Revista Centro Azúcar
Vol. 52, 2025
ISSN: 2223-4861

Una Publicación de la Editorial Feijóo, UCLV

Disponible en:
http://centroazucar.uclv.edu.cu

http://scielo.sld.cu/scielo.php?script=sci_serial&pid=2223-4861&lng=es&nrm=iso

Article Original

AN OPTIMIZATION MODEL FOR CANE TRANSPORTATION IN THE ARGENTINE SUGAR INDUSTRY

UN MODELO DE OPTIMIZACIÓN PARA EL TRANSPORTE DE CAÑA EN LA INDUSTRIA AZUCARERA ARGENTINA

Gabriela Corsano[1*] https://orcid.org/0000-0002-0235-4262
Luciana Melchiori[1] https://orcid.org/0000-0003-1993-4113

[1] *Instituto de Desarrollo y Diseño, CONICET-UTN, Santa Fe, Argentina.*

Recibido: Abril 24, 2025; Revisado: Mayo 15, 2025; Aceptado: Junio 2, 2025

ABSTRACT

Introduction:

Over the past decade, significant industrial and academic efforts focused on improving sugarcane harvesting, transportation, and sugar production have been carried out. While most studies focus on decision-making at a strategic and tactical level, the operational level remains less explored. This work develops a tool for daily sugarcane transportation planning within the Argentine industry.

Objective:

To generate a daily transportation schedule considering in-field loading and mill unloading activities, aiming to optimize transportation costs and synchronize truck arrivals.

Materials and Methods:

Sugarcane harvest scheduling involves cane cutting, loading in the field, transport, and mill unloading. These tasks greatly influence supply chain costs and production efficiency due to cane deterioration. To address this, we propose an Integer Linear Programming model that simultaneously assigns harvest fields, routes trucks, and schedules both loading and unloading operations.

Results and Discussion:

Two case studies assess the model: a small-scale instance for detailed result analysis and an industrial-scale example to demonstrate the model's scalability and effectiveness.

* Autor para la correspondencia: Gabriela Corsano, Email: gcorsano@santafe-conicet.gob.ar

Conclusions:
The proposed model provides a comprehensive plan for sugarcane harvest and transport, supporting efficient operational decisions in the sugar industry.

Keywords: combinatorial optimization; mathematical programming; routing; scheduling; sugarcane.

RESUMEN

Introducción:
En la última década, se han realizado importantes esfuerzos industriales y académicos enfocados en mejorar la cosecha, el transporte de caña de azúcar y la producción de azúcar. Mientras que la mayoría de los estudios se centran en la toma de decisiones a nivel estratégico y táctico, el nivel operativo ha sido menos explorado. Este trabajo desarrolla una herramienta para la planificación diaria del transporte de caña en el contexto de la industria argentina.
Objetivo:
Generar una programación diaria del transporte considerando las actividades de carga en el campo y descarga en el ingenio, con el objetivo de optimizar los costos de transporte y sincronizar los arribos de los camiones.
Materiales y Métodos:
La programación de la cosecha de caña implica el corte, la carga en el campo, el transporte y la descarga en el ingenio. Estas tareas impactan significativamente en los costos de la cadena de suministro y en la eficiencia del proceso productivo, debido al deterioro de la caña. Para abordar estas cuestiones, se propone un modelo de Programación Lineal Entera que asigna simultáneamente los campos a cosechar, las rutas de los camiones y los horarios de carga y descarga.
Resultados y Discusión:
Se presentan dos estudios de caso para evaluar el modelo: uno de pequeña escala, que permite analizar resultados detalladamente, y otro de escala industrial, para demostrar su escalabilidad y efectividad.
Conclusiones:
El modelo propuesto ofrece un plan integral para la cosecha y el transporte de caña de azúcar, sirviendo como una herramienta eficiente para la toma de decisiones operativas en la industria azucarera.

Palabras clave: optimización combinatoria; programación matemática; ruteo; programación; caña de azúcar.

1. INTRODUCTION

The diversification in the sugar industry, especially biofuels production and electricity generation in past decade, has increased the interest in improving both the economy and the efficiency of the sugarcane supply chain (SC). Consequently, this sector needs technical and scientific support. Particular attention was focused on the modernization of harvesting activities, in the production process, and logistics, since these activities strongly impact in the overall performance of the SC (Kaup, 2015). Mathematical programming and optimization have been extensively used for guiding decision-making in sugarcane SC with the objective of improving its management. The list of published works in this topic is large, and most approaches have directed their studies towards decision-making at the strategic and tactical levels (Kostin et al., 2012; Gilani & Sahebi, 2021; Florentino et al., 2022; Lima et al., 2023), with the operational level receiving less attention. Recently, dos Santos et al. (2023) presented a review work about sugarcane SC optimization models, covering papers about planting, harvesting, transporting, industrial processing, and marketing decisions for the different decision levels: strategic, tactical and operational. They emphasize the importance of mathematical modeling and optimization to build planning tools and conclude that most approaches addressed harvesting optimization at the strategic and tactical level, while only few works were identified considering integration of the activities from harvesting to milling at the operational level. They also highlight that, given the perishable characteristics of the sugarcane, simultaneous decisions at operational level must be directed.

In this work, the Daily Sugarcane Transportation Planning (DSTP) problem is addressed at the operational decision level, aiming to effectively meet product demand while efficiently managing short-term decisions. This problem is also referred to in the literature as harvest scheduling (Le Gal et al., 2008). Specifically, given a set of fields to be harvested-each with known sugarcane availability-and the existing harvesting machinery, as well as a fleet of trucks stationed at the sugar mill for cane transportation and a known sugarcane demand at the mill, the problem involves assigning trucks to fields to collect the cane harvested by each machine, determining the route each truck takes during the day, synchronizing harvesting with truck loading, and coordinating truck arrivals at the mill. Thus, allocation, routing, and scheduling are addressed simultaneously in the context of the Argentine sugarcane supply chain. It is worth noting that the assumptions and decisions in sugarcane supply chain models may vary depending on the specific characteristics of each application context (Higgins et al., 2007).

