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Development of a simulation model as a decision support system for sugarcane supply

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Abstract
This research presents a discrete-event simulation model of cane supply as a decision support system for managers in a sugarcane mill. The research considers harvesting, transporting, and unloading cane at the mill yard, including the time windows, inherent uncertainty in the system, and queues of all operations. The model was implemented in *C++*, and the *Qt Creator* development environment was used to generate a graphical interface. We found that fifty percent of the time, the trailers are waiting; we also assessed the impact of mill downtime on the unloaded cane in the mill yard. Additional environments were also evaluated: rainy period, harvesting in remote places, and an alternative configuration at the unloading area that improves the process efficiency.

Keywords: Discrete-event simulation; sugarcane supply; decision support system.

Desarrollo de un modelo de simulación como un sistema de soporte de decisiones para el abastecimiento de caña de azúcar

Resumen
Esta investigación presenta un modelo de simulación de eventos discretos del sistema de abastecimiento de caña como sistema de soporte a las decisiones para los administradores en los ingenios azucareros. Comprende las operaciones de cosecha, transporte y descarga de la caña en el patio del ingenio, además tiene en cuenta ventanas de tiempo, la incertidumbre inherente del sistema y considera las colas de todas las operaciones. El modelo fue implementado en C++ utilizando el entorno de desarrollo *Qt Creator* para generar una interfaz gráfica. Se encontró que el 50% del tiempo las tractomulas se encuentran en espera, además se evaluó el impacto de los paros de molienda en la cantidad de caña descargada. Otros ambientes fueron también evaluados: época lluviosa, cosecha en campos lejanos y una configuración alternativa en la zona de descarga de caña que mejora la eficiencia del proceso.

Palabras clave: Simulación por eventos discretos; abastecimiento de caña de azúcar; sistema de soporte a las decisiones.

1. Introduction

Sugarcane supply systems at mills are complex due to the high uncertainty in the system and the interrelationships among processes. There is a central administration of a sugarcane mill that coordinates the management and logistics of the supply operations. This coordination is achieved through communication with stakeholders using information systems. Historical average values are used for decision making and compensate for the differences created by the system uncertainty with buffers, whose sizes are based on the experience of decision makers. Uncertainties can cause delays in cane deliveries and transportation overcosts. The primary sources of uncertainty are weather, cane milling rate, design of fields, traffic on roads, and equipment damage.

Power [1] defined a decision support system (DSS) as an interactive computer-based system that helps people use computer communications, data, knowledge, and models to solve problems and make decisions. A DSS based on a discrete event simulation (DES) answers questions concerning what-if scenarios in a statistically valid manner [2] and considers uncertainty, system dynamics, and their interrelationships. Lejars et al. [3] implemented a DSS based on a simulation model that improved the transparency of

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revenue for both millers and growers. A DSS has been used to improve harvesting and transportation processes [4-8]. The authors in [9] presented a web-based tool that can support decisions for biomass multi-crop production systems on the strategic, tactical, and operational levels.

Specifically for the sugarcane industry, South African and Reunion Island have developed several DESs in Arena, Excel, and a simulation tool called MAGI for decision support of cane supply management [10-15]. For a Mexican sugar plantation, researchers developed a DES to analyze the utilization of machinery and personnel [16]. The researchers in [17] applied a simulation model to reduce the number of mechanical harvesting machines, and the researchers in [18] implemented a simulation model in several sugarcane mills in Australia to decrease harvesting and transportation costs. Jannoni and Morabito [19] developed a DES in Arena focused on the reception area in a Brazilian mill to decrease the time vehicles spent in queues. For the Moroccan sugar industry, the researchers in [20] developed a simulation in SIMUL8; their results showed that the number of transportation units could be reduced by 50% while maintaining the same efficiency. The researchers in [21] developed a simulation model to analyze the impact of the freight and lead time on sugarcane supply profit in a mill. An object-oriented simulation model was built in [22] as an integral part of a DSS to advise farmers with making in-field operational decisions and machinery dimensioning. Other models exist that are different from a simulation such as DSS for sugarcane logistics; these models include algorithms for hierarchical planning of sugarcane harvests [23], a sugar cane operational planning model using mixed-integer programming and adaptive genetic algorithms [24], and a multi-choice goal programming model for sugarcane harvest scheduling, which was proposed in [25].

