Short Paper

A Mixed Integer Programming model for peasant farmers in developing countries: A study case from Paraguay

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ABSTRACT

In developing countries, governmental programs push agricultural supply chain networks to optimize farmer food security and rural growth. Decision-making in this system includes available cropping options and criteria regarding nutrition, income, work capacity that must be satisfied. We propose a mathematical optimization model to help the decision-making, tested in a case study: Caazapá-Paraguay, where the rural population is 80%, and 42% is poor. The optimization model addresses the problem complexity, suggests the crops, improves the production and rotation mix, decreases the total cost, and satisfies almost the same nutritional requirements.

KEYWORDS

agricultural supply chain, peasant farmers, food security, mathematical model

1 INTRODUCTION

Peasant farmers depend on the natural capital availability in rural areas where most of the population is poor and vulnerable. The operations are small-scale, and the work culture is individualistic. According to the Food and Agriculture Organization (FAO), one-eighth of the worldwide population has chronic hunger. Organizations as the Community of Latin American and Caribbean States (CELAC) propose guidelines to look forward to the developing countries' food security and poverty eradication. They suggest sustainable access to foods to support nutritional well-being and the development of public policies (FAO, 2012 and FAO, 2013 cited by [1], [2]). In that context, we propose a mixed-integer linear problem including mainly economic and social issues to address the peasant farmers' profitability and food security from a supply network perspective, considering their inter-connections. The contribution is a mathematical model with multi-periods, multi-products, and multi-operations. We consider the sowing, harvest, storage, and distribution of crops to satisfy three demands (self-consumption, interchange between farmers, external sell), reaching food security, and profitability for the family farms.

2 LITERATURE REVIEW

Agricultural Supply Chain Management (ASCM) is the process from farming to delivering fresh products to consumers [3]. The management goal for the ASCM is traditionally to minimize the total system costs satisfying the service levels; in that sense is necessary to integrate and coordinate the chain stakeholders [4].

Many factors make complex the ASCM, such as the perishable nature of the products, fluctuations in demand, prices and yields, operations dependence on weather conditions, and consumers' awareness for food safety and sustainability (Simchi-Levi, 2008 in [5]).

An essential aspect of these chains is the peasant farmers' food security. Food security includes the permanent physical, social, and economic access to foods that are safe, nutritious, available in enough quantity, to fulfill the population's nutritional requirements and food preferences to allow them to have an active and healthy life [6]. The farmers as stakeholders are producers and consumers at the same time in the ASCM. Considering this aspect, Operations Research (OR) could be a helpful tool to make decisions. Some operations to consider could be the crop's land allocations, harvest scheduling, resources planning, equipment, and workforce requirements planning and scheduling. The economic goal could be to reduce costs and the social purpose to increment the farmer's food security, mainly in developing countries where the poverty levels and natural resource dependence are higher.

There is evidence of using quantitative methods to address strategic, tactical, and operational agricultural decision problems with techniques such as linear programming. Table 1 presents some research that addresses operations problems at the farm level in developing countries applying deterministic mixed-integer linear programming models for vegetables and grains production.

3 CASE STUDY

The case study was developed for a developing country, Paraguay, in South America, where 92% of the farmers are small, with less than 50ha of land to farm. In particular, the Caazapá Department has 150.000 inhabitants, with an 80% living in rural areas and 42%

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Table 1: OR applied to agricultural operations in developing countries.

Author	Country	Research objective
Dogliotti et al., 2005	Uruguay	Evaluate alternative strategies to achieve sustainable development at farm scale, with resources availability and income improvement while soil conditions are improved.
Yiridoe et al., 2006	Ghana	Asses the technical and economic feasibility of including alternative rice cropping technologies in a mixed crop-livestock subsistence production system with an optimal farm planning model.
Singh and Nath Panda, 2012	India	Allocation of land and water resources to maximize net annual returns by mitigating the water logging problems.
Hosu and Mushunje, 2013	South Africa	Evaluate the optimal and efficient adoption of integrated crop-livestock farming systems among smallholder farmers, satisfying the profitability and subsistence production.
Delgado and Pukkala, 2013	Angola	Optimize land-use system and evaluate gender labor roles and work seasonality maximizing the land value.
Kenny et al., 2014	Togo	Land allocation between crops and trees for smallholder farmers to optimize financial returns.
Alary et al., 2016	Brazil	Assess the impact of the introduction of Direct seeding mulch-based cropping (DMC) with and without cover crops for three types of rural family farms: subsistence-oriented, dairy and meat market-oriented.

in poverty conditions [14][15]. In Caazapá, the Ministry of Agriculture and Livestock (MAG) assists 2.000 farmers, which produce 51 types of fruits and vegetables, although an 80% of the land is destined to only four products (sesame, cassava, corn, bean). Furthermore, 70% of the production is used for the consumption of farmers' own families.