Sugarcane degradation occurs when delays between the different stages are long. For this reason, detailed operational planning is essential and necessary. Also, scheduling consideration must be taken into account to coordinate the use of resources at the fields (harvesters and truck loading) and at the mill (truck arrivals and unloading) to avoid overlapping and idle time. López-Milán et al. (2006) presented a mixed integer linear programming (MILP) model that jointly solves the sugarcane harvesting and transportation at operational level. They consider two means of transportation (railway and road) and two types of harvesting (manual and mechanized). They divide the daily time horizon into one-hour periods to indicate when harvesting and transportation occur throughout the day. This assumption has two drawbacks: an increase in the number of binary variables in the proposed MILP model, and a simplification of the real case due to the use of one-hour time periods. In a later work, López-Milán & Plà-Aragonès, (2014) proposed a Decision Support System (DSS) to efficiently solve the same problem, resulting in significant fuel cost savings when the DSS was applied to a real-life scenario. A more realistic approach incorporates uncertainty in sugarcane yield at harvesting stage. This was addressed by Morales et al. (2020), who proposed a multi-objective stochastic optimization model for harvest, maintenance, transport and workforce scheduling, considering economic, environmental and social objectives.

Building on previous insights, this work proposes an Integer Linear Programming model that realistically schedules sugarcane supply operations—harvest planning, truck routing, and timing—using detailed time slots. The model minimizes transport costs while accounting for machinery and vehicle characteristics, and solves complex, simultaneous decisions efficiently within practical computational times.

2. MATERIALS AND METHODS

This section introduces the Daily Sugarcane Transportation Problem (DSTP). Given a set of sugarcane fields p, $p \in P$, each with a maximum availability O_p (in full-truckloads, FTL) and a time window $[W_j^-, W_j^+]$, the goal is to select suppliers, route trucks $v \in V$, and schedule arrivals to meet the mill's demand D (in FTL) at minimum cost.

The transportation network includes the fields and the mill m, where all trucks start and end. The homogeneous fleet has identical capacity and is based at the mill. Travel times $T_{i,j}$ are defined for all $i, j \in P \cup \{m\}$, along with service resources R_j per location, which represent harvesters in fields and unloaders at the mill.

T_p^L represents the time required for the harvesting machinery to harvest and load a truck and it depends on the harvester technology, while T^U denotes unloading time. Trucks may wait if no resource is available, with maximum allowed waiting time, T_j^W, Routes include departure trips from the mill, loaded trips to the mill, and repositioning trips. Trucks are limited by daily working time L^{time} and number of trips, L^{trips}. The objective function includes fixed truck costs C_v^f and variable trip costs $C_{i,j}$, which depend on distances, truck load condition, and road characteristics. Figure 1 outlines the DSTP. The model determines:

- The sugarcane fields that supply the mill.
- The routing decisions, i.e., the sequence of trips to be performed by each truck.
- The scheduling of trucks arrivals in each sugarcane field and the mill.

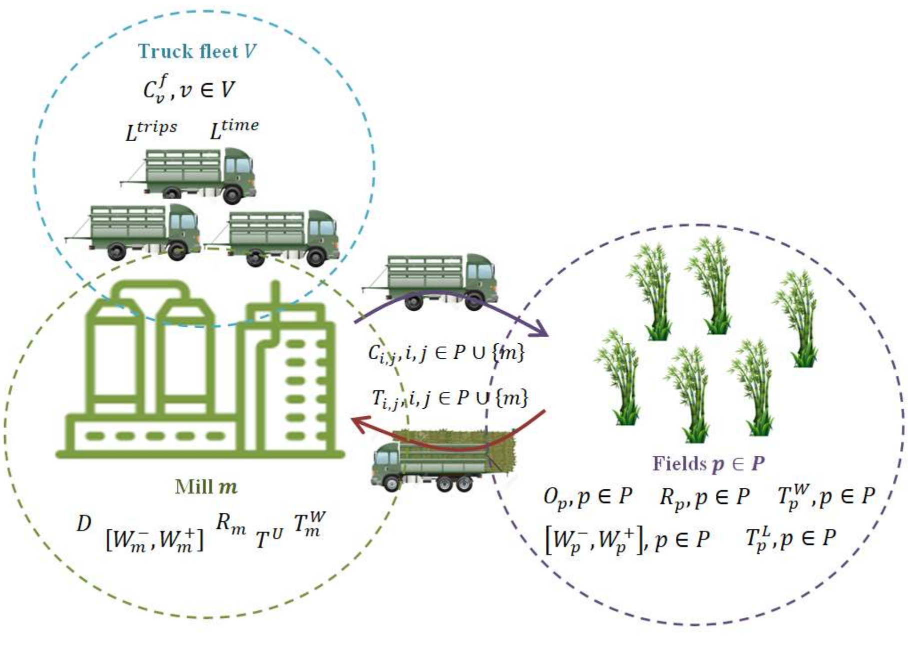

Figure 1. Proposed sugarcane SC and parameter definitions

2.1. Proposed approach

For the harvesting scheduling, a slot-based formulation is proposed, discretizing the time windows of each harvest site and the mill in shifts. The methodology used for synchronizing the activities of harvesting, loading, transporting, and unloading sugarcane is thoroughly explained in the following subsections.

