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# A mixed-integer linear programming model for harvesting, loading and transporting sugarcane. A case study in Peru

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## Abstract

Due to opportunities for economic and social development in the biofuels market, improvement to the supply chain has become a relevant matter. In agro-industrial supply chains, procurement costs are highly relevant. Since sugarcane is a high performance raw material for ethanol production, this paper proposes a Mixed-Integer Linear Programming Model for cost optimization for harvesting, loading and transportation operations. The model determines the quantity of machines and workers to meet the biofuel plant requirements. Costs of resources for harvesting and loading as well as transportation costs from the land parcel to the production plant are minimized. Also, the model calculates the cost of penalties for shortages (unmet demand) and the cost of equipment idle time. The implementation of the model in a Peruvian biofuels company, showed a cost reduction of around 11 % when compared to the current costs.

**Keywords:** mixed-integer lineal programming; supply chain planning; sugarcane; biofuels.

# Modelo de programación lineal entera mixta para el corte, carga y transporte de caña de azúcar. Un caso de estudio en Perú

## Resumen

Debido a las oportunidades de desarrollo económico y social del mercado de los biocombustibles, el mejoramiento de su cadena de suministro se ha convertido en un tema altamente relevante. Dado que la caña de azúcar es una de las materias primas de mayor rendimiento para la producción de etanol, el presente artículo propone un modelo de Programación Lineal Entera Mixta para optimizar los costos en las operaciones de corte, cargue y transporte. El modelo determina la cantidad de máquinas y trabajadores para satisfacer los requerimientos de la planta de biocombustible. Se minimizan los costos de asignación de equipos, costos de transporte y adicionalmente se consideran los costos de penalización por demanda no satisfecha y por ociosidad de los equipos disponibles. La aplicación de este modelo en una empresa Peruana, presentó un porcentaje promedio de disminución de costos del 11 % al ser comparados con los costos actuales de la empresa.

**Palabras clave:** programación lineal entera mixta; planeación de cadenas de abastecimiento; caña de azúcar; biocombustibles.

## 1. Introduction

Biofuel supply chains have been identified as a strategic sector for Latin America [1]. Some countries are stimulating biofuel production to reduce fossil fuel dependency and, in this way, guarantee their energy security at lower prices [2-4]. Although several investigations on biofuel production have focused on identifying a more efficient feedstock, sugarcane is considered to be a high yield biomass in the

production process [5].

In Peru, biofuel production is considered to be one of the seven most important sectors [6]; therefore, ethanol production from sugarcane is highly relevant for economic growth projections. The supply chain is made up of a group of companies involved in the flow of materials, information and capital, starting with the unprocessed raw materials and finishing with the end consumer [7-9]. Fig. 1 shows the general structure of the biofuel supply chain from sugarcane.

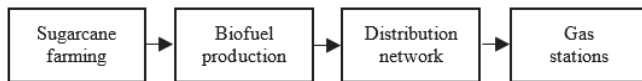


Figure 1. Supply chain structure  
Source: Own elaboration

Bearing in mind that between 47% and 58% of ethanol production costs depend on the sugarcane crop [10], this stage becomes an important target to reduce costs in the entire supply chain. Some operations related to harvesting and loading cane are relevant. Also, given the complex nature of agro-industrial processes [9], it is important to consider the penalties derived from unmet demand and idle machines. In addition, harvesting, loading and transporting sugarcane are operations commonly affected by several constraints, such as land conditions, grinding requirements, availability and resource capacity (machinery and manpower) and production scheduling. Therefore, identifying the optimal resource allocation to reduce costs without affecting delivery goals is a decision of great complexity and economic relevance in supply chain planning.

In this sense, this paper shows a Mixed-Integer Linear Programming Model (MILP), for operations planning for the harvesting, loading and transportation of sugarcane to supply a biofuel production plant. The model takes into account optimization of four types of costs: allocation of machinery and workforce, transportation from the farm to the biofuel production plant, penalties for unfulfilled orders and idle machinery. Also, in the case of the mechanical harvesting method, land conditions for machinery selection are considered. The model was implemented in a case study in Peru, resulting in a cost reduction of around 11 % when

compared to the current costs.

In order to explain the model, this paper has been structured as follows: First, a literature review is presented in Section 2. Several papers that discuss the improvement of a biofuel supply chain in the upstream stage are examined. Second, in Section 3, the structure of the proposed optimization model is explained in two phases: in the first, the general procedure is described by identifying its purpose, as well as the resources and costs that must be taken into account; in the second, the structure and some details of the mathematical model are explained. Third, in Section 4, a case study is solved using a well-known computational tool. Finally, in Section 5, the conclusions and some suggestions for future model applications are outlined.