The structures of sugar mills in these countries are different from those in Colombia in terms of harvest time, capacity, type of equipment, and farm layout. This research describes a DSS based on a DES created with free software called COMDES (Colombian Mill's Discrete Event Simulation) for logistics supply cane of a sugar mill. The system considers time windows, cane download settings, problems at the farm, and the effect of distance, among other factors. To demonstrate the importance of this technique as a decision-making tool for configurations (tactical decisions), policies (strategic decisions), and the effect of uncontrollable variables in the system, in section 2, the logistics of sugarcane mill supply is presented. Next, in section 3, the simulation model is described. Section 4 presents the results and a discussion, and section 5 presents the main conclusions.

2. Supply logistics of sugarcane mills

The sugar cane industry in Colombia is located in the Andean valley of the Cauca River; its climatic conditions allow harvesting throughout the year. Harvesting is performed by an *alce* (set of operators and machines used to harvest) allocated to a *frente* (current field being harvested). Harvest can be done manually or mechanically and uses two types of trucks: tractor with a chaser bin in the farm and trailer-truck (TT) for road transportation. The latter uses two train configurations (tractor unit + semitrailer + 3 trailers) and a *cabezote* (tractor unit). Fig. 1 shows a trailer-truck. Although part of the harvest and transport of sugarcane is done by outsourcing, the sugar mills have a central command of operations, where decisions are made by experts using information systems, such as SIAGRI, and communication with stakeholders using radiotelephones and cellphones. The experts use buffers to deal with randomness.

In this case, the average distance between the cane field and sugarcane mills is 25 km. The harvesting and processing of sugarcane is performed continuously every day for 24 hours.

Fig. 2 illustrates the basic operations of a sugarcane supply system from the transport unit point of view. The process between the *frente* and the sugarcane mill is as follows: "harvesting" occurs when sugarcane stalks are cut and thrown onto the tractor, and "loading" occurs when the cane in the tractor is loaded onto the train; "transporting" occurs when the train is full or when there is a shift change. The "weighing" operation describes the arrival of every train to the sugarcane mill, and the "sampling" operation describes its inspection. Then, the train goes to the "unloading" area, and the cane is delivered. In the "fuel" operation, the trailer

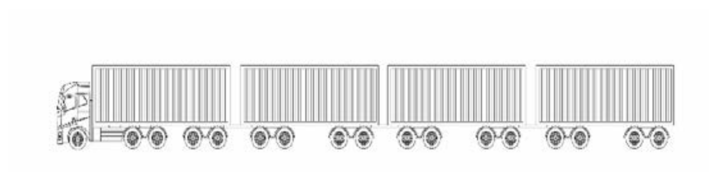

Figure 1. Trailer-truck configuration.
Source: The authors.

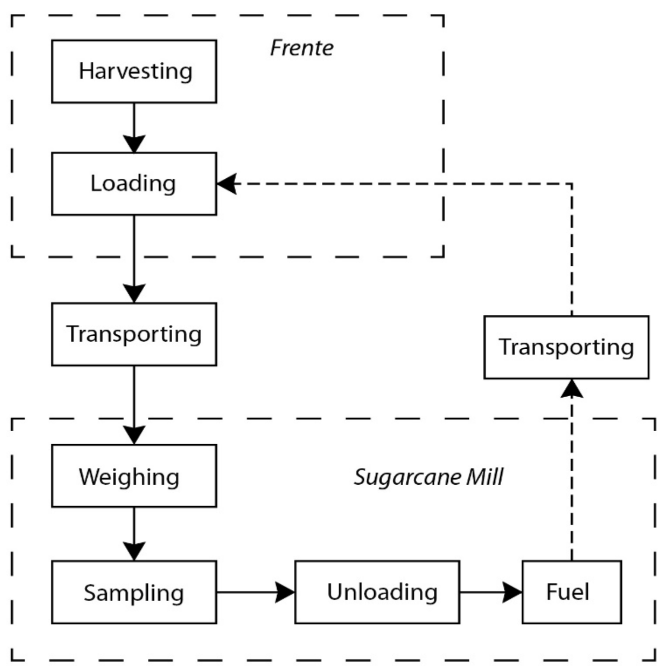

Figure 2. Scheme of sugarcane supply system.
Source: The authors.

truck fills up with fuel and returns to the field as "empty transporting". The simulation model described in the next section highlights the queues, related random rates, and service times at each stage.

3. Simulation of sugarcane supply system

3.1. Model building and assumptions

The model was built in three steps: conceptual model, implementation of the simulation, and validation.