2.2. Time discretization

Each field and the mill have their time windows discretized into service shifts, based on available loading or unloading resources. To minimize the number of shifts while ensuring feasibility, adjusted time intervals are defined for each location, considering distances and the daily nature of harvesting and transport planning. For $p \in P$, the feasibility interval $\left[F_p^-, F_p^+\right]$ is considered, where initial and final values are calculated as

$$F_p^- = \max\left\{W_p^-, W_m^- + T_{m,p}\right\} \quad (1)$$

and

$$F_p^+ = \min\left\{W_p^+, W_m^+ - T^U - T_{p,m}\right\} \quad (2)$$

For the mill, the feasibility interval $[F_m^-, F_m^+]$ is considered, and its endpoints are calculated as

$$F_m^- = \min_p\left\{F_p^- + T_p^L + T_{p,m}\right\} \quad (3)$$

and

$$F_m^+ = \min\left\{W_m^+, \max_p\left\{F_p^+ + T_{p,m}\right\} + T_m^W + T^U\right\} \quad (4)$$

Thus, for each field p, the time interval $\left[F_p^-, F_p^+\right]$ is partitioned into $\left\lfloor (F_p^+ - F_p^-)/T_p^L \right\rfloor$ shifts of length T_p^L, where $\lfloor\cdot\rfloor$ indicates the floor function. Let I_p be the set of these shifts. Analogously, the time interval $[F_m^-, F_m^+]$ for the mill is partitioned into $\lfloor (F_m^+ - F_m^-)/T^U \rfloor$ shifts of length T^U. Let L be the set of these shifts. For each shift s, with $s \in I_p \cup L$, S_s denotes the start time of s and E_s indicate the end time of s.

In Figure 2, the construction of feasible intervals and the corresponding shifts for an example with a field, is illustrated. Part (a) displays the shifts for the field, while part (b) shows the shifts obtained for the mill.

2.3. Successive pairs of shifts

Based on the chronology, including travel and maximum waiting times, it is evident that not every pair of shifts can be used successively. For this reason, subsets of $I_p \times L$ and $L \times I_p$ are defined below. These relations between pair of shifts reduce the number of decision variables improving its performance.

2.3.1. Trips from the field to the mill

Given $p \in P$, let Δ_p be the set of all pairs of shifts (i, l) with $i \in I_p$ and $l \in L$ such that l is allowed to be used after shift i. Then, $(i, l) \in \Delta_p$ if it fulfills the following conditions:

- The shift l begins after the ending time of shift i plus the traveling time from p to the mill, i.e.,

$$E_i + T_{p,m} \leq S_l \tag{5}$$

○ If shift l is used after shift i, then the maximum waiting time allowed in the mill is not exceeded, i.e.,