This work includes strategic and tactical ASCM planning decisions for peasant farmers in a specific rural area in Paraguay. We consider: social aspects as the fulfillment of human dietary needs, improved health and educational level to overcome a subsistence economy, i.e., production is almost limited to self-consumption inside the peasant families. Also, environmental issues, like the promotion of crops rotation and the use of green fertilizers as an effective way to protect biodiversity. Economic aspects, like the availability of workforce, seeds, or other inputs.

Figure 1 shows the stakeholders and operations to be considered to develop the mathematical model. The stakeholders considered are: supplier, farmers, consumer, farmers. The main operations included are: supply of agricultural inputs, crops production, harvesting, storage, distribution (demand share), and crop rotation.

The arrows show the interaction between the stakeholders when they perform the agricultural operations in the period, in this case, in months during five years.

The aim is to design and coordinate an Agricultural Supply Chain network and its interconnections for peasant farmers to perform agricultural functions, producing multiple products in multiple periods to satisfy their nutritional requirements and external demand at a minimum possible cost.

We observe in the figure that at the beginning of the production season with the supplier is decided the individual or associative purchase raw materials, as lime, seeds, fertilizers. Then, the crop production planning includes the crop assignment to land and workforce uses for the farmers. After some months, harvesting and storage decisions are made, depending on the crop. The production is destined to three demands, considering the type of consumers: self-consumption at the farm, the interchange between farmers, and the external market. The figure shows that it will be necessary to open a Gathering Center (GC), but only to satisfy the external demand (q=3). The final stage, for the farmers, is the crop rotation for some periods after the production cycle begins again.

To define the values of the base parameters, we used information available in sources from the Ministry of Agriculture and Livestock (MAG), the Faculty of Agrarian Sciences of the National University of Asunción (FCA UNA), and the International Cooperation Agencies (JICA and GTZ). Also, for the parameters related to food security, we collect data from the Food and Agriculture Organization of the United Nations (FAO) and the National Institute of Food and Nutrition from Paraguay (INAN).

4 MATHEMATICAL MODEL FORMULATION

We model the supply chain described previously by a mathematical optimization model, specifically a mixed integer linear programming model. The model objective function seeks to maximize the farmer's profit and food security, considering the sales, equivalent values for self-consumption and products interchange, and the costs of supplies, production, harvest, storage, crop rotation, and distribution.

The model considers both strategic and tactical decisions. The first are related to supplies purchasing, crop production and rotation strategies, and the gathering center allocations. The second one comprises crops allocation, harvest and post-harvest programming, and workforce planning.

Table 2 defines the various indexes we use in the model. The parameters and variables descriptions are presented below.

In the objective function, the income depends on the product quantity assigned for external demand and the product price.

Food security depends on the quantity of product assigned to self-consumption plus the amount received from the other farmers. The farmer does not need to buy these quantities to value them as an opportunity value perceived (or saved) by the farmer.

Table 2: Index identification.

Index	Index
i: crop product	m: family member
j: farmer	n: nutrient
s: farmer who receives crops	p: type of purchase and storage
k: rotation product	q: demand
l: production resource	t: period in month

