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A discrete simulation analysis of a logistics supply system

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Abstract

An important aspect of logistics supply systems in agro industries is to manage the processes of harvesting and transporting raw materials, from the rural fields to the processing plants. The truck waiting times in the various queues of the plant reception area are of particular concern. This paper applies discrete simulation techniques to study the reception area processes of a sugarcane plant, analyzing the performance of the system and investigating alternative configurations and policies for its operations. The analysis is also useful for other agro industries with similar supply systems, such as orange and wood industries.

Keywords: Discrete simulation; Logistics supply system; Agro industries; Sugarcane

1. Introduction

In the last few decades agro industries, especially commodity producers, have carried out research and development in an effort to assure prominence and competitiveness in their sectors. For agro industries with continuous processing such as sugarcane, orange and wood industries, the logistics supply systems represent relevant sources of opportunities to increase their efficiency, integrating agricultural and industrial operations. A problem inherent in such systems is to manage the processes of harvesting and transporting raw materials, from the rural fields to the

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processing plants. Several studies have pointed out the importance of inbound logistics systems to assure a continuous and uniform feeding of sugarcane, orange and wood to the processing facilities, such as Hansen et al. (1998), Neves et al. (1998), Martin et al. (2002), Higgins and Muchow (2003), Bradley and Winsauer (2004), Neves (2004), Raicu and Taylor (2004), Bredstrom et al. (2004) and Carlsson and Ronnqvist (2005). For these agro industries, the supply operations can comprise a large percent of the overall production costs, as discussed in Seixas (1992), Caixeta Filho et al. (1998), Sousa (2000), Martin et al. (2002), Neves (2004) and the aforementioned references.

The reception operations in the processing plant yard include the processes from the initial weighing of the vehicles loaded with raw materials to their unloading in the processor's cranes and conveyors. Therefore, trucks, upon arriving at a processing plant, go through several operations such as net weighing on a scale, sampling tests to determine content quality, unloading on intermediary storage areas and/or on the processor's cranes and conveyors. The truck waiting times in the various queues of the reception area are of special concern because of the possible interruptions in the production process due to shortages of raw material (since longer waiting times delay the return of the trucks to the rural fields, thereby reducing their availability to transport raw material to the processing plant, as well as causing machine and worker idleness in the fields). The costs of idle drivers and wasted fuel of the trucks while waiting in the lines are also important, but in second place if compared to the shortage costs. Another concern of the sugarcane and orange agro industry, which process perishable products, is that the quality of the raw materials deteriorates the longer the period between harvesting and grinding. According to Semenzato (1995), Arjona et al. (2001) and Neves (2004), sugarcane and orange should be milled within a certain time period after it is harvested to preserve its weight, sucrose content and juice quality. Therefore, primary concerns of logistics managers are to assure a continuous and uniform feeding of raw material at the mills, maximize the unloading rates and minimize the amount of raw material waiting in the unloading lines.

The purpose of this paper is to analyze the performance of the reception area processes and investigate alternative configurations and policies for their operations. Due to several sources of uncertainty and the operational complexity inherent in these systems, the method of analysis is based on discrete simulation techniques. The simulations were completed using Arena software (SMC, 1994). An analytical queuing network approach could also be employed, but it is disregarded due to the complexity of the dispatching policies involved. We used the case study of a large Brazilian sugarcane plant located in Sao Paulo State, which has a daily grinding capacity of approximately 36,000 tons of sugarcane. Brazil is the largest sugarcane producer in the world, followed by India and Australia. The typical amount of sugar produced annually in Brazil is approximately 18 million tons and 60% is produced in Sao Paulo State (Unica, 2004). Based on this case study, it is shown how the simulation of a logistics supply system can detect efficiencies to be gained from such a system.

The main performance measures are related to the average waiting times of trucks, average unloading rates of sugarcane at the mills, and the mill's workloads. There are few studies similar to this in the literature that focus on the supply system of the processing plant's reception area, especially related to a sugarcane plant which has a large capacity and it is as operationally complexity as the present case. The analysis of the present study has wider applicability than just to sugarcane plants, such as orange and wood plants with similar inbound logistics systems. Related work that uses discrete simulation to analyze other logistics systems in agro industries can be found in Mathew and Rajendran (1993), Hahn (1994), Semenzato (1995), Lopes (1995), Hansen et al. (1998), Arjona et al. (2001), Bradley and Winsauer (2004) and Higgins et al. (2004).

The present paper is organized as follows: Section 2 briefly describes the logistics supply system of the case study. Section 3 introduces the simulation model and its validation process. Section 4 provides an analysis of the results obtained using the stochastic simulation. Section 5 discusses the application of the model to analyze alternative configurations and policies, and finally, Section 6 presents some concluding remarks and perspectives for future research.