## 2. Literature review

Biofuel supply chain improvement has been a matter of great interest in recent years. A systematic literature review was carried out using the ISI – Web of Science and SCOPUS databases. The search was confined to identifying papers that were concerned with the specific objective of the research presented in this paper. About 43 papers associated with the selected key words were found; however only 21 of these were considered to be relevant. According to the results, an important increase in contributions on this topic, especially over the last five years (73.9%), was detected. Most of these studies have been carried out in the United States (28%), Italy (12%), France and Cuba (8%). Papers on this subject in relation to Peru were not found. Table 1 summarizes a brief comparison of the 21 analyzed papers based on the scope of the objective function and the set of decision variables.

Table 1.  
Literature Review of optimization models of sugarcane supply-chains

Objective function	References																														
	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31										
Economic	x	x	x	x		x	x	x	x			x	x	x	x		x	x	x	x											
Government policies					x										x				x												
Environment	x								x		x		x	x	x				x												
Social aspects															x				x												
Computational response															x	x															
Type of biomass	x			x		x	x		x	x	x		x		x		x	x			x										
Production capacity	x	x		x	x	x				x	x				x		x	x													
Number of production facilities	x						x	x		x	x			x	x																
Technology selection	x		x				x					x	x		x						x										
Transportation fleet size						x		x									x	x		x											
Location of production facilities		x		x						x	x				x																
Machinery availability in the field								x									x	x		x											
Financial performance	x	x													x																
Number of land parcels to harvest																				x											
Land parcels assignment per type of crop		x																													

Source: Own elaboration based on the quoted authors

According to Table 1, the focus of a significant part of the studies is on supply chain design that included biomass type, technology selection, capacity allocation and the facilities required for the production stage. In other words, few contributions on supply chain planning were found. Regarding the first echelon of the supply chain (upstream), few studies examined the characteristics of the typical logistics operations for sugarcane, such as harvesting, loading and transportation from the land parcel to the production plant. It is important to emphasize that 91.3% of the articles examine operations where the crop is an input parameter, which reinforces the originality of this article where land parcel selection for sugarcane cultivation is a decision variable.

Additionally, the economic criterion is the most common objective function defined for sugarcane supply-chain optimization, although some of the articles take into account economic factors and environmental impact simultaneously. From the economic point of view, 21.41% of the studies aim to maximize expected net revenues and the rest are focused on cost minimization, emphasizing transportation, harvesting and warehousing operations. Likewise, only two researchers addressed opportunity cost analysis taking into account sugarcane maturity and crop investment.

Finally, models considering cost of equipment downtimes and cost of penalties for unmet demand were not identified in the literature review. Models focused on resource allocation (machinery and labor) to land parcels based on terrain constraints were not detected.

### 3. Structure of the model

The purpose of the mathematical model is to select the quantity of hectares to be collected per land parcel. It also allows for the selection of the type of harvesting method from three alternatives: mechanical, semi-mechanical and manual. In addition, the model selects the type of equipment for harvesting and loading operations, as well as the workforce required for a semi-mechanical or manual method. Table 2 shows the subscript indices used in the model; in turn, Tables 3 and 4 summarize the decision variables and the parameters respectively.

#### 3.1. Objective function

The cost parameters in the objective function were grouped as follows:

- Machinery costs (harvesting and loading machines). This includes the operation costs and the cost of equipment idle time. The latter is obtained based on the fixed cost of unassigned machinery.
- Workforce costs for cut and loading operations.
- Costs related to harvesting method. This includes maintenance personnel costs, staff and other inputs.
- Penalty costs for unfulfilled demand. This cost is agreed in the supply contract.
- Transportation costs.

The main purpose of the model is the minimization of the total costs, which is determined by:

Table 2.

Subscript indices.

Subscripts	Variation
Loading machine $p$	$p: 1, 2, 3, \dots, v$
Harvesting machine $r$	$r: 1, 2, 3, \dots, z$
Land parcel $i$	$i: 1, 2, 3, \dots, n$
Harvesting method $j$	$j = 1$ (Mechanical); $j = 2$ (Semi-mechanical)*; $j = 3$ (Manual)

\*Sugarcane is harvested manually; then, loading operations are carried out by loading machines.

Source: Own elaboration based on the quoted authors

Table 3.

Decision variables.