The model conceptualization defines the scope and level of detail; the main assumption is that the only scarce resources are *cabezotes* and mechanical harvestings. The rates and service times exhibit a random behavior that can be described by a statistical distribution. Figs. 3 and 4 show the flowchart for events in the sugarcane mill and the *frentes* that occur within a shift. However, the simulation also takes into account shift changes and equipment setups.

The model was implemented in C++ as an object-oriented model and used the Qt Creator 2.72 development environment to generate the graphical interface. The model was structured into 25 events that represent each of the outcomes necessary to describe the actual system; each event has its own parameters

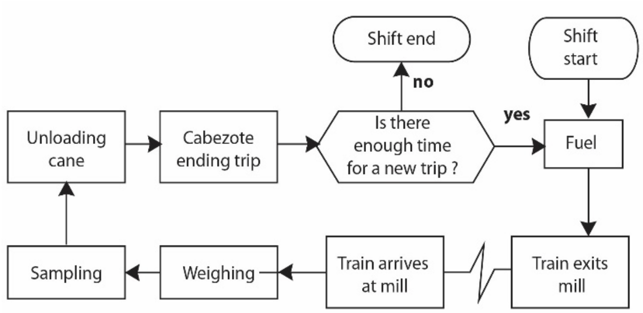

Figure 3. Flowchart of sugarcane mill's events.
Source: The authors.

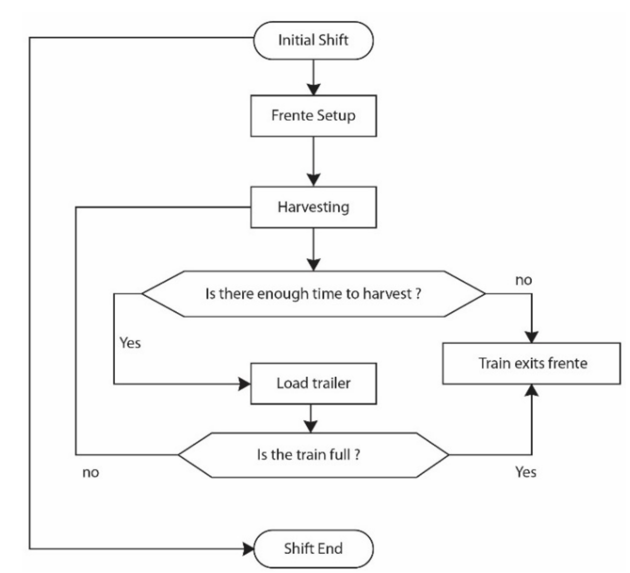

Figure 4. Flowchart of *frentes'* events.
Source: The authors.

and variables. To quantify the parameters, historical sugar mill data found in literature [26] and data collected through interviews with staff from different mills were used. Most data are given as random distributions to imitate the actual behavior.

The system components are accessed through a menu structure that is easy to use (see Fig. 5), which allows data manipulation, such as the number of tractors in service, number of *alces*, distributions rates, and working speeds; the simulation output is displayed and can be exported to a spreadsheet format. The simulated system is nonterminating, i.e., it reaches steady state using minutes as the unit of time. For verification and validation, both the conceptual model and the translation to the computer were made from simple to complex.

Throughout the translation process, the proper behavior and its resemblance to the real system were constantly checked using ASSERTs, message lists, visual presentation, and a response variables list. Fig. 6 shows the input values and the performance measures of the simulation.

3.2. Decision rules

Several routines were made inside events, which considered the inherent uncertainty of the system; the following highlights the most important ones:

- Trains to assign to an *alce* per shift: This routine calculates the minimum number of trains required according to eq. (1)-(5). The allocation of tractor-trailers to an *alce* is done at the beginning of the shift in the zone of *cabezotes* that represent the driver change; there are two rules: begin shift, by which trailer-trucks in the zone of *cabezotes* are allocated to every *alce* and ending a trip, by which the current *alce* is no longer required; then, the train can be allocated to another *alce*.