2. The supply system of sugarcane mills

Fig. 1 schematically illustrates the basic operations of the logistics reception system (from the weighing location to the mills' conveyors) encountered at a typical sugarcane processing plant. Trucks of different types arrive in the reception area at the weighing location (Fig. 1), where data is collected and the net weight is recorded. After receiving a dispatching instruction at the dispatching location (Fig. 1), the vehicle proceeds to the assigned unloading line to feed the mill. The dispatching instruction takes into account not only the queuing state of the unloading lines, but also the truck type, the capacity of the mill, the state of the intermediary storage and the sugarcane types (whole stalk and chopped sugarcane). An appropriate decision is required in order to

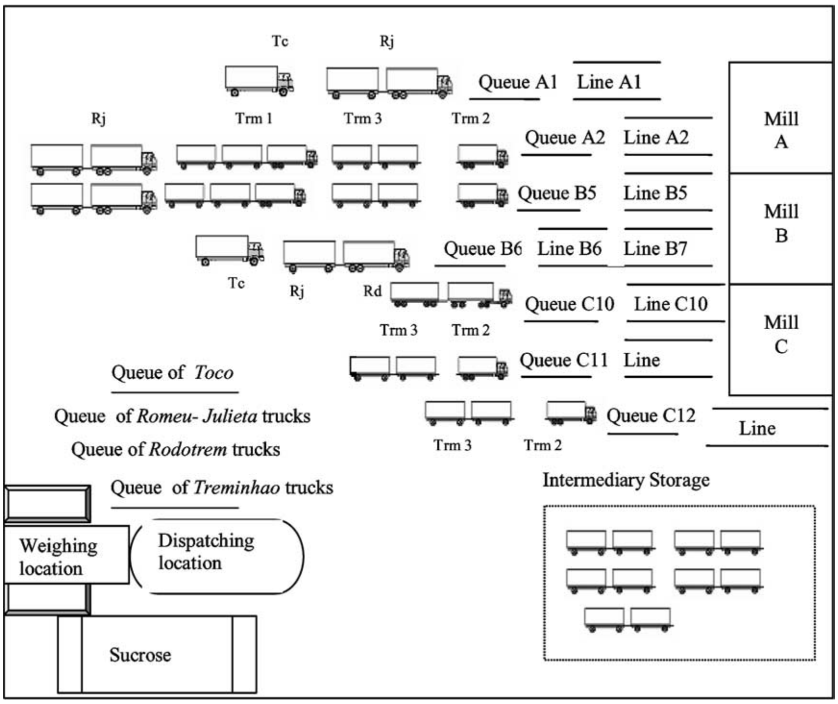

Fig. 1. Supply system of sugarcane at the processing plant: weighing location, dispatching location and unloading area.

avoid shortage or excess of sugarcane at the mills. The truck priority list for each unloading line is shown in Fig. 1.

Of the total amount of sugarcane processed by the mills of the plant under consideration, approximately 70% is chopped sugarcane, and the remaining 30% is whole stalk sugarcane. The plant has three mills (Fig. 1): mills A and B process both whole stalk and chopped sugarcane. These mills have a grinding capacity of 450 tons per hour (ton/h) and two (A_1, A_2) and three (B_5, B_6, B_7) unloading lines, respectively. Mill C processes only chopped sugarcane and has three unloading lines (C_{10}, C_{11}, C_{12}) with a grinding capacity of 600 ton/h. As soon as a vehicle finishes the unloading process, it returns to the rural fields to be reloaded, and the cycle begins again. The cycle time includes the time spent in the plant's reception area until unloading, the travel time back to the fields, the time spent in the fields until loading is complete, and the travel time back to the plant.

The transportation system operates with four types of trucks: *rodotrem* (Rd), *treminhão* (Trm1), *romeu-julieta* (Rj) and *toco* (Tc). The different configurations of these vehicles are described in Widmer (2002). *Rodotrem* (tractor unit + semi-trailer + trailer, Fig. 2) is the largest type of truck. These trucks can transport up to 65 tons of chopped sugarcane, have the highest priority, and use a dedicated unloading line (C_{10} in mill C, as Table 1). *Treminhão* (truck + two trailers, Fig. 2) is the second largest truck and can transport up to 45 tons of chopped sugarcane. Its dispatching policy depends on the number of trucks holding whole stalk sugarcane at the reception area at its time of arrival. In other words, it depends on whether or not there is a suitable amount of whole stalk sugarcane to supply the mills for a certain period of time. If the amount of whole stalk

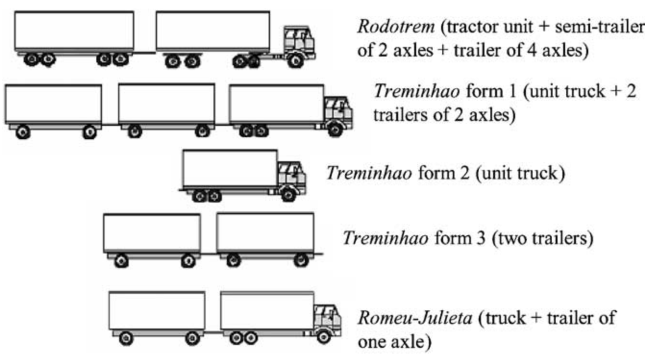

Fig. 2. Trucks to transport chopped sugarcane.

