profit increases by more than 26% compared to the Model 2 solution profit for the baseline. All cost shares in (1.2), except for the import cost share (which is null in Scenario 6 and in the baseline), had increases compared to the baseline. Revenues from the other two demands, ethanol production and corn exports, were reduced by less than 1%. Even with these situations that negatively influence the total value of the chain, revenue from animal nutrition demand increased by almost 34%, which explains the 26% growth in the chain's total profit.

In Scenario 7, the impact of the price increase on consumers in the ethanol production sector is analyzed. The rate used was also the average of the historical price paid for the internal demands, that is, the same price increase used for the previous Scenario 6 (9.2%). Being a relatively recent aspect in the fuel industry, the demand for corn for ethanol production is still small in this chain, compared to the other demands. Therefore, the increase in the price paid in this demand for ethanol production generates a negligible impact on the chain's profit, which was observed in the Model 2 solution for this Scenario 7.

In Scenario 8, the impact of the price increase on external consumers (exports) is analyzed. Unlikely prices paid by domestic demand, commodity prices paid by foreign demand showed an average increase of 12.4% per year, and this was the value used in this scenario. When solving Model 2 for Scenario 8, the solution shows a substantial growth of 58% in the chain's profit in relation to the baseline. By way of illustration, the values obtained for each portion of the objective function (1.2) in the solutions for the baseline and Scenario 8 are detailed in Table 3. Note that there is an increase of 55.44% in the revenue obtained by exports in relation to the baseline, but a small reduction in the revenue obtained by meeting the internal demand. Note the different increases in the costs of planting and harvesting crops, transportation to external and internal customers, drying grains and contracting extra capacity, in relation to the costs of the baseline. Despite this, the amounts paid by international customers considered in Scenario 8 allow for an advantageous financial compensation. An important observation is that exports were given priority in this scenario. In the baseline scenario, the percentage of non-compliance with external demand is 59.7%, while in scenario 8, this percentage drops to 16.6%.

Table 3 – Comparison of Model 2 solutions for baseline and Scenario 8.

	Baseline	Scenario 8	Difference between absolute values
Billing installments of the objective function (1.2)			
External demand	59.57%	69.67%	55.43%
Animal nutrition demand	40.41%	30.32%	-0.30%
Ethanol demand	0.02%	0.02%	0.000%
Objective function costs (1.2)			
Planting and harvesting crops	61.10%	60.83%	27.57%
Transport for external customer	22.06%	25.00%	45.26%
Transport for internal customer	13.41%	10.85%	3.74%
Grain drying	2.41%	2.33%	23.77%
Extra capacity contracting	1.04%	0.99%	22.49%
Grain import	0.00%	0.00%	0.00%
Total	100.00%	100.00%	57.89%

The models presented here serve to assist government policies and support planning decisions in the corn supply chain. In an increasingly competitive agro-industrial environment, the interest in developing tactical plans to meet export targets with a quality product can be analyzed through optimization models, investigating with which quantities and which prices would be more compensatory to meet the demands of the foreign market. These analyses would also make it possible to assess the extent to which meeting increases in external demands can impact meeting internal demands in the chain, as well as evaluating the limits of the chain's capabilities to meet growth in internal and external demands, as illustrated in Scenario 9 next.

In Scenario 9, the impact of increases in the quantities demanded in the internal and external markets is analyzed, while also analyzing the limitations of the capacities. In this last scenario, it was considered that the demands are free variables instead of parameters of the problem, that is, one can either fail to meet part of the internal and external demands defined by the parameters σ_{kt}, Ψ_{kt} and λ_{kt} of Model 2, or produce and deliver quantities greater than these quantities to customers. For this and for the sake of simplicity, the parameters σ_{kt}, Ψ_{kt} and λ_{kt} in Model 2 were kept, but the non-negativity constraint of the auxiliary slack variables A_{kt}, L_{kt} and D_{kt} of Model 2 was relaxed to solve the baseline scenario. Note that these variables are now unconstrained in the model, i.e., they are free to assume any positive, negative, or null values. Thus, even though Scenario 9 is not so realistic, it provides us with indications of the demands that deserve more attention and the costs that must be reduced in the chain.