$$S_l \leq E_i + T_{p,m} + T_m^W \tag{6}$$

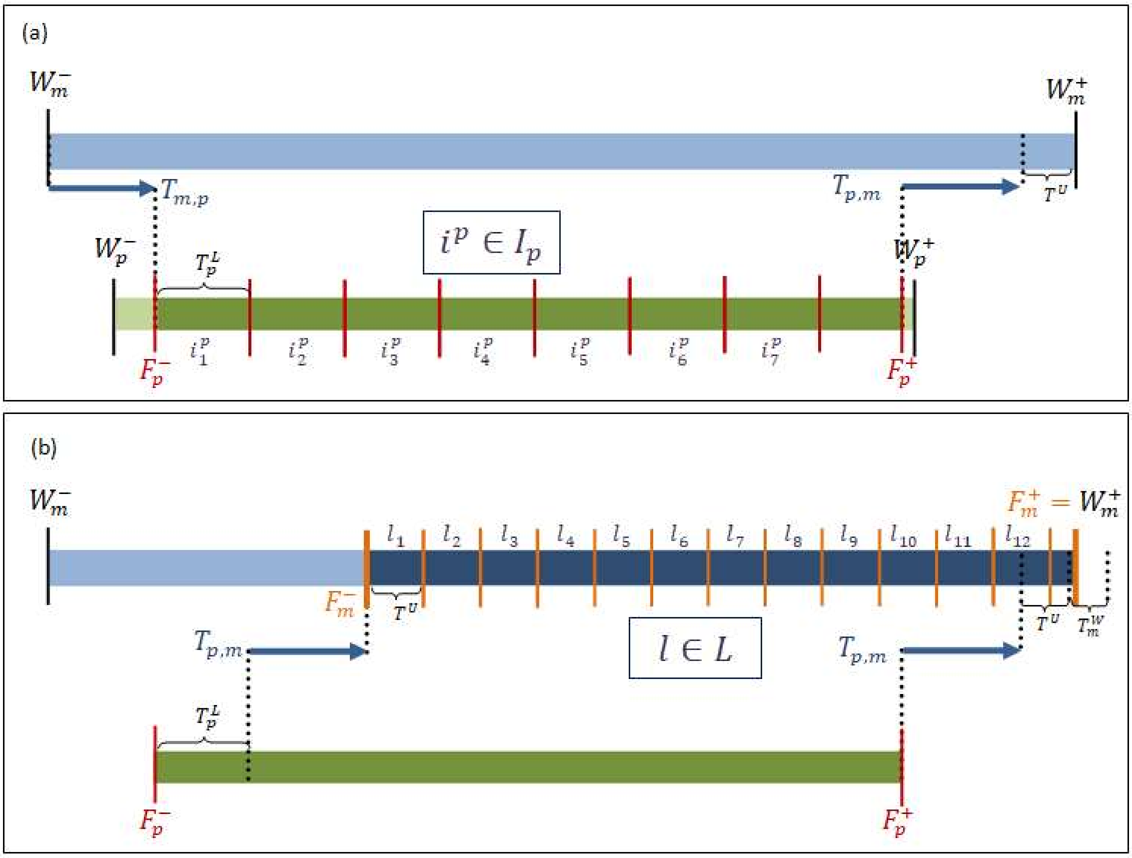

Figure 2. Definition of feasible time intervals

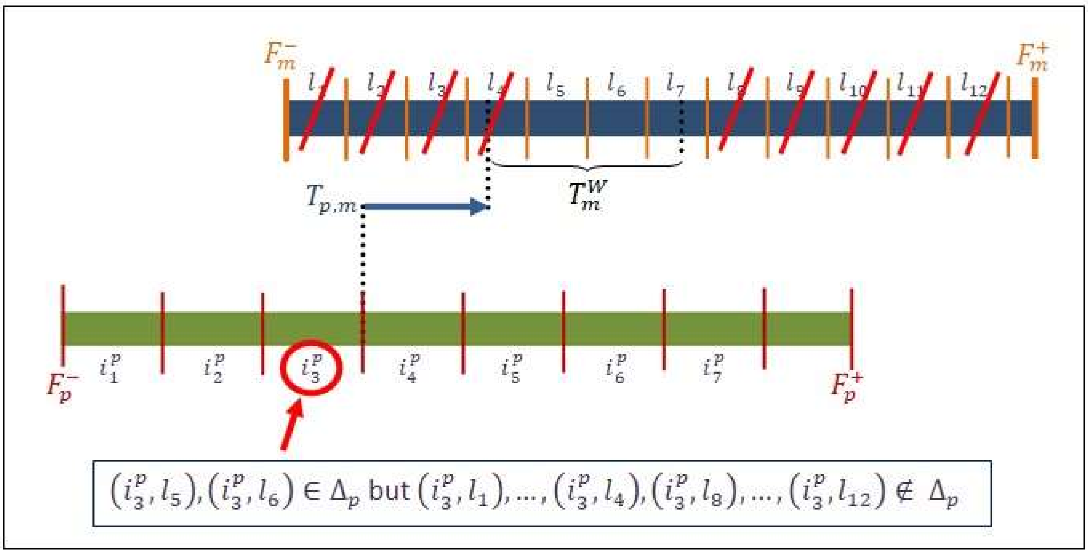

Figure 3. Relations between consecutive shifts in trips from the field to the mill

2.3.2 Trips from the mill to the field

Given $p \in P$, let Π_p be the set of every pair of shifts (l, i) with $l \in L$ and $i \in I_p$ such that i is allowed to be used after shift l. Then, $(l, i) \in \Pi_p$ if the following conditions are fulfilled:

○ The starting time of shift i is later than the ending time of shift l plus the traveling time between the mill and p, i.e.,

$$E_l + T_{m,p} \leq S_i \quad (7)$$

The starting time of shift i must be earlier than the ending time of shift l plus the traveling time between the mill and p, plus the maximum allowed waiting time at p, i.e.,

$$S_i \leq E_l + T_{m,p} + T_p^W . \quad (8)$$

Figure 4 shows an example of allowed and not allowed consecutive shifts for trips from the mill to field.

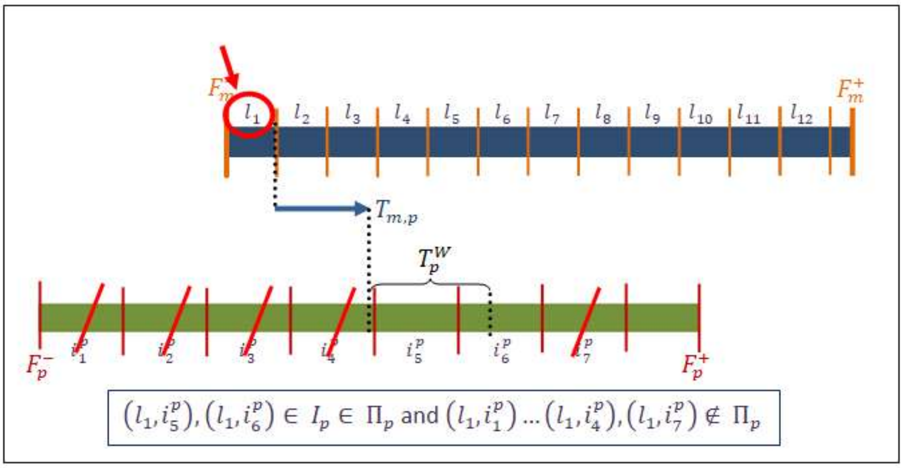

Figure 4. Relations between consecutive shifts in trips from the mill to the field

2.4. Mathematical Programming Model

Only trips associated with successive pairs of shifts for in-field harvesting/loading and unloading the cane, or for unloading and harvesting/loading, are considered. That is, pairs of shifts included in the sets described in Subsection 3.2. Accordingly, the following binary variables are defined:

- For each $v \in V$, $p \in P$, and $i \in I_p$, the corresponding variable $x_{v,p,i}$ takes the value 1 if the truck v departs in its first trip from the mill to the field p for in-field harvesting and loading sugarcane during shift i.
- For each $v \in V$, $p \in P$, and $(i, l) \in \Delta_p$, the corresponding variable $x_{v,p,i,l}$ takes the value 1 if the truck v leaves the field p at the end of shift i to be unloaded at the mill during shift l.
- For each $v \in V$, $p \in P$, and $(l, i) \in \Pi_p$, the corresponding variable $x_{v,l,p,i}$ takes the value 1 if the truck v leaves the mill at the end of shift l to the field p to be loaded during shift i.

An additional variable is defined to represent the end of every route:

- For each $v \in V$ and $l \in L$, the corresponding variable $x_{v,l}$ takes the value 1 if the truck v finishes this route at the end of shift l.

2.4.1. Objective function

The overall transportation cost C^{total} to be minimized is calculated as follows:

$$C^{total} = \sum_{v\in V}\sum_{p\in P}\sum_{i\in I_p}\left(C_v^f + C_{m,p}\right)x_{v,p,i} + \sum_{v\in V}\sum_{p\in P}\sum_{(i,l)\in\Delta_p} C_{p,m}x_{v,p,i,l} + \sum_{v\in V}\sum_{p\in P}\sum_{(l,i)\in\Pi_p} C_{m,p}x_{v,l,p,i}. \quad (9)$$

The objective function includes costs for truck trips: fixed and variable costs for departures from the mill to fields, loaded trips back to the mill, and unloaded repositioning trips from the mill to fields.