Table 1
Type of truck and respective unloading lines in the mills

Type of truck	Number of trucks	Type of sugarcane	Unloading lines	Mills
Rodotrem (Rd)	8	Chopped	C_{10}	C
Treminhão (Trm)	50	Chopped	C_{11}, C_{12}, A_2, B_5	A, B, C
Romeu-julieta (Rj—chopped)	60	Chopped	A_2, B_5, C_{11}, C_{12}	A, B, C
Romeu-julieta (Rj—whole stalk)	12	Whole stalk	A_1, B_6, B_7	A, B
Toco (Tc)	6	Whole stalk	A_1, B_6, B_7	A, B

sugarcane is suitable, the *treminhão* releases its two trailers of chopped sugarcane in the intermediary storage (Fig. 1) within the reception area. The purpose of the intermediary storage is to avoid shortages. If the storage is full, the *treminhão* waits in a line at the dispatching location. Otherwise, as soon as the two trailers are released by the dispatcher, the unit truck of the *treminhão* moves to an unloading line for chopped sugarcane where it receives the highest priority. After unloading at the mill, and before returning to the fields, the unit truck passes through a holding area of empty trailers, where two new trailers are assigned, and it becomes a *treminhão* again.

The third type of truck, *romeu-julieta* (truck + one trailer, Figs. 2 and 3), can carry up to 25 tons of either chopped or whole stalk sugarcane and represents 53% of the fleet, as shown in Table 1. Finally, *toco* (single truck, Fig. 3) is the smallest type of truck, carrying only 15 tons of whole stalk sugarcane. Due to the current trend in the sugarcane industry of decreasing whole stalk grinding, the number of *romeu-julieta* and *toco* trucks is being reduced in the plant. The dispatching policy of these trucks depends on the queuing length in front of the whole stalk sugarcane unloading lines. If the length of the queue in a particular line is smaller than a predefined number, then trucks are assigned to that line. Dispatching rules dictate that waiting trucks be assigned to the line with the smallest queue; otherwise they wait in a queue at the dispatching location.

An example of a dispatching rule is presented below in order to illustrate how these rules are structured (for more details of the dispatching rules, the reader is referred to the flowchart in Fig. 4). Note that the unloading decisions in a line can depend on the state of other lines. In this example, we will focus on line C_{11} to illustrate the physical interference between lines C_{10} and C_{11}. Line C_{10} is dedicated to unloading *rodotrem* trucks. However, the physical restrictions of the reception area and the mills' conveyors imply that the *rodotrem* is allowed to unload in line C_{10} only if there are no trucks unloading in line C_{11}, and vice versa. More details of the present supply system can be found in Iannoni and Morabito (2002). The *rodotrem* (tractor unit + semi-trailer + trailer) dispatching rule:

Is it a truck carrying chopped sugarcane? Then:
    Is it a *rodotrem* truck? Then:
        Is the queue in front of C_{10} line smaller than the limit p? Then:
            Are trucks unloading in C_{11} line? Then:
                Wait in queue at the dispatching location.
            Otherwise:
                Unload in C_{10} line.
        Otherwise:
            Wait in queue at the dispatching location.

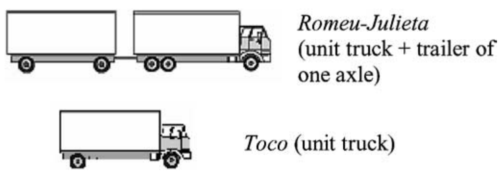

Fig. 3. Trucks to transport whole stalk sugarcane.

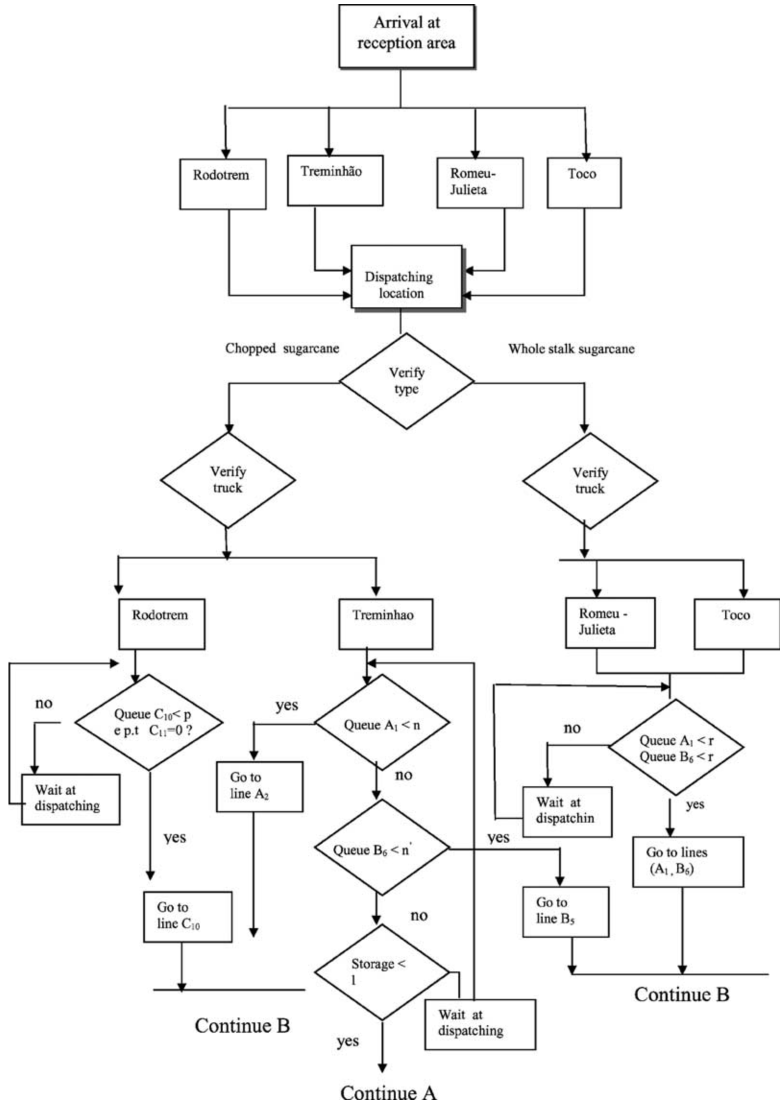

Fig. 4. Flowchart of the simulation model.