The Model 2 solution in Scenario 9 indicated that even though the demand for corn for ethanol production is still small, the price paid is compensatory and there was an increase in this billing by 119.8% in Scenario 9 compared to the baseline solution. This was due to corn sales being well beyond the amounts demanded by customers for ethanol production. On the other hand, in relation to the demand for corn for export, the price paid does not cover the costs involved, and as a result, sales to the foreign market were well below the quantities demanded by customers. About 79.6% of the external demand was not met in the solution of Scenario 9, that is, 20% higher than in the baseline solution. This resulted in a 14.8% drop in sales in these sales when compared to the baseline. With this reduction in exports, the cost of transporting from silos to the ports reduced by 13.7%. Still analyzing the results of Scenario 9 in comparison to the baseline scenario, the cost of growing corn and drying the grain rose by 31.4% and 27.4%, respectively, due to the increase in sales to the domestic market (animal nutrition and ethanol production). As a result, the cost of contracting extra storage increased by 27% and the cost of internal transport also increased by 97.3%. These outcomes highlight the importance of the transportation cost for this supply chain.

Figure 11 shows the solutions obtained by Model 2 for the baseline and Scenarios 6, 7, 8 and 9 discussed above. Note that in all these scenarios, the chain profit grows in relation to the baseline profit. For example, the chain profit in the Model 2 solution for scenario 6 is 26.2% higher than the chain profit in the Model 2 solution for the baseline. For more details about the results, please refer to (Marins, 2021).

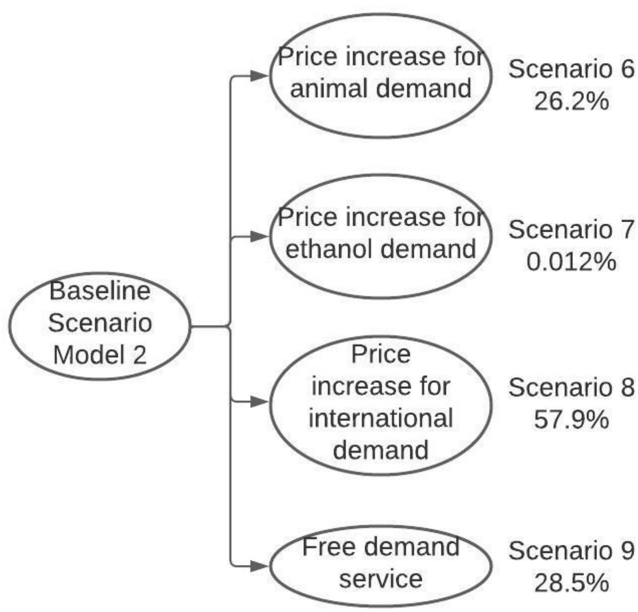

Figure 11 – Comparison of Model 2 solutions between the baseline and Scenarios 6, 7, 8 and 9.

Model limitations

The outcomes of this study are based on mathematical modelling and data obtained from contacts with government institutions, organizations, and companies, or estimated through open databases. In spite of our scientific rigor, such data may not be up to date or not very accurate to ensure an appropriate representation of the real supply chain. One of the difficulties in the data collection refers to the monetary values of the corn prices over time, mainly caused by the constant variation between the Brazilian currency real and the US dollar. Conducting a more in-depth study, or even an analysis of a governmental nature, can be carried out using the optimization model proposed here, but equipped with well-updated and more accurate parameters. This technical care in the data treatment is essential for an effective analysis of the real supply chain.

Other limitations of using the models, such as those proposed here, include estimating the amounts and costs of crop cultivating and post-harvest losses in the areas available, as well as in other parts of the chain, such as in transportation. This study was limited to road and rail modes of transport, disregarding possibilities of waterway routes. One of the reasons for these limitations was the difficulties in accessing this information. The study also did not consider costs related to ethanol mills and distilleries, partly justified by the fact that it is a relatively recent practice in the supply chain studied.