2.4.2. Constraints

The constraints related to the supply and demand of sugarcane correspond to (10) and (11). Equation (10) guarantees that the total loaded movements arriving at the mill must fulfill its demand. Constraint (11) states that for every sugarcane field, the total loaded movements performed from this place to the mill cannot exceed the availability of sugarcane at that location.

$$\sum_{v\in V}\sum_{p\in P}\sum_{(i,l)\in\Delta_p} x_{v,p,i,l} = D \quad (10)$$

$$\sum_{v\in V}\sum_{(i,l)\in\Delta_p} x_{v,p,i,l} \leq O_p, \forall p \in P. \quad (11)$$

Constraint (12) guarantees that each truck has at most one route. Constraint (13) ensures that if a truck performs a route, then it must finish it. Constraints (14) and (15) are the flow conservation constraints per shift.

$$\sum_{p\in P}\sum_{i\in I_p} x_{v,p,i} \leq 1, \qquad \forall\, v \in V. \quad (12)$$

$$\sum_{p\in P}\sum_{i\in I_p} x_{v,p,i} = \sum_{l\in L} x_{v,l}, \qquad \forall v \in V. \quad (13)$$

$$x_{v,p,i} + \sum_{l:(l,i)\in\Pi_p} x_{v,l,p,i} = \sum_{l:(i,l)\in\Delta_p} x_{v,p,i,l}, \qquad \forall v \in V, p \in P, i \in I_p. \quad (14)$$

$$\sum_{p\in P}\sum_{i:(i,l)\in\Delta_p} x_{v,p,i,l} = \sum_{p\in P}\sum_{i:(l,i)\in\Pi_p} x_{v,l,p,i} + x_{v,l}, \qquad \forall v \in V, l \in L. \quad (15)$$

Constraints (16) and (17) impose that at most R_j trucks attend each shift of the fields and the mill, for $j \in P \cup \{m\}$, respectively.

$$\sum_{v\in V} x_{v,p,i} + \sum_{v\in V}\sum_{l:(l,i)\in\Pi_p} x_{v,l,p,i} \leq R_p, \qquad \forall p \in P, i \in I_p. \quad (16)$$

$$\sum_{v\in V}\sum_{p\in P}\sum_{i:(i,l)\in\Delta_p} x_{v,p,i,l} \leq R_m, \qquad \forall l \in L. \quad (17)$$

Considering that there is a maximum working time L^{time} that sets an upper bound for the duration of a route, the set $\varphi_{p,i}$ is defined to associate the start and end shifts of the route such that its duration does not exceed that time. Specifically, given $p \in P$ and $i \in I_p$, let $\varphi_{p,i}$ be the set of all $l \in L$ such that a truck's route, which departs from the mill and attends shift i of p after its first trip, can end in shift l without exceeding L^{time}. Since the duration of a route is calculated as $E_l - (S_i - T_{m,p})$, the set $\varphi_{p,i}$ is defined as

$$\varphi_{p,i} = \{l: l \in L \ and \ E_l - (S_i - T_{m,p}) \leq L^{time}\}.$$

Constraint (18) states that if a truck attends shift i of p after its first trip, it cannot attend shift l of the mill before its last trip if $l \notin \varphi_{p,i}$:

$$\sum_{l \notin \varphi_{p,i}} x_{v,l} \leq 1 - x_{v,p,i}, \quad \forall v \in V, p \in P, i \in I_p. \tag{18}$$

Eq. (19) states that trucks cannot perform more than L^{trips} trips, setting an upper bound on the number of trips per vehicle from the mill to the fields.

$$\sum_{p \in P} \sum_{(l,i) \in \Pi_p} x_{v,l,p,i} \leq \left\lfloor \frac{L^{trips} - 2}{2} \right\rfloor, \qquad \forall v \in V. \tag{19}$$

2.4.3. Valid inequalities

To strengthen the model formulation and improve computational efficiency, existence constraints and symmetric breaking constraints are considered:

Constraint (20) ensures that the truck that leaves the mill makes trips from fields to the mill.

$$\sum_{p \in P} \sum_{i \in I_p} x_{v,p,i} \leq \sum_{p \in P} \sum_{(i,l) \in \Delta_p} x_{v,p,i,l}, \forall v \in V. \tag{20}$$

Constraints (19) can be rewritten to impose an upper bound on the number of trips per vehicle from fields to the mill as follows:

$$\sum_{p \in P} \sum_{(i,l) \in \Delta_p} x_{v,p,i,l} \leq \left\lceil \frac{L^{trips} - 2}{2} \right\rceil, \qquad \forall v \in V \tag{21}$$

where $\lceil . \rceil$ indicates the ceil function. This condition can be tightened by introducing an additional factor to the right-hand side (RHS) of the constraint, which accounts for whether the truck leaves the mill. The modified constraint is as follows:

$$\sum_{p \in P} \sum_{(i,l) \in \Delta_p} x_{v,p,i,l} \leq \left\lceil \frac{L^{trips} - 2}{2} \right\rceil \sum_{p \in P} \sum_{i \in I_p} x_{v,p,i}, \qquad \forall v \in V. \tag{22}$$

As all vehicles have equal fixed costs, symmetries are avoided with the constraint (23):

$$\sum_{p \in P} \sum_{i \in I_p} x_{v_{n+1},p,i} \leq \sum_{p \in P} \sum_{i \in I_p} x_{v_n,p,i}, \qquad \forall 1 \leq n \leq |V| - 1. \tag{23}$$

2.5. Case Studies

Two test cases based on the Argentine context are used to evaluate the model, which is implemented in GAMS and solved with CPLEX. A 900-second CPU time limit is set, considering the model's use as a daily scheduling tool.

For both examples, the trucks fixed cost is equal to \$650, while the costs related to travelled distance of loaded and unloaded trucks are \$25 and \$15 per km, respectively. It is assumed that the routes have similar characteristics. The loaded truck speed is 55 km per hour, and the unloaded truck speed is 65 km per hour. Additionally, each truck driver has a maximum working time $L^{time} = 8$ hours and each truck can make at most $L^{trips} = 8$ trips.

3. RESULTS AND DISCUSION

3.1. Example I

The first example considers five fields (p_1–p_5) and 19 trucks (v_1–v_{19}) to deliver 72 FTL in one day. Table 1 shows FTL availability, distances to the mill, time windows, and harvesting/loading times. Waiting times are limited to 40 minutes in fields and 20 at the mill, which uses two 10-minute unloading resources. Feasible intervals and shifts appear in Table 2. The model includes 14,877 binary variables and 6,429 constraints, reaching optimality in 640.19 CPU seconds at a cost of $43,030. Table 3 shows truck routes and shifts; and Figure 5 presents the Gantt chart.