$$\boldsymbol{Cane\ to\ haverst\ per\ shift}\ \left[\frac{ton}{frente\cdot shift}\right] = Min(Total\ Cane\ per\ shift, Alce\ Capacity, Milling\ Capacity) \quad (1)$$

$$\boldsymbol{Number\ of\ trips\ per\ shift}\ \left[\frac{train}{shift}\right] = round.up\left(\frac{Cane\ to\ harvest\ per\ shift}{Train\ Capacity}\right) \quad (2)$$

$$\boldsymbol{Cycle\ time}\ [h] = \frac{Distance\ mill\ to frente}{Speed\ of\ empty\ train} + \frac{Distance\ frente\ to\ mill}{Speed\ of\ full\ train} + Time\ in\ mill + Time\ in\ frente \quad (3)$$

$$\boldsymbol{Number\ of\ a\ train\ trips\ per\ shift}\left[\frac{1}{Shift}\right] = round.down\left(\frac{Work\ hours\ per\ shift}{Cycle\ time}\right) \quad (4)$$

$$\boldsymbol{Number\ of\ Trains}\ [train] = round.up\left(\frac{Number\ of\ trips\ per\ shift}{Number\ of\ a\ train\ trips\ per\ shift}\right) \quad (5)$$

- Working time for transporting: This is used to decide when a train that is unloading cane can make another trip in the same shift:

if current time + cycle time < ending time of shift ***then***
Return to *frente*
Else
End shift for train
End if

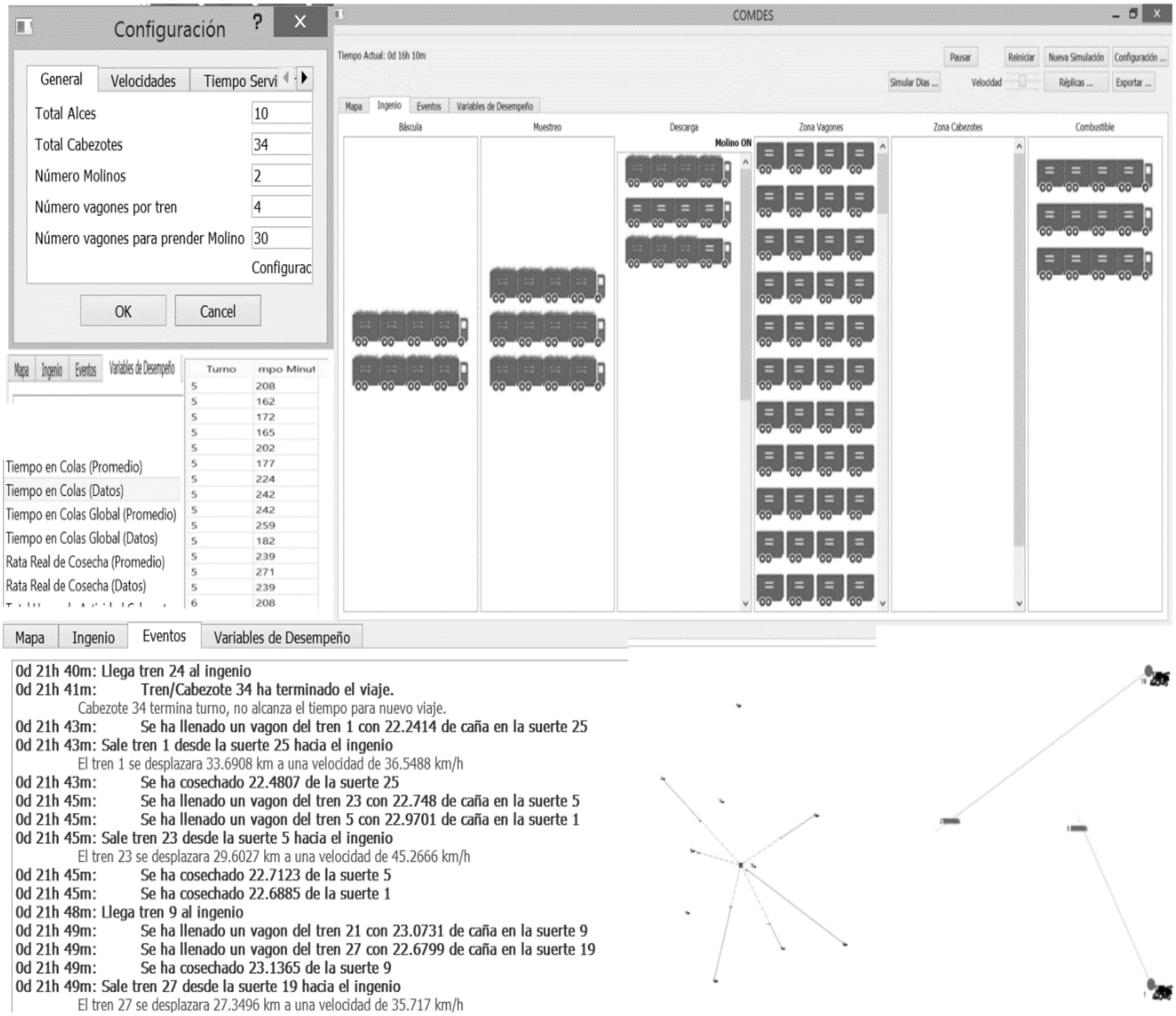

Figure 5. Collage of snapshot of COMDES.
Source: The authors.