Symbol	Description
$A_{pi}$	Number of loading machines $p$ assigned to the land parcel $i$ during the week.
$AO_p$	Number of unassigned loading-machines $p$ (idle machines) during the week.
$EA_i$	Number of employees assigned to the land parcel $i$ for manual loading during the week.
$K_{ri}$	Number of harvesting machines $r$ assigned to the land parcel $i$ during the week (mechanical method)
$KO_r$	Number of unassigned harvesting-machines $r$ (idle machines) during the week.
$N$	Quantity of sugarcane not sent to the production plant (t/week).
$Q_i$	Number of employees assigned to land parcel $i$ for manual harvesting during the week.
$QS_i$	Number of employees assigned to land parcel $i$ for semi-mechanical harvesting during the week.
$X_{ij}$	Size of land parcel $i$ to be harvested by the method $j$ during the week (ha)

Source: Own elaboration based on the quoted authors

Min (Costs) = Operation cost per harvesting method + Transportation cost for sugarcane delivered from each land parcel to the production plant + Penalty cost for unfulfilled demand + Cost per assigned harvesting machine + Cost per idle harvesting machine + Cost per assigned loading machine + Cost per idle loading machines + Cost of assigned workforce for manual harvesting + Cost of assigned workforce for manual loading.

$$\begin{aligned}
 MIN\_Z = & \sum_{j=1}^3 CH_j \left( \sum_{i=1}^n X_{ij} \right) + \sum_{i=1}^n CT_i (TH_i) \left( \sum_{j=1}^3 X_{ij} \right) + \\
 & CN(N) + \sum_{r=1}^z \left( CK_r \sum_{i=1}^n K_{ri} \right) + \sum_{r=1}^z (CKO_r KO_r) + \\
 & \sum_{p=1}^v \left( CA_p \sum_{i=1}^n A_{pi} \right) + \sum_{p=1}^v (CAO_p AO_p) + \\
 & CQ \sum_{i=1}^n (QS_i + Q_i) + CEA \sum_{i=1}^n EA_i
 \end{aligned} \quad (1)$$

#### 3.1. Model constraints

Model constraints are represented by equations 2 to 14. The set of constraints includes land availability, production plant demand, equipment capacity, workforce availability and land conditions.

The system of equations is as follows:

Table 4.  
Parameters.

Symbol	Description	Unit
$CA_p$	Operating cost per assigned loading machine $p$ during the week	US\$/Week
$CAO_p$	Operating cost per unassigned loading machine during the week.	US\$/Week
$CEA$	Operating cost per assigned employee during the week	US\$/Week
$CH_j$	Fixed cost of the harvesting method $j$	US/ha
$CK_r$	Operating cost per assigned harvesting machine $r$ during the week	US\$/Week
$CKO_r$	Operating cost per unassigned harvesting machine during the week	US\$/Week
$CN$	Penalty cost for unfulfilled demand	US\$/t
$CQ$	Labor cost (for manual and semi-mechanical harvesting)	US\$/person-week
$CT_i$	Transportation cost from land parcel $i$ to production plant	US\$/t
$HD_i$	Available area of the land parcel $i$	ha
$MAS_p$	Capacity of the loading machine $p$	t/week
$MEAS$	Loading capacity per employee	t/week
$MKS_r$	Capacity of the harvesting machine $r$	t/week
$MQS$	Harvesting capacity per employee	t/week
$NAA_p$	Availability of loading machine $p$	Number of machines/week
$NEA$	Availability of employees for manual loading	Number of employees/week
$NK_r$	Availability of harvesting machine $r$	Number of machines/week
$NQS$	Availability of employees for manual harvesting	Number of employees/week
$TH_i$	Quantity of expected sugarcane per ha of land parcel $i$	t/ha
$TMS$	Maximum quantity of sugarcane delivered to the production plant	t/week
$TRS$	Minimum quantity of required sugarcane	t/week

Source: Own elaboration based on the quoted authors

Land:

Available area per land parcel (ha)

$$\sum_{j=1}^3 X_{ij} \leq HD_i \quad \forall i \quad (2)$$

**Demand:**

- Minimum amount of sugarcane required (t/week)

$$\sum_{i=1}^n \sum_{j=1}^3 TH_i X_{ij} \geq TRS \quad (3)$$

- Maximum amount of sugarcane to be sent to the production plant (t/week)

$$\sum_{j=1}^3 \sum_{i=1}^n TH_i X_{ij} + N = TMS \quad (4)$$

**Equipment availability:**

- Harvesting machines availability (quantity/week)

$$\left( \sum_{i=1}^n K_{ri} \right) + KO_r = NK_r \quad \forall r \quad (5)$$

- Loading machines availability (quantity/week)

$$\left( \sum_{i=1}^n A_{pi} \right) + AO_p = NAA_p \quad \forall p \quad (6)$$

**Workforce availability:**

- Workers' availability for harvesting (quantity/week): workers are divided into two groups; first one of them takes part in the semi-mechanical method; the second one is assigned to the manual method.