Table 1. Details of sugarcane fields for Example I: supply, distance to the mill, time window, and harvesting-loading time of resources

	O_p *(FTL)*	D_p *(km)*	W_p^- *(h)*	W_p^+ *(h)*	T_p^L *(min)*
p_1	16	15	6:00	20:00	50
p_2	16	6	6:00	20:00	50
p_3	10	20	0:00	24:00	50
p_4	17	8	0:00	24:00	80
p_5	17	10	0:00	24:00	80

Table 2. Feasible generated shift in Example I

	F_p^-*(h)*	F_p^+ *(h)*	$\lvert I_p \rvert$	F_m^- *(h)*	F_m^+ *(h)*	$\lvert L \rvert$
p_1	06:00	20:00	16	-	-	-
p_2	06:00	20:00	16	-	-	-
p_3	00:18	23:10	27	-	-	-
p_4	00:07	23:16	17	-	-	-
p_5	00:09	23:05	17	-	-	-
m	-	-	-	01:30	24:00	134

Table 3. Trucks routes descriptions for the optimal solution of Example I

Truck	*Assigned route*	*Routing time (h)*
v_1	$m - p_2, i_8 - m, l_{69} - p_5, i_{11} - m, l_{83} - p_2, i_{13} - m, l_{94} - p_4, i_{14} - m, l_{107}$	7:36
v_2	$m - p_4, i_4 - m, l_{27} - p_1, i_2 - m, l_{40} - p_1, i_4 - m, l_{50} - p_1, i_6 - m, l_{60}$	7:30
v_3	$m - p_4, i_6 - m, l_{43} - p_1, i_5 - m, l_{55} - p_1, i_7 - m, l_{65} - p_3, i_{16} - m, l_{77}$	7:40
v_4	$m - p_5, i_{12} - m, l_{90} - p_1, i_{14} - m, l_{101} - p_4, i_{15} - m, l_{115} - p_3, i_{26} - m, l_{126}$	7:50
v_5	$m - p_5, i_8 - m, l_{59} - p_3, i_{15} - m, l_{71} - p_2, i_{10} - m, l_{80} - p_2, i_{12} - m, l_{89}$	7:00
v_6	$m - p_2, i_2 - m, l_{40} - p_2, i_4 - m, l_{50} - p_2, i_6 - m, l_{60} - p_5, i_{10} - m, l_{74}$	7:06
v_7	$m - p_4, i_2 - m, l_{11} - p_5, i_4 - m, l_{26} - p_2, i_1 - m, l_{34} - p_1, i_3 - m, l_{45}$	7:40
v_8	$m - p_2, i_3 - m, l_{45} - p_4, i_8 - m, l_{59} - p_4, i_{10} - m, l_{75} - p_2, i_{11} - m, l_{84}$	7:55
v_9	$m - p_5, i_6 - m, l_{43} - p_2, i_5 - m, l_{55} - p_2, i_7 - m, l_{65} - p_1, i_9 - m, l_{76}$	7:30
v_{10}	$m - p_1, i_8 - m, l_{70} - p_1, i_{10} - m, l_{80} - p_1, i_{12} - m, l_{91} - p_5, i_{14} - m, l_{107}$	7:44
v_{11}	$m - p_5, i_2 - m, l_{10} - p_3, i_5 - m, l_{23} - p_1, i_1 - m, l_{35} - p_3, i_{10} - m, l_{46}$	7:52
v_{12}	$m - p_4, i_1 - m, l_3 - p_4, i_3 - m, l_{19} - p_4, i_5 - m, l_{34}$	7:10
v_{13}	$m - p_4, i_{12} - m, l_{90} - p_2, i_{14} - m, l_{100} - p_1, i_{16} - m, l_{110} - p_5, i_{16} - m, l_{123}$	7:20
v_{14}	$m - p_1, i_{13} - m, l_{95} - p_2, i_{15} - m, l_{105} - p_3, i_{24} - m, l_{116} - p_5, i_{17} - m, l_{130}$	7:24
v_{15}	$m - p_1, i_{11} - m, l_{86} - p_4, i_{13} - m, l_{99} - p_2, i_{16} - m, l_{110} - p_4, i_{16} - m, l_{122}$	7:44
v_{16}	$m - p_4, i_7 - m, l_{51} - p_5, i_9 - m, l_{66} - p_2, i_9 - m, l_{75} - p_3, i_{18} - m, l_{86}$	7:50
v_{17}	$m - p_5, i_1 - m, l_3 - p_5, i_3 - m, l_{19} - p_5, i_5 - m, l_{35}$	7:20
v_{18}	$m - p_5, i_{13} - m, l_{99} - p_5, i_{15} - m, l_{115} - p_4, i_{17} - m, l_{131}$	7:20
v_{13}	$m - p_4, i_{12} - m, l_{90} - p_2, i_{14} - m, l_{100} - p_1, i_{16} - m, l_{110} - p_5, i_{16} - m, l_{123}$	7:20

The model provides detailed information for each truck. For instance, Figure 6 shows the scheduling for truck v_{10}, starting at the mill and arriving at field p_1 during shift shift $i_8^{p_1}$. After loading, it travels to the mill and waits from shift l_{69} to l_{70} to unload. It then returns to field p_1, arriving at shift $i_9^{p_1}$ but waiting until $i_{10}^{p_1}$ to load. This pattern repeats for additional shifts, including visits to p_1 and later p_5, with multiple waiting periods due to shift overlaps and resource unavailability. The entire tour lasts 7 hours 44 minutes, including 1 hour 23 minutes of waiting.