3. Simulation of the system

3.1. Model building and assumptions

A simulation is a computer recreation of the operations of a real-world process, or system, over time. Simulations are used to describe and analyze the behavior of a system, ask what-if questions about the real system, and aid in the design of real systems (Banks, 1998). A simulation model enables us: (i) to explore a real system through the modification of policies, procedures, operations

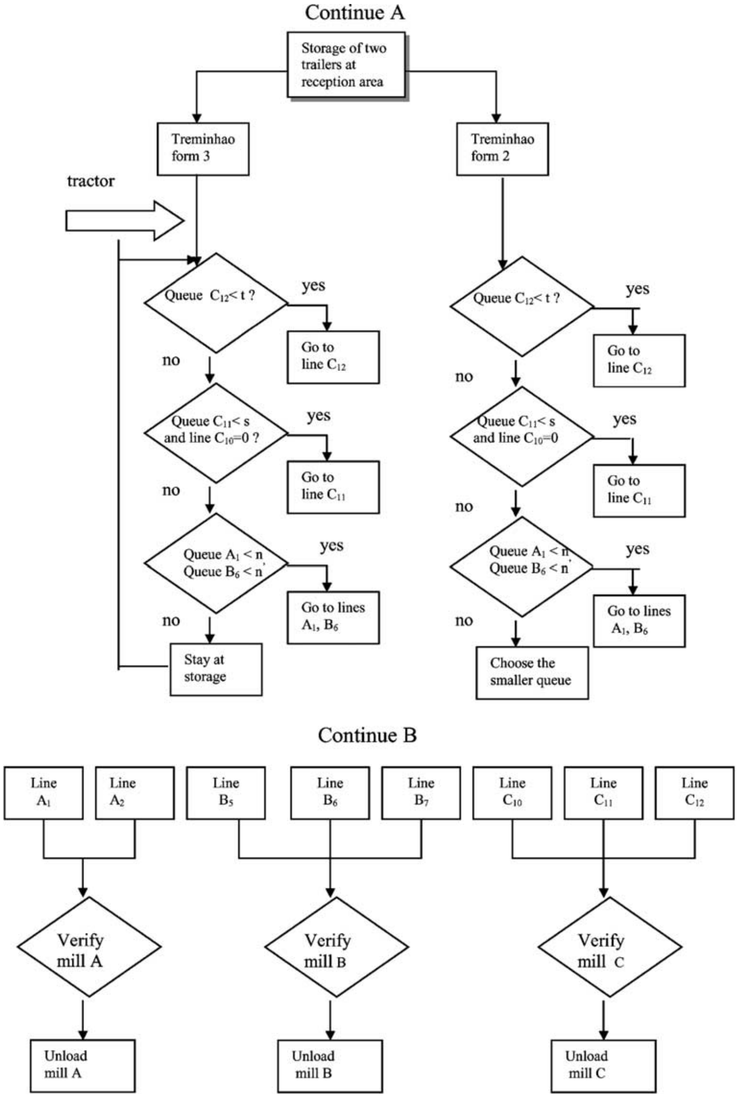

Fig. 4 (*continued*)

and methods at a relatively low cost and without interfering with the real-world system; (ii) to speed up, or slow down, a phenomena of interest so that they can be investigated thoroughly. There are several available simulators on the market, most of them are relatively easy to use and provide users with dynamic graphical animation of a process. Arena software, for instance, which is used in this study, provides an animated graphical image of the process as it simulates real-world events at an accelerated speed (SMC, 1994; Kelton et al., 2002).

The data of the supply system were collected during a typical harvest period. During this period, the harvesting and processing of sugarcane proceeded continuously every day for 24 h. It should be noted that interruptions of the sugarcane supply, even for short periods of time, could disrupt the synchronization between the agricultural and industrial activities. The simulation data

Table 2
Parameters used to dispatching order

Parameter	Meaning	
l	Maximum number of two trailers in storage	32
m	Maximum number of trucks in front of lines A_2 and B_5	2
n	Minimum number of trucks in front of the line A_1 that assures feeding of whole stalk sugarcane in the mill A	3
n'	Minimum number of trucks in front of the line B_6 that assures feeding of whole stalk sugarcane in the mill B	2
p	Maximum number of trucks in front of the line C_{10} (*rodotrem*)	1
r	Maximum number of trucks in front of whole stalk sugarcane (A_1 and B_6)	5
s	Maximum number of trucks in front of the line C_{11}	2
t	Maximum number of trucks in front of the line C_{12}	1

included the time intervals the trucks spent in activities inside the reception area and outside the plant (i.e., traveling to, queuing and loading in the fields). Statistical analysis was performed using *Best-Fit* software (PC, 1996) in order to obtain descriptive measures, histograms, and the best-adjusted statistical distributions representing the data (using goodness-of-fit tests).