Although it has brought interesting insights to the analysis of the corn supply chain, the coherence of part of the results depends on the conformity of the dataset. In the research question (i) raised in Section 1, based on the data obtained for this study from different secondary sources and on the results obtained with the application of Model 1 in the baseline scenario and in Scenarios 1, 2, 3, 4 and 5, it can be concluded that the production, storage, and distribution capacities of the studied chain are relatively limited to meet the current demands of the domestic and foreign markets. Network's bottlenecks found are in the grain storage capacity and seaport storage capacity and railway transportation capacity, which limit increases in meeting growth in demand.

In the research question (ii) raised in Section 1, based on the dataset for this study from different secondary data sources and on the results obtained with the application of Model 2 in the baseline scenario and in Scenarios 6, 7, 8 and 9, it can be concluded that it is not profitable to fully meet all the current demands of the domestic and foreign markets, taking into account the prices informed of these demands and the costs considered in the chain. For example, in an experiment carried out with Model 2 using all data from the baseline scenario, except for the prices charged for domestic demands, it was concluded that the prices of these domestic demands should be, on average, 17% higher than the prices informed of these demands, so that it would be profitable to meet all the internal demand of the chain in this scenario. These results indicate the importance of additional studies on prices and costs practiced in the corn supply chain, with possible adjustments in these data to answer this question more reliably and precisely.

6 FINAL REMARKS

In this study, linear optimization models were was presented to analyze and support agricultural and industrial decisions in the tactical planning of corn grain supply chains to meet domestic consumption and exports. Model 1 (minimization of supply chain costs) and Model 2 (maximization of supply chain profits) can be useful for the management of an agent with some control and power to interfere in the supply chain, such as governments and large sector companies. The limitations of this study are not particularly associated with the complexity of the mathematical models, but mainly due to access to more reliable and accurate data and information in this supply chain. We highlight the excellent computational processing times to solve the model, allowing the construction of many scenarios for different types of analysis. Future research would be to develop an in-depth study, preferably together with a government agent, to validate the application of this optimization approach in a case provided with sufficiently updated and accurate data from a corn supply chain. This technical care in the data collection and treatment is fundamental for an effective analysis of the real supply chain. Other future research would be to extend the proposed models to explicitly consider uncertainties in the problem parameters, using, for example, robust optimization techniques and stochastic programming.

The explicit consideration of harvest and post-harvest losses is also an interesting topic for future research, with a greater level of detail and data precision. The consideration of the waterway mode can also enrich the research of the Brazilian corn supply chain. Due to the difficulties in obtaining reliable and accurate data, in the present study, the models were applied to optimize the tactical planning of a chain with a planning horizon of only one period (i.e., one year with two harvests). Another interesting perspective for future research would be to apply the models in cases with planning horizons with multiple periods (i.e., several years). In these cases, several consecutive corn crops must be considered, and it seems opportune to also consider discrete decisions in the tactical (or even strategic) planning of the chain, such as: installation or not of new silos, intermodal terminals, additional stretches of railways and additional berths in ports, deactivation or not of existing facilities and facilities over periods, in addition to considering options for discrete variables increases in capacity in existing facilities, such as silos and intermodal terminals, for example.

In this study, the possible interdependencies of the corn supply chain with other grain supply chains or other products (soybean, sorghum wheat etc.) were not considered. Analyses considering these interdependencies involve additional research challenges; however, they allow for more realistic representations of the structures and capabilities of the chains. The study of integrated several supply chains, which share parts of their structures and capabilities with more than one agricultural product are also relevant perspectives for future research. For example, one of the main agricultural chains that influence the corn chain is the soybean chain, particularly in the case of countries such as Brazil, and studies addressing these two chains in an integrated way can be innovative and effective for optimizing the tactical planning of these chains, considering demands from both the domestic and foreign markets.

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