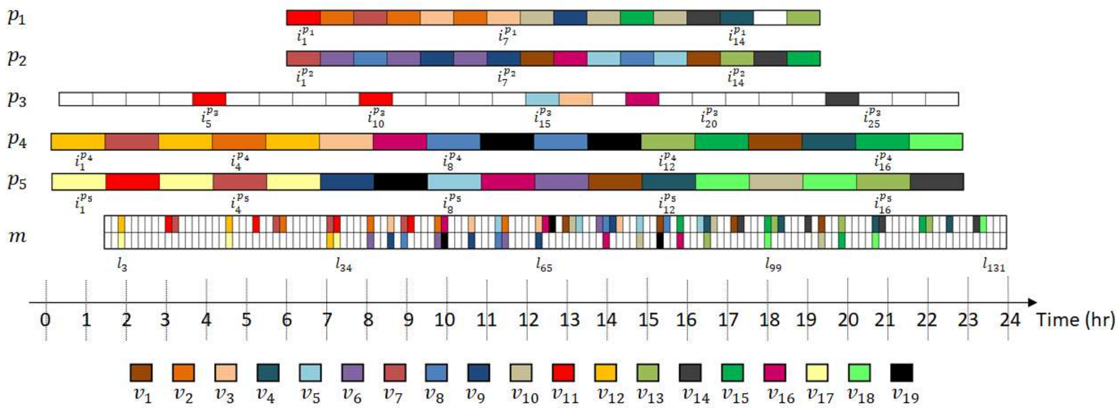

Figure 5. Gantt-chart for the optimal solution of Example I

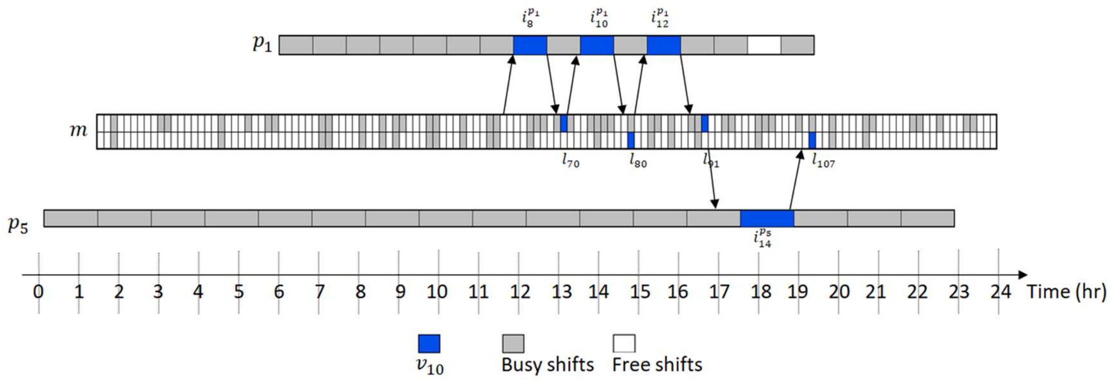

Figure 6. Example of a daily truck route obtained in Example I

The proposed model enables detailed daily planning by selecting fields, scheduling harvest and loading times, and routing each truck with precise arrival, waiting, and idle times. It also outputs resource utilization, travel distances, and times, ensuring efficient coordination of harvesting, transport, and unloading operations.

3.2. Example II

In this example, the truck fleet includes 90 vehicles. On the selected working day, 27 harvest areas (p_1–p_{27}) supply the mill with a total of 240 FTL. Table 4 presents the FTL availability per field, field-to-mill distances, operational time windows (in hours from day start), and the number of loading resources R_p per site. The harvesting and loading operation requires 80 minutes per task. Based on field distances, Table 4 also includes the feasible truck arrival intervals $\left[F_p^-, F_p^+\right]$ and the number of shifts per location. The mill remains open all day, with four unloading resources (10 minutes per operation). This results in a feasible mill interval of [01:30, 24:00] and 134 generated shifts. The allowed waiting times are 50 minutes at fields and 20 minutes at the mill.

This case includes 266,400 binary variables and 80,446 equations. Using the initialization from Melchiori et al. (2023), a feasible solution with 8.66% gap was found in 100 CPU seconds. The optimal solution was reached in 612.09 seconds, requiring 83 trucks at a cost of $148,911.60. The average travel time was 6h52 (incl. waiting). Table 5 shows FTL deliveries per field. As before, the model provides detailed and efficient planning.

As was mentioned for the previous example, the detailed harvesting, routing and scheduling plan is obtained through the proposed approach. Moreover, the efficiency of the model solution allows testing different scenarios for a given set of model parameters in few CPU seconds.

Table 4. Fields characteristics in Example II: supply, distance to the mill, time window, number of resources, feasible time interval, and number of shifts

	O_p (FTL)	D_p (km)	W_p^- (h)	W_p^+ (h)	R_p	F_p^- (h)	F_p^+ (h)	$\lvert I_p \rvert$
p_1	20	14.75	0:00	24:00	2	00:13	23:33	17
p_2	20	13.75	0:00	24:00	2	00:12	23:35	17
p_3	20	18.83	0:00	24:00	2	00:17	23:29	17
p_4	20	19.55	0:00	24:00	2	00:18	23:28	17
p_5	20	14.20	0:00	24:00	2	00:13	23:34	17
p_6	20	11.11	0:00	24:00	2	00:10	23:37	17
p_7	20	20.50	0:00	24:00	2	00:18	23:27	17
p_8	20	8.70	0:00	24:00	2	00:08	23:40	17
p_9	20	7.10	0:00	24:00	2	00:06	23:42	17
p_{10}	20	9.50	0:00	24:00	2	00:08	23:39	17
p_{11}	20	7.90	0:00	24:00	2	00:07	23:41	17
p_{12}	20	6.50	0:00	24:00	2	00:06	23:42	17
p_{13}	20	10.80	0:00	24:00	2	00:09	23:38	17
p_{14}	6	10.07	10:00	18:00	1	10:00	18:00	6
p_{15}	20	5.35	0:00	24:00	2	00:04	23:44	17
p_{16}	17	17.83	0:00	24:00	2	00:16	23:30	17
p_{17}	1	4.31	8:00	12:00	1	08:00	12:00	3
p_{18}	2	8.10	10:00	18:00	1	10:00	18:00	6
p_{19}	9	16.70	6:00	20:00	1	06:00	20:00	10
p_{20}	13	12.78	0:00	24:00	2	00:11	23:36	17
p_{21}	5	11.80	10:00	22:00	1	10:00	22:00	9
p_{22}	7	3.30	10:00	24:00	1	10:00	23:46	10
p_{23}	3	15.25	10:00	18:00	1	10:00	18:00	6
p_{24}	7	20.00	10:00	22:00	1	10:00	22:00	9
p_{25}	15	12.00	0:00	24:00	2	00:11	23:36	17
p_{26}	6	13.15	10:00	22:00	1	10:00	22:00	9
p_{27}	20	21.00	0:00	24:00	2	00:19	23:27	17