$$\sum_{i=1}^n (QS_i + Q_i) \leq NQS \quad (7)$$

- Workers' availability for manual loading (quantity/week)

$$\sum_{i=1}^n EA_i \leq NEA \quad (8)$$

**Equipment capacity:**

The equal symbol in the capacity constraints is required to achieve maximum equipment exploitation when assigned to every land parcel (uptime - maintenance time). The uptime for loading machines depends on the maximum time that sugarcane can wait to be processed after being cut without affecting its yield.

- Harvesting machines capacity per land parcel (t/week)

$$TH_i(X_{i1}) = \sum_{r=1}^z MKS_r(K_{ri}) \quad \forall i \quad (9)$$

- Loading machines capacity per land parcel (t/week)

$$MQS(QS_i) = \sum_{p=1}^v MAS_p(A_{pi}) \quad \forall i \quad (10)$$

**Workforce capacity:**

There are two groups of workers for harvesting operations: group 1 is assigned to semi-mechanical harvesting and group 2 is assigned to manual harvesting. The constraints are:

- Workers' capacity for semi-mechanical harvesting in every land parcel (t/week)

$$TH_i(X_{i2}) = MQS(QS_i) \quad \forall i \quad (11)$$

- Workers' capacity for manual harvesting in every land parcel (t/week)

$$TH_i(X_{i3}) \leq MQS(Q_i) \quad \forall i \quad (12)$$

- Workers' capacity for manual loading in every land parcel (t/week)

$$MQS(Q_i) \leq MEAS(EA_i) \quad \forall i \quad (13)$$

**Land conditions:**

The proper operation of harvesting machines (powered by a caterpillar engine or wheel-mounted) depends on the land parcel characteristics; for example, wheel-mounted

machines encounter difficulties when assigned to wetlands. Therefore, depending on the foreman assessment of each type of land, the following constraint will come in to play:

- Harvesting machines  $t$  unassigned to the land parcel  $i$  due to land conditions.

$$K_{ri} = 0 \quad (14)$$

#### Non- negativity condition and integer variables:

All variables are constrained to values greater than or equal to zero. Furthermore, the following variables are constrained to integer values.

$$A_{pi}, AO_p, EA_i, K_{ri}, KO_r, Q_i, QS_i$$

#### 4. Case study

This model was implemented in a Peruvian ethanol production company. The supply chain was comprised of sugarcane harvesting and loading operations, raw material transportation, the ethanol production process and finally, transportation to the international market. Although the company had several land parcels planted with sugarcane, the model was applied to support the operations programming of harvesting, loading and transportation for only two of these. This decision was made because, when the study was conducted, the generated raw material (41,300 t) exceeded the ethanol plant requirement (28,000 t). However, the model can be adjusted insofar as ethanol demand increases. Table 5 shows the input parameters given by the company; however, information about costs was omitted due to confidentiality agreements with the company.

By using GAMS (General Algebraic Modeling System)

professional software, the model was solved. The model was run on a microcomputer provided with 1.66 GHz Intel processor and 4.6 GB of memory RAM. The problem was solved efficiently since the computational time was of a thousandth of second.

According to the results, 300 ha of land parcel 1 should be harvested using the mechanical method, assigning five machines for this operation (three Case brand, one John Deere brand powered by caterpillar engine and one John Deere brand powered by wheel-mounted). This outcome highlights another advantage of the proposed model, which allows for programming of different types of machines for this operation. Also, 40 ha of land parcel 1 must be processed using the manual method, which implies the assignment of 147 workers to harvesting and loading operations. Regarding land parcel 2, the model chose the mechanical method to collect 60 ha; however, due to terrain conditions, the harvesting machine powered by the caterpillar engine was assigned instead of the wheel-mounted machine. Based on this resource allocation, 28,000 tons of sugarcane (23,800 from land parcel 1 and 4,200 from land parcel 2) can be processed, satisfying 100% of the ethanol plant requirements.

Although the model penalizes equipment idle time, the semi-mechanical method was not included in the final solution, even though four loading machines and one harvesting machine are unnecessary. This decision shows the existing overcapacity in the agricultural echelon of the supply chain. As a consequence, the company must increase its marketing efforts. From another point of view, the company can take advantage of idle machines to implement preventive maintenance activities. The obtained total cost was approximately 11% less than the current costs, showing significant savings for the company. Table 6 summarizes the obtained solution.