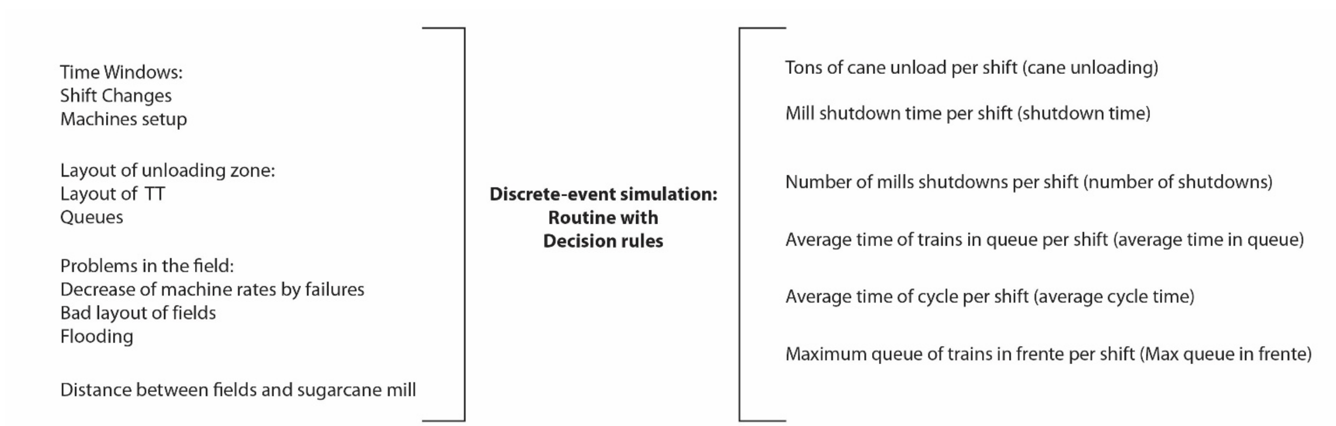

Figure 6. General model with inputs and outputs.
Source: The authors.

- Time between successive trains: When a shift starts, tractor-trailers are allocated to every *alce*. Immediately, a train is directed to the field, and then, the other tractor-trailers leave with a departure time described by eq. (6).

$$\boldsymbol{Departure\ time} = \boldsymbol{Tractortrailer\ in\ field}[\boldsymbol{min}] = \frac{Maximun\ capacity\ of\ train}{Harvest\ Rate * Number\ of\ harvestings} \quad (6)$$

- Mill shutdown: When the amount of cane is not enough, the mill is interrupted and restarts when there is a certain amount of sugarcane in the unloading area.

4. Results and discussion

4.1. Current system

The maximum capacity of milling considered was 10,000 t of sugarcane per day with two tandems of mills, 11 alces, and 34 trailer-trucks. In the yard, trains must wait until the cane is unloaded in the mills to continue the route. The simulation warm-up period is the time taken to reach steady state, which was calculated by Welch's method. The system rapidly reaches steady state in 48 hours, and the shift change subsequently forces the transportation and alces to return to the initial state.

The experiments were executed with 12 runs (each run with a different random seed), and each run had 120 batches of 12 h, which results in a total of 1,440 simulation results for every trial and scenario. Table 1 summarizes the results; there is a low variability in the measures except for shutdown time and the number of shutdowns because in a few shifts, the mill breaks down randomly, which is due to the occasional downtime of the mill caused by a random delay in sugarcane delivery.

The maximum amount of cane that can be delivered is approximately 5,520 t per shift. There is a 1:1 ratio between the transport time and the time in queue; in other words, a tractor-trailer spends half its time waiting. It is important to focus on decreasing downtime waiting to improve transport efficiency. Furthermore, because of the need for trailer-trucks drivers to be at the starting place before the shift change, we observed that transportation cannot be fully used at all times.