Table 5. Sugarcane supplied by each field in the planning day

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}
m	4	3	3	2	4	19	2	20	20	20	20	20	20	5
	p_{15}	p_{16}	p_{17}	p_{18}	p_{19}	p_{20}	p_{21}	p_{22}	p_{23}	p_{24}	p_{25}	p_{26}	p_{27}	-
m	20	2	1	2	3	13	4	7	2	1	15	5	3	-

4. CONCLUSIONS

This work presents an ILP model for integrated field selection, in-field harvesting, truck routing and scheduling, and synchronization of field and mill resources. It is tailored to the Argentine context, where harvesting and loading occur simultaneously at the sugarcane fields. The model supports strategic decision-making in daily operations, with the aim of improving both cost efficiency and product quality.

Case Study 1 demonstrates the model's capacity to provide optimal, highly detailed scheduling and routing plans within reasonable computation times, illustrating its utility for small to mid-scale operations. Case Study 2 shows the model's scalability and how initialization algorithms can enable the solution of large, complex instances, relevant for real industrial applications.

Overall, the approach proves to be a powerful planning tool, adaptable to different scenarios and robust under varying operational constraints, making it valuable for enhancing logistics performance in the sugarcane industry.

ACKNOWLEDGMENTS

The authors would like to acknowledge financial support from Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) and Fondo para la Investigación Científica y Tecnológica (FONCyT) for research activities through their projects PIP 2020-1401 and PICT 2020-1644.

REFERENCES

dos Santos, E., Rangela, S., Florentino, H.O., & de Araujo, S.A. (2023). A review of mathematical optimization models applied to the sugarcane supply chain. *International Transaction in Operation Research*, *30*, 1755–1788. https://doi.org/10.1111/itor.13056

Florentino, H.O., Jones, D.F., Irawan, C.A., Ouelhadj, D., Banafesh, B., & Cantane D.R. (2022). An optimization model for combined selecting, planting and harvesting sugarcane varieties. *Annals of Operations Research*, *314*, 451– 469. https://doi.org/10.1007/s10479-020-03610-y

Gilani, H., & Sahebi, H. (2021). A multi-objective robust optimization model to design sustainable sugarcane-to-biofuel supply network: the case of study. *Biomass Conversion and Biorefinery*, *11*, 2521 - 2542. https://doi.org/10.1007/s13399-020-00639-8

Higgins, A., Thorburn, P., Archer, A., & Jakku, E. (2007). Opportunities for value chain research in sugar industries. *Agricultural Systems*, *94*(3), 611-621. https://doi.org/10.1016/j.agsy.2007.02.011

Kaup, F. (2015). The sugarcane complex in Brazil: the role of innovation in a dynamic sector on its path towards sustainability. Springer International Publishing AG, Switzerland.

Kostin, A., Guillen-Gosalbez, G., Mele, F., Bagajewicz, M., & Jiménez, L. (2012). Design and planning of infrastructures for bioethanol and sugar production under demand uncertainty. *Chemical Engineering Research and Design*, 90, 359–376. https://doi.org/10.1016/j.cherd.2011.07.013

Le Gal, P.Y., Lyne, P.W.L., Meyer, E., & Soler, L.G. (2008). Impact of sugarcane supply scheduling on mill sugar production: a South African case study. *Agricultural Systems*, *96*(1), 64-74. https://doi.org/10.1016/j.agsy.2007.05.006

Lima, C., Batista, M., Relvas, S., & Barbosa-Póvoa, A. (2023). Optimizing the Design and Planning of a Sugar-Bioethanol Supply Chain under Uncertain Market Conditions. *Industrial & Engineering Chemical Research*, 62(15), 6224–6240. https://doi.org/10.1021/acs.iecr.3c00085

López-Milán, E., Miquel-Fernández, S., & Plà-Aragonés, L.M. (2006). Sugar cane transportation in Cuba, a case study. *European Journal of Operational Research, 174*(1), 374–386. https://doi.org/10.1016/j.ejor.2005.01.028

López-Milán, E., & Plà-Aragonés, L.M. (2014). A decision support system to manage the supply chain of sugar cane. *Annals of Operations Research*, *219*(1), 285–297. https://doi.org/10.1007/s10479-013-1361-0

Lozano-Moreno, J.A., & Maréchal, F. (2019). Biomass logistics and environmental impact modelling for sugar-ethanol production. *Journal of Cleaner* Production, *210*, 317-324. https://doi.org/10.1016/j.jclepro.2018.10.310

Melchiori, L., Nasini, G., Montagna, J.M., & Corsano, G. (2023). Resources synchronization in a full truckload pickup and delivery problem: An exact approach. *Computers and Operations Research*, *151*, 106118 - 106131. https://doi.org/10.1016/j.cor.2022.106118

Morales, M.M., Sarache, W., Costa, Y., & Soto, J. (2020). Multiobjective stochastic scheduling of upstream operations in a sustainable sugarcane supply chain. *Journal of Cleaner Production*, *276*, 123305-123319. https://doi.org/10.1016/j.jclepro.2020.123305

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

AUTHORS' CONTRIBUTIONS

- PhD. Gabriela Corsano. Project management, conceptualization, formal analysis, methodology, writing - revision and editing.
- PhD. Luciana Melchiori. Conceptualization, software, writing - first draft.