The simulation model built in Arena represents a truck's way upon entering the system at the weighing location until its departure out of the reception area after the unloading operations (Fig. 1). In this model the sugarcane supply system is considered a closed (cycled) system. After passing through the weight and check in operations, trucks unload in the reception area and then return to the sugarcane fields. Once reloaded, the cycle continues with the trucks returning to the processing plant. Thus, the mean arrival rate of the trucks is not an input parameter, but it is an output of the simulation model determined by the cycle time of the trucks. This cycle time corresponds to the sum of the time spent inside and outside the reception area (i.e., the time it takes to complete one cycle in the system).

In practice, some aspects can affect the operators' decisions and, consequently, the dispatching rules previously described may not be rigorously followed. This may occur in continuous and complex systems, when occasional events such as vehicles and machines breakdowns may require different decisions during a short period of time. Furthermore, as the system mostly depends on human work and decisions, we can expect that, eventually, operations may be out of the rules' control for short intervals. Our simulation model was built on the assumption that the dispatching rules are rigidly adhered to, considering the priority of each vehicle and all features of the unloading system, such as dedicated unloading lines and limitations related to storages and queues. The parameters $(l, m, n, n', p, r, s, t)$, whose meanings are described in Table 2, were defined by the operators of the reception area and correspond to limitations on the number of vehicles allowed in the unloading lines and the available size of the intermediary storage. For more details of the simulation model, the reader is directed to the flowchart in Fig. 4, which illustrates the basic model structure according to the dispatching rules used in the plant.

3.2. Model validation

According to Shannon (1975) and Banks (1998), the main purpose of the validation process is to assure that the assumptions and simplifications of the real system are reasonable and correctly

Table 3
Comparison of simulation measures and sample measures

	Sample	Simulation of data	Deviation (%)
Mean waiting time (min)			
Mean	24.3	22.1	−9.0
Rodotrem	14.2	11.7	−17.6
Treminhão	14.7	15.8	7.5
Romeu-julieta (whole stalk)	30.5	25.7	−15.7
Romeu-julieta (chopped)	20.7	22.8	10.1
Toco	21.0	20.4	−2.9
Mean arrival rate (truck/min)			
Rodotrem	0.057	0.060	5.3
Treminhão	0.220	0.225	2.3
Romeu-julieta (whole stalk)	0.280	0.290	3.6
Romeu-julieta (chopped)	0.082	0.085	3.7
Toco	0.022	0.020	−9.1
Average amount of sugarcane (tons/day)			
Total of sugarcane transported	31,959.6	32,157.4	0.6
Total of sugarcane unloaded	31,953.9	32,153.5	0.6

implemented. This validation was accomplished as follows: (i) specialists and operators of the supply system under investigation were asked to assess the accuracy and consistency of the simulation results, and (ii) a comparison of output data obtained from inputting a raw data file into the simulation model with historical data of performance measures obtained during the typical day to day operations of the actual system. Notice that the simulation run used actual raw data related to the amount of sugarcane unloaded by trucks, and the arrival and departure time instances of trucks. That is, the simulation did not use best-fit statistical distributions representing these input data (Section 4 uses such distributions in a stochastic simulation). In this way, applying rigorously all dispatching rules of Section 2, this model tries to reproduce the operations time period for which the data was collected.

To perform the simulation run and initiate the variables, we use a warm-up period of 1440 min (24 h). The results of the simulation were compared to the following performance measures as calculated by the plant: (i) mean sojourn time of each truck type in the reception area, (ii) mean arrival rate of each truck type, and (iii) mean daily amount of sugarcane entering and unloading in the sugarcane reception area. Table 3 presents this comparison in terms of measures (i), (ii) and (iii). Note that the differences are reasonably small (for instance, a deviation of only 2 min in the overall mean sojourn time of the system, in other words, only 9% over the sample). These variations are due in part to the fact that in practice the operators do not always rigorously apply the dispatching rules. These variations, together with the assumptions and simplifications of the model, contribute to the differences between the results of the actual system and those obtained by the simulation model in Arena. Therefore, it is assumed that the differences are acceptable and the model valid.

The value to the mean sojourn waiting time $\bar{w}$ may be calculated as follows: $\bar{w} = \sum_{i=1}\lambda_i w_i / \sum_{i=1}\lambda_i$, where w_i is the mean waiting time of truck type i (min) and λ_i is the mean arrival rate of truck type i (vehicles per min), both obtained as the simulation results. Based on the above formula, the mean waiting time for the sample data and simulation data should be 22.3 min and 20.7 min, respectively. However, as can be seen in Table 3, the actual waiting times were 24.3 min and 22.1 min, respectively. The differences in the expected mean waiting time as derived from the formula and the data derived from the system may be explained due to specific dispatching policy associated to the *treminhão*. For example, for this type of truck the arrival rate cannot be directly related to the waiting time since it often unloads at the intermediary storage and therefore can assume three different forms (see Figs. 1 and 2): Form 1—truck + two trailers remain intact as they proceed through the system (Trm1). Form 2—truck separated from its last two trailers and reassigned to new trailers upon returning to the fields (Trm2). Form 3—set of two trailers separated from the truck that might wait in the intermediary storage to unload (Trm3).