Table 5.  
Input parameters of the case study

TIME AVAILABILITY			
	Labor	Harvesting machine	Loading Machine
Hours/day	8	20	12
Days/week	7	7	7
Maintenance (Hours/week)		4	4
HARVESTING			
	Mechanical method		Manual method
	Case brand	Jhon Deere brand	Employee
Availability	4	3	200
Capacity (t/hour)	30	30	0.625
Capacity (t/day)	600	600	5
Capacity (t/week)	4200	4200	35
LOADING			
	Mechanical method		Manual method
	Cameco brand	John Deere brand	Employees
Availability	2	2	200
Capacity (t/hour)	24	24	0.75
Capacity (t/day)	288	288	6
Capacity (t/week)	2016	2016	42
DEMAND			
Minimum: 17500		Maximum: 28000	
LAND			
	Land parcel 1	Land parcel 2	
Availability (ha)	500	90	
Expected sugarcane (t/ha)	70	70	
Land constraints	None	Humidity	

Source: Own elaboration based on the quoted authors

Table 6.  
Final results

NUMBER OF HARVESTED AND LOADED HECTARES			
	Land parcel 1	Land parcel 2	
Mechanical	300	60	
Semi-mechanical	0	0	
Manual	40	0	
RESOURCE ASSIGNMENT PER WEEK			
	Land parcel 1	Land parcel 2	Unassigned
Number of harvesting machines (Case brand)	3	0	1
Number of harvesting machines (John Deere brand; powered by caterpillar engine)	1	1	0
Number of harvesting machines (John Deere brand; powered by wheel-mounted)	1	0	0
Number of workers for semi-mechanical harvesting	0	0	
Number of workers for manual harvesting	80	0	
Number of loading machines (Cameco brand)	0	0	2
Number of loading machines (John Deere brand)	0	0	2
Number of workers for manual loading	67	0	
DEMAND SATISFACTION			
	Land parcel 1	Land parcel 2	Unfulfilled
Quantity of sugarcane (t)	23.800	4.200	0

Source: Own elaboration based on the quoted authors

## 5. Conclusions

Biofuel supply chain improvement has been a matter of great interest in recent years. Although the literature review shows an important number of papers on this topic, most of them are aimed at supporting decisions regarding supply chain design. The analysis showed that a significant part of the studies oriented to supply chain design, considered the biomass type, technology selection, capacity allocation and facilities as the most important decision variables; however few papers on optimization models for supply chain planning were found, specifically those oriented toward analyses of the particularities of the first echelon (upstream) of the sugarcane supply chain.

For instance, few studies examined the characteristics of the typical logistics operations for sugarcane, such as harvesting, loading and transportation from the land parcel to the production plant. Also, models that took into account the cost of equipment downtime and the cost of penalties for unmet demand were not identified in the literature review. Models oriented to resource allocation (machinery and labor) to the land parcels based on the terrain constraints were not detected.

In contrast, the proposed model shows several advantages that can be summarized as follows: 1) it analyzes operations programming related to harvesting, loading and transporting sugarcane, using land parcel selection as a decision variable; 2) the model considers the optimization of four types of costs: allocation of machinery and workforce, transportation from the farm to the biofuel production plant, penalties for unmet orders and idle machinery; 3) in the case of the mechanical harvesting method, terrain constraints for machinery selection were taken into account.

According to the results obtained in the case study, the current cost of the company was reduced by approximately 11%. By analyzing three alternatives for harvesting and loading operations (mechanical, semi-mechanical and manual), 300 ha with the mechanical method and 96 ha with

the manual method were assigned. Because the model did not take into account the use of the semi-mechanical alternative, four loading machines and one harvesting machine were not used affecting the idle time cost. In general, the model established the required resources to support the operations programming in the first echelon of the supply chain; thus, the results show the number of machines, work force and staff necessary to meet the raw material requirements of the production plant.

Due to the level of complexity of the present model in relation to the number of land parcels analyzed, computer time was not a problem; nevertheless the effect on the set of variables and constraints must be checked for a greater amount of land parcels. The model shows some disadvantages that suggest some future research lines. For example, it is necessary to analyze other features related to operations such as internal transportation, yield for several sugarcane varieties and other soil constraints. Other variables such as demand uncertainty and multi-period and environmental conditions could be analyzed in order to provide a better tool to support decision-making.

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