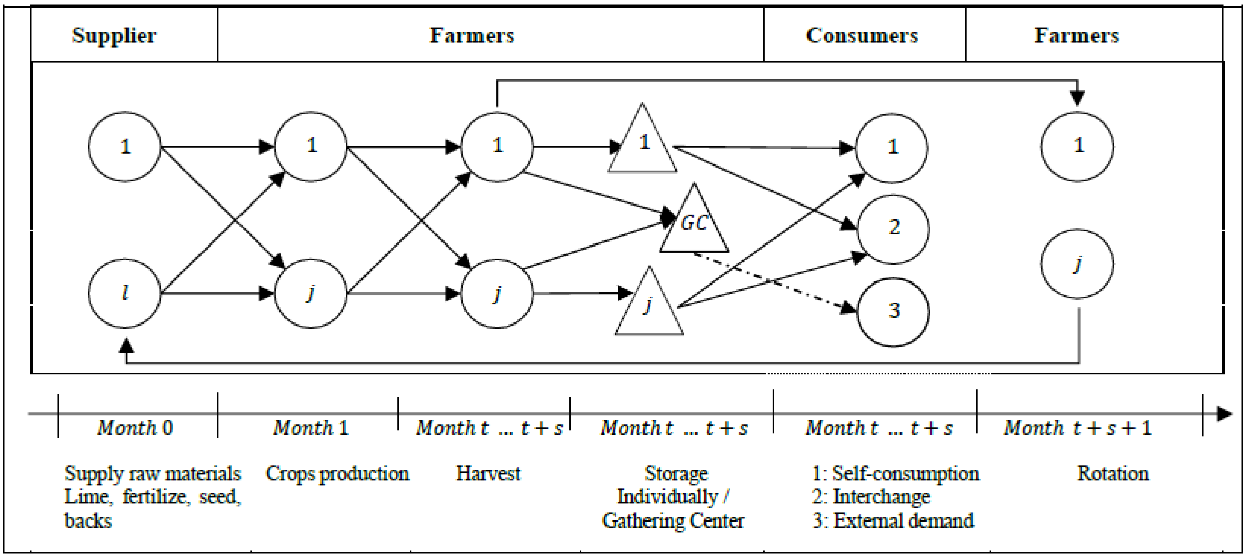

Figure 1: General structure of the ASCM.

Definition of parameters (for some constraints)
Demand share:
nt_{in}: Availability of nutrient n in product i [mg]
p_{it}: Sale price of product i in period t [$/product]
qm_{jm}: Quantity of family member's type m in the farm j
req_{jn}: Total nutritional requirement from nutrient n in farm j [mg]
$rmax_{mn}$: Maximum requirement from nutrient n for the family member type m [mg]
$rmin_{mn}$: Minimum requirement from nutrient n for the family member type m [mg]

Definition of variables
A. Supply of agricultural inputs:
XS_{ijlpt}: Quantity to produce of crop i, by farmer j, using resource l, bought in mode p in period t
YS_{ijlpt}: 1, if crop i is produced by farmer j using resource l in mode p in period t, 0 i.a.c

B. Crops production and rotation
XP_{ijt}: Area to assign for crop i by farmer j in period t
XPL_{ijt}: Labor quantity required for crop i by farmer j in period t
XR_{jkt}: Area to assign for crop rotation k by farmer j in period t
YP_{ijt}: 1, if crop i is produced by farmer j in period t, 0 i.a.c
YR_{jkt}: 1, if crop rotation k is produced by farmer j in period t, 0 i.a.c

C. Harvest
XH_{ijt}: Quantity of crop i to harvest by farmer j in period t
XHL_{ijt}: Labor quantity required to harvest crop i by farmer j in period t
YH_{ijt}: 1, if crop i is harvested by farmer j in period t, 0 i.a.c

D. Storage
IH_{ijt}: Quantity of crop i available by farmer j at the end of t
XST_{ijpt}: Quantity of crop i to storage by farmer j in mode p in t
YG_j: 1, if farmer j farm is selected as a gathering center, 0 i.a.c
YST_{ijpt}: 1, if crop product i is stored by farmer j in mode p in t, 0 i.a.c

E. Distribution
XD_{ijqt}: Quantity of crop i produced by farmer j to satisfy demand q in t
$XN1_{jnt}$: Nutritional deficit for farmer j in t, to satisfy the type n nutritional requirements with products produced by the farmer
$XN2_{snt}$: Nutritional deficit for farmer s in t, to satisfy the type n nutritional requirements with products received in the interchange (exchange)
XPR_{ijst}: Quantity of product i received by farmer j and sent by farmer s in t
YD_{ijqt}: 1, if crop i produced by farmer j is destined to satisfy demand q in t , 0 i.a.c

The model objective function seeks to maximize the farmer's profit and food security:

Max Z = Income − [Supplies Costs + Production Costs + Rotation Costs + Harvest Costs+ Labor Costs + Storage Costs]+ Food Security

The income depends on the crops harvested and assigned for external demand (sold) and the product market price.

Food security depends on the quantity of product assigned to self-consumption plus the amount received from the other farmers. The farmer does not need to buy these quantities to value them as an opportunity value perceived (or saved) by the farmer.

The inclusion of food security in the objective function its relevant because the farmers consume most of their productions, therefore they produce withe the aim of feed their families. The excess food, that they not consume, are destined to another farmers or are sold.