Table 3 shows the mean waiting time and mean arrival rate for *treminhão*. Hence, the mean waiting time reported for this type of truck in Table 3 (columns 2 and 3) does not show the differences related to the different forms a *treminhão* can take once inside the reception area (e.g., they have different dispatch behavior and waiting time). Furthermore, the sample data and the simulation of the data represent a relatively short period of time (24 h) and therefore do not show the number of trucks type *treminhão* that split at the reception area, and also the number of vehicles that, upon entering the reception area, remain intact at the intermediary storage locations after the end of daily operations in the real system, as well as in the simulation run. The result for the average amount of sugarcane shown in Table 3 (columns 2 and 3) was obtained by calculating the real amount of sugarcane transported by each truck on each trip during an average day. In the real operation of the system, this amount can be less than the capacity of each truck.

4. Stochastic simulation

4.1. Assumptions of the stochastic simulation model

The stochastic simulation model is accomplished using statistical distributions to represent input data. The supply system is considered *non-terminal* since, during the harvest period, the transport and grinding operations occur continuously 24 h a day, seven days a week. Banks (1998) and Kelton et al. (2002) refer to this type of simulation as a *steady-state* simulation. In the present study, this was empirically verified by a graphical analysis of data, which shows that the truck arrival process within the plant does not experience significant fluctuations throughout the day (that is, it is reasonably uniform). Even for short periods of time, these fluctuations would be an important concern, since they can result, for example, in congestion of vehicles at the reception area, excessive amounts of sugarcane in storage and shortages of sugarcane for the mills. Such problems may interrupt the uniform grinding of sugarcane. Therefore, the additional assumptions considered in the stochastic simulation are:

1. The present system is a closed (cyclic) system in that the average time outside the industrial area is represented by a statistical distribution, one for each of the four truck types. It takes into consideration the travel times to and from the sugarcane fields, and the waiting and loading times in the fields. Estimates for these times were obtained from data of a typical day's operation.

2. The grinding time of each mill depends on the mill's capacity and the amount of sugarcane transported by each vehicle. It is assumed that the mills can operate full time without interruptions. In fact, in practice actual interruptions in the grinding process are rare and undesirable, since they can result in serious problems for the continuous production process of sugar and alcohol.

4.2. Determination of the transient period and length of simulation

The tool *Output Analyzer* within Arena was used to determine the transient period of the present simulation in order to remove any initialization bias. Considering the main performance measures, the transient period was close to 3000 min (or 50 h). The *batch means* method (Law and Kelton, 1991; Pegden et al., 1995; Banks, 1998; Kelton et al., 2002) was applied to determine the simulation run-length period. The *Output Analyzer* performed the statistical procedures to obtain the correlation between different *batches* of individual points. Then, the number of observations in each *batch* was determined to assure a correlation close to zero. Using a procedure proposed by Law and Kelton (1991) and Pegden et al. (1995), the simulation run length was calculated to be 987.33 h (e.g., 41.1 days, including the transient period).

The runtime of the stochastic simulation was a couple of minutes on a standard Pentium III microcomputer, and the results obtained were compared to the actual data of the sample. For instance, the overall mean sojourn time in the system was of 21.5 min (a deviation of less than 3 min, or −11.5% to the sampled value of Table 3) and the average daily amount of sugarcane transported was of 34,009.7 tons (a deviation of 6.4%). These results show that the stochastic simulation yields some deviations with respect to the sample values, mainly due to its random features, the assumptions and simplifications of the model as discussed in Section 2, and the fact that the analysis is carried out along a continuous time period of more than 40 days. In spite of this, the results are acceptable for the type of decisions involved and may be used to measure the overall performance of the system.

4.3. Performance measures

One of the main measures considered by logistics managers of agro industries with continuous processes, such as sugarcane, wood and orange industries, is related to truck waiting times in the reception area. Time saved when waiting, besides reducing the driver's idleness and fuel consumption, can also reduce the amount of raw material waiting to unload in the queues, and increase the unloading rates of raw material at the mills. Therefore, the congestion of vehicles in the reception area can disrupt the uniformity of agricultural and industrial operations. In addition, for some agro industries, the cost of the raw material waiting at the reception area is affected by the deterioration of the perishable products transported by trucks, such as sugarcane and orange.

A major important measure for the evaluation of the agro industries supply system is the mean daily amount of raw material unloaded, defined as R. System configurations with R close to the daily grinding capacity of the plant are preferable because they result in high utilization of the mills. In estimating the waiting time impact of a truck type, we can consider the measures related to the waiting time, the arrival rate and the load size of the truck. Thus, each truck type has inherently different impacts per unit of waiting time in the reception area. For instance, we cannot consider that the impact of a minute of waiting time for a *rodotrem* truck (storing 65 tons of sugarcane) is the same as a minute of waiting time for a *romeu-julieta* truck (storing 25 tons). Based on these considerations, an interesting measure to evaluate the supply system performance should relate the mean waiting time for each truck type to its arrival rate in the reception system and its mean amount of sugarcane transported. Note that this gives the mean amount of raw material waiting in the queues of the processing plant's reception area for each truck type i, which can be calculated as: $Q_i = w_i\lambda_i q_i$, where w_i is the mean waiting time of truck type i (min), λ_i is the mean arrival rate of truck type i (trucks per min), both measures obtained as the simulation results, and q_i is the mean cargo of truck type i (ton). The summation for all truck types with respect to Q_i yields the aggregate measure: $Q = \sum_i Q_i$, where Q corresponds to the overall amount of raw material waiting in the queues of the reception area.