In this research, we suggest four scenarios to demonstrate the impact of the use of simulation techniques by sugarcane mill managers for analysis and decision making in the supply system.

Scenario 1. *Environmental*: Rainy period. This scenario considers the random (uncontrollable) factors in operations during rainy periods, recreates the decreased train speed due to wet roads and the decrease in the harvesting rate due to the risk of soil compaction.

Table 1.
Summary of results of original scenario.

Measure	Units	Expected Value $(\overline{X})$	Coefficient of Variation (CV)
Cane unloading	t / shift	5,509	0.014
Shutdown time	min	1.504	6.380
Numbers of shutdowns		0.024	6.355
Average time in queue	min	168.0	0.032
Average cycle time	min	335.4	0.017
Max queue in *frente*		2.923	0.092

Source: The authors.

4.2. Analysis of scenarios

Scenario 2. *Policy*: All *frentes* are located away from the sugarcane mill. In many occasions, due to the need to achieve daily production targets and the lack of strategic and tactical planning, sugarcane mills with mature cane are at distances far away.

Scenario 3. *Setting:* Change of layout in the unloading area. This situation considers that all trailer-trucks release their cane-filled trailers by unloading cane, and the empty trailers return to the trailers area to continue travel. The loaded trailers will be pulled by a tractor.

Table 2 summarizes the findings. In Scenario 1, it was necessary to adjust a single mill in use, which is a common practice in rainy periods. The amount of unloaded cane decreases by 57%; however, the milling operation is never shut down at any time. The percentage of trains waiting is 65%, which increases the cycle time because of the slower load capacity, which reduces the amount of performed and results in slower milling. Due to the weather, it is important to design new plans for operational decisions to address new *frentes,* which is a task that is easier done using COMDES by constructing a hierarchical plan.

In Scenario 2, the amount of unloaded cane decreases by 15% due to the increase in the distances of the *alce* with respect to the sugarcane mill; also, the cycle time increases to 46 minutes, and thus, more tractor trailers are required. In this case, a mill shutdown always occurs per shift, and the expected value of shutdown time increases to 110 minutes. The layout of Scenario 3 has a better performance because it increases the amount of unloaded cane and decreases the time in queues (36% from the queue time). Furthermore, the queue time decreases, the travel time is reduced, and the mill does not stop; therefore, the amount of unloaded cane increases by 0.2% and reaches maximum capacity. An economic and financial evaluation is required to assess if less tractor-units and drivers compensate for the increase in the number of trailers and tractors.

Table 2.
Summary of performance operations of the scenarios.

Measure	Units	Scenario 1		Scenario 2		Scenario 3	
		$\overline{X}$	CV	$\overline{X}$	CV	$\overline{X}$	CV
Cane unloading	t/shift	2,385	0.005	4,663	0.012	5,520	0.001
Shutdown time	minutes	0.000	-	111.7	0.066	0.000	-
Numbers of shutdowns		0.000	-	1.000	0.000	0.000	-
Average time in queue	minutes	529.1	0.010	180.4	0.020	80.80	0.062
Average cycle time	minutes	819.5	0.006	380.9	0.009	223.0	0.023
Max queue in *frente*		2.000	0.000	2.138	0.162	2.930	0.087

Source: The authors.

5. Conclusions

When making decisions, one of the primary problems of sugarcane mills in Colombia is not considering the effect of process capability given time windows, uncertainty, and the interactions of system elements. Moreover, due to the large number of variables that change over time and their unclear interactions, it is important to use a DSS, such as COMDES, which uses discrete-event simulations and is adapted to the features of Colombian sugarcane mills. We highlight the fact that the DSS was created using free software and allowed the realization of different types of analyses, both visible and transparent, and improved operational performance of the sugarcane supply chain. COMDES can help make decisions, analyze decisions made by managers, and measure the consequences in a matter of seconds.

Scenario 1 showed the results of difficult environmental conditions by rainy weather (random factors). Scenario 2 presented the effects of a bad policy, in which *frentes* are located far away from the mill. Scenario 3 showed the impact of a new setting in the yard; however, economic and financial evaluations are required to complete the analysis.

Although the simulation does not use an optimizer, its internal algorithm explores different factors and can help determine near optimal system configurations under the considered performance measures. As future work, it is important to use business software for decision making that can be adapted to the simulation with real time data. This model can be used to study the effect of disturbances, such as transportation breakdowns (terminal simulation) and thus, is recommended for future studies.

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