The constraints are presented in groups according to the main agricultural operations: supply of agricultural inputs, crops production, harvesting, storage, distribution (demand share), and crop rotation. We only express the constraints for the demand share.

Production:

- For each farmer and range of periods, crops quantities produced cannot exceed the available surface in each farm and the maximum surface for a small family farmer.
- Resources acquisition, individually or in association, should be enough to fulfill the requirements for the crop's production.
- Farmers must buy resources and produce crops only in the chosen periods.
- The minimum labor quantity available to produce crops must be enough and depends on the amount produced and the labor requirements for this operation.

Harvesting:

- There must be a balance between production and harvesting.
- The farmers must harvest only in the chosen periods.
- The minimum labor quantity available to harvesting crops must be enough and depends on the amount to harvest and the labor requirements for this operation.
- The total labor quantity for production and harvesting should not exceed the maximum labor that annually could be hired in a small family farmer.

Storage:

- The products harvested must be stored individually or in an association.
- The total products harvested must be stored.
- The products could be stored if it were decided to hold them.
- The products destined for self-consumption must be stored individually.
- The products destined to external demand must be stored in association.
- The products that are stored in an association must be stored in a gathering center.
- Only one gathering center could be opened on a farmer's farm that belongs to a cooperative, representing the set of producers that belong to the cooperative.
- The gathering center would be opened on the farm with the most extensive surface available for production.
- The number of products to be stored should not exceed the maximum capacity of the gathering center.

Demand share:

The quantity of product destined to each type of demand should not exceed the harvested products, in XD_{ikqt}, *q=1* represents self-consumption and *q=3* is external demand:

$$XD_{ij1t} + \sum_{s=1}^{S} XPR_{ijst} + XD_{ij3t} \leq XH_{ijt} \qquad \forall i \in I, j \in J, t \in T \tag{1}$$

The farmers must satisfy a demand type only in the decided periods:

$$XD_{ijqt} \leq M \cdot YD_{ijqt} \qquad \forall i \in I, j \in J, q \in Q, t \in T \tag{2}$$

The crops that contributed nutrients, produced by the farmer, and received in the interchange, should not exceed the maximum nutritional requirements:

$$\left(\sum_{i=1}^{I} XD_{isqt} + \sum_{j=1}^{J} XPR_{ijst} \right) \cdot nt_{in} \leq \sum_{m=1}^{M} qm_{jm} \cdot rmax_{mn} \qquad \forall s \in S, n \in N, t \in T, j \in J, q = 1 \tag{3}$$

The crops that contributed nutrients, produced by the farmer, fulfill part or completely the minimum nutritional requirements:

$$XN1_{jnt} \equiv req_{jn} - \sum_{i=1}^{I} XD_{ijqt} \cdot nt_{in} \qquad \forall j \in J, n \in N, t \in T, q = 1 \tag{4}$$

The crops that contributed nutrients, received in the interchange, fulfill part or completely the minimum nutritional requirements:

$$XN2_{snt} = XN1_{snt} - \sum_{i=1}^{I} \sum_{j=1, j \neq s}^{J} XPR_{ijst} \cdot nt_{in} \qquad \forall s \in S, n \in N, t \in T \tag{5}$$

There are balance equations for the products destined to self-consumption, to the interchange and to the external demand:

- The harvested products that are not used for self-consumption are destined to the interchange or to the external demand.

$$XH_{ijt} - XD_{ij1t} = \sum_{s=1}^{S} XPR_{ijst} + XD_{ij3t} \qquad \forall i \in I, j \in J, t \in T \tag{6}$$

- The harvested products that are not used for self-consumption or the interchange, are destined to the external demand.

$$XH_{ijt} - XD_{ij1t} - \sum_{s=1}^{S} XPR_{ijst} = XD_{ij3t} \qquad \forall i \in I, j \in J, t \in T \tag{7}$$

Crop rotation:

- Rotation is performed only in the chosen periods.
- Total production area must be destined to a rotation product, according to the last harvesting operations.

5 RESULTS AND DISCUSSION

We obtain the values of all the variables relevant for five cooperatives of peasant farmers in the case study from Caazapá.

The types of products to cultivate for the base case vary. For example, cooperatives with 13 and 15 farmers will produce green pepper, and the cooperatives with 20, 29, and 30 farmers must cultivate five products: cassava, peanuts, yerba mate, green pepper, and onion. In all the cases the rotation it is relevant due to the soil need to be improved with periodically crop rotations, which are different from the usual crops.