4.4. Results to the case study

Table 4 presents the values obtained in the simulation model of the present case study to the measures w_i, λ_i, q_i and Q_i for each truck type i, as well as Q = 508.2 tons and R = 34,009.7 tons per day (or approximately 1417.07 tons/h). In order to provide a more accurate analysis, separated analyses were obtained related to the three forms of *treminhão* (as described in Section 3). Table 5 presents the mean hourly amount of sugarcane unloaded at each mill, as well as the aggregate mean distribution between chopped and whole stalk sugarcane. Recall that mills A, B and C have grinding capacities of 450, 450 and 600 tons/h, respectively, which are close to the means for each mill shown in Table 5. The mill utilization rates for A, B, and C are 0.96, 0.96 and 0.92, respectively, and the total hourly amount of chopped sugarcane unloaded is 1003.2 tons/h; this represents roughly 70.6% of the total amount of sugarcane in the system (e.g., chopped plus whole stalk sugarcane at all the mills).

Table 4
Overall amount of sugarcane waiting in the queues of the reception area

Type of truck, i	Mean waiting time, W_i (min)	Mean arrival rate, λ_i (trucks/min)	Mean amount of sugarcane p/trip, q_i (tons)	Amount of sugarcane waiting, Q_i (tons)
Rodotrem	13.0	0.059	65	49.8
Treminhão form 1	19.9	0.095	45	85.1
Treminhão form 2	18.6	0.148	15	41.3
Treminhão form 3	28.9	0.148	30	128.3
Romeu-julieta (whole stalk sugarcane)	22.9	0.258	25	147.7
Romeu-julieta (chopped sugarcane)	23.1	0.086	25	49.7
Toco	22.1	0.019	15	6.3
Total (Q)				508.2
Average amount of sugarcane unloaded (tons/day) (R)				34,009.7

Table 5
Average amount of sugarcane unloaded per hour (tons/h)

	Mean	Mean of minimums	Mean of maximums
Mill A	435.5	412.1	442.0
Mill B	435.8	415.3	445.2
Mill C	548.3	521.0	562.1
Chopped sugarcane	1003.2	766.7	1106.1
Whole stalk sugarcane	416.2	401.3	466.3

5. Alternative configurations

An interesting application of simulation models is the ability to analyze alternative configurations and to compare their performance with each other. In this study, we suggest examples of alternative configurations analyzed for the case study to show how the logistics managers from agro industries with continuous processes could similarly use the simulation techniques to analyze their supply systems. In this section three different scenarios are analyzed and compared to the original model.

5.1. Scenario 1

Scenario 1 considers that all *treminhão* trucks release their two trailers in the intermediary storage of the reception area. The dispatching rules for the two trailers (*treminhão* form 3) waiting in the intermediary storage must be changed in order to maintain the trailer's circulation. This scenario is motivated by the supposition that with a larger number of *treminhão* form 2 (unit truck) and form 3 (two trailers), these vehicles can be better distributed among the unloading lines, with reduced mean waiting times at the reception area. A similar scenario could be considered by the logistics managers from other industries operating with trucks of multiple trailers or vans, which can split in the reception area. The purpose is to provide improved circulation and distribution of the raw material among the unloading lines and uniform feeding of the mills and the industrial processors. Although we expect that the splitting of vehicles results in lower waiting times for a truck, the simulation model can also show the effects to the waiting time to other types of trucks and to the operations of other components in the system. Recall that the trucks are competing for the same processors, and for various industries, the intermediary storage has restrictions such as space to assure the free traffic of vehicles or time to avoid the deterioration of the raw material.

Table 6 compares the results of scenario 1 with those of the original scenario. Note that significant reductions occur in the waiting times of the *romeu-julieta* trucks (whole stalk sugarcane) and *toco* (27.9% and 21.7%, respectively). This occurs because without *treminhão* trucks form 1 in the unloading lines of chopped sugarcane (as in the original scenario), the mills are available to receive whole stalk sugarcane in whole stalk sugarcane unloading lines. Recall that, the *treminhão* only unloads in chopped sugarcane lines, but its dispatching instruction is related to the number of *romeu-julieta* trucks in the whole stalk sugarcane lines (see flowchart in the Fig. 4). Therefore, the waiting times associated with these types of vehicles (*romeu-julieta* (whole stalk sugarcane) and *toco*) decrease. On the other hand, no significant changes occur in the waiting times of the

Table 6
Results from scenario 1 compared to the results of original scenario

Type of truck, i	Mean waiting time, W_i (min)	Deviation (%)	Mean arrival rate, λ_i (trucks/min)	Deviation (%)	Mean amount of sugarcane p/trip, q_i (tons)	Amount of sugarcane waiting, Q_i (tons)
Rodotrem	13.7	5.4	0.059	0.0	65	52.5
Treminhão form 1	–		–	–	–	–
Treminhão form 2	18.8	1.2	0.237	60.1	15	73.9
Treminhão form 3	28.1	−2.9	0.237	60.1	30	146.5
Romeu-julieta (whole stalk)	16.5	−27.9	0.263	2.0	25	108.5
Romeu-julieta (chopped)	24.6	6.5	0.086	0.0	25	52.9
Toco	17.3	−21.7	0.020	5.3	15	5.2
Total (Q)						439.5
Average amount of sugarcane unloaded, tons/day (R)						34,392.4

treminhão trucks form 2 (unit truck) and *treminhão* form 3 (two trailers) (recorded deviation are only 1.2% and −2.9%, respectively).