Table 3 summarizes the Objective Functions in USD, the total costs in USD, the nutritional requirements to be fulfilled (amount of nutrients), the five cooperatives, and the 60 months considered. The results show that as the number of producers per cooperative is duplicated, the costs and value of objective function increase around 50%. As was explained previously, the number of products cultivated increases from 1 to 5. The nutritional requirements will be higher for a cooperative with more families, but the dietary requirements fulfilled can be satisfied 36% more if the cooperative size is higher.

We compare the results with the actual production plan from the peasant farmers. In Table 4, we show the solutions for one cooperative in 24 months. With these solutions, we pretend to compare the initial and the final situation in a production period for a cooperative.

The Objective Function for the actual production represents only 2% of the objective from the proposed plan production, which means the proposed solution has a better economic result. In the actual production, the farmers do not perform crop rotations; this operation does not represent financial incomes in the short term but has environmental benefits for the soil and the production yield.

Regarding the size of the resulting problem, it has at most 997,230 continuous variables, 313,230 binary integer variables, and 484,233 constraints. It was solved using an HP laptop with an Intel (R) Core (TM) i5-8250U processor, and 8 GB RAM. The model was programmed with the Python language and the Gurobi optimization software was used for the resolution, the longest running time being 200 seconds.

6 CONCLUSION

We propose a mixed integer linear programming model and its solution to satisfy the nutritional requirements of family farmers at the lowest cost. The case study is the Department of Caazapá, Paraguay, considered for the initial parameter's definition. The results obtained can guide farmers' decision-making and generate public policies with national and regional interest.

Currently, the producers in that area are associated in cooperatives only to receive technical assistance. They could use that previous structure to purchase resources jointly, store jointly harvested products, exchange and sell their products. However, a culture change will be necessary to prove more profitable crops and work jointly with other farmers. Will be interesting to verify the proposal through the successful improvement case for some cooperatives to facilitate the change.

We include the three axes of sustainability. In economic terms, the results are obtained at the lowest possible cost by maximizing the total profitability for five years, considering the sale of products to external demand, generating income for the farm. In the environmental field, crop rotation and obtaining a mix of various products are considered. Finally, the social aspect is achieving the satisfaction of a percentage of families' nutritional requirements with safe products.

Some examples of policies that could be considered from the results of this work are:

- Promote cooperatives' interaction of agricultural small family farmers to satisfy their internal demand and external demand jointly.
- Encourage the participation of farming cooperatives in public tenders of government entities such as schools, colleges, hospitals, and others to supply their crops together, considering long-term planning and the inputs joint purchase.
- Include in agricultural production plans the three sustainability axes: economic, environmental, and social, so that their operations are sustainable over time.

The contribution of this work is to obtain a better solution to the current situation, through the developed model that describes the main activities of family farming. Due to its large size and the interaction of operations, it is not possible to obtain a plan intuitively, so traditionally, producers obtain few types of products that they then consume themselves with their families.

Future works for this research could be in terms of the model structure, considering the exchange of products between cooperative members and other cooperatives. In the last case, the transport costs must be considered since the farmers would not live close to each other. It is possible to propose obtaining a cluster of producers who exclusively produce to have more experience and focus their attention on few crops. Also, we could prove that all the farmers from the cooperatives perceive an adequate profit. In this case, it is possible to consider a restriction to obtain earnings according to the production yields for the farmers.

Finally, will be determined the parameters that can be considered stochastic for a robust optimization probabilistic model, for example, the values of demand, sale or exchange prices, and production yield.

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Table 3: Results for the case study.

Cooperative #	1	2	3	4	5
Number of farmers	13	15	20	29	30
Objective Function (USD)	1,939,612	2,167,529	3,471,024	3,906,548	3,938,959
Total Cost (USD)	135,625	144,851	283,103	348,998	351,734
Nutritional req. missing	51,657,753	52,415,879	69,299,601	93,641,898	106,623,400
Nutritional req.fulfilled (%)	38	54	69	61	59

Table 4: Summary of results for one cooperative.

Cooperative #	3	3 actual production
Number of farmers	20	20
Objective Function (USD)	864,220	13,597
Total Cost (USD)	123,846	81,010
Nutritional req. missing	31,997,682	20,740,821
Nutritional req.fulfilled (%)	52	69