However, the mean arrival rate of *treminhão* form 2 and form 3 increases substantially (60.1% for both form 2 and form 3). This result was expected given that upon arrival the *treminhão* trucks always release their two trailers in the intermediary storage area. The aggregate measures of scenario 1 are better than those of the original scenario: $Q = 439.5$ tons (−13.5%) and $R = 34{,}392.4$ tons per day (1.1%). This implies a higher utilization of the mill C capacity, due to the new dispatching policy related to *treminhão*. One of the factors that contribute to this result is that, when there are low amounts of sugarcane in the unloading lines, the intermediary storage of two trailers is more efficient to avoid possible shortages of sugarcane at the mills. The utilization rates for mills A, B and C are of 0.93, 0.96 and 0.97, respectively, under scenario 1. Note that a simple modification in the dispatching policy, which does not require changes in the fleet of trucks, can bring about significant contributions to the supply system of agro industries operating trucks that can split their compositions at the reception area. This may be the case, for example, of trucks transporting sugarcane, orange, wood and other raw materials requiring uniform supply in the processing plants.

5.2. Scenario 2

As aforementioned, the simulation can be used to investigate more complex alterations in the real system, for example, modifications in the fleet mix. Some agro industries may be interested in the economy of scale of transporting raw materials in larger vehicles. In some cases, these vehicles can also transport the cargo more safely than the other types of trucks. According to Seixas (1992) and Sousa (2000), this has been a motivation to managers in the forest industry, who are trying to increase the fleet of *treminhão* or *rodotrem* trucks and to reduce the fleet of *romeu-julieta* trucks,

Table 7
Results from scenario 2 compared to the results of original scenario

Type of truck, i	Mean waiting time, W_i (min)	Deviation (%)	Mean arrival rate, λ_i (trucks/min)	Deviation (%)	Mean amount of sugarcane p/trip, q_i (tons)	Amount of sugarcane waiting, Q_i (tons)
Rodotrem	18.2	40.0	0.086	45.8	65	101.7
Treminhão form 1	22.7	14.1	0.012	−87.4	45	12.3
Treminhão form 2	12.6	−32.2	0.206	−39.2	15	38.9
Treminhão form 3	34.1	17.9	0.206	−39.2	30	210.7
Romeu-julieta (whole stalk)	27.5	20.1	0.252	−2.3	25	173.2
Romeu-julieta (chopped)	28.1	21.6	0.082	−4.6	25	57.6
Toco	23.2	5.0	0.014	−26.3	15	4.9
Total (Q)						599.4
Average amount of sugarcane unloaded, tons/day (R)						34,223.1

since the latter has smaller cargo capacity. Considering the present case study, a current trend in transport operations of Brazilian sugarcane plants is the increase in the sharing of *rodotrem* trucks in the fleet mix. Thus, the objective of scenario 2 is to analyze the effects of a 50% increase of *rodotrem* trucks (from 8 to 12 trucks), followed by a proportional decrease of *treminhão* trucks (to compensate the increase in the amount of chopped sugarcane transported by the larger number of *rodotrems*). This scenario also includes a dedicated unloading line (installed at mill A) to absorb part of the increase in chopped sugarcane delivered by *rodotrem* trucks.

A new distribution of unloading lines is considered so that the mean amount of sugarcane unloaded at each mill approaches its capacity. In particular, the priority list is changed so that *rodotrem* trucks lose their unloading priority over *treminhão* form 2 (unit truck), otherwise the increase of *rodotrem* trucks would tend to reduce the flow of *treminhão* trucks. Thus, the distribution of unloading lines becomes as follows: mill A is supplied by lines A_3 (the unloading line dedicated to *rodotrem*) and A_2, mill B is supplied by line A_1 (in the original scenario it belongs to mill A) besides lines B_5, B_6 and B_7, and mill C is supplied by lines C_{10}, C_{11} and C_{12}.

Note that in Table 7 only the *treminhão* form 2 has shorter mean waiting times than the original scenario (deviation of −32.2%). This result is due to the reduction in the fleet of the *treminhão* trucks, and the new dispatching priority of the *treminhão* form 2 over *rodotrem* trucks. The increase in the mean waiting times of the other types of trucks was expected because of the increase in the number of *rodotrem* trucks with a higher priority. This also explains the increase in the arrival rates of *rodotrem* (45.8%), and the decrease in the arrival rates of the other types of trucks. The significant reduction in the arrival rate of the *treminhão* form 1 (−87.4%), caused by the increase of *rodotrem* trucks, should be noted. This assures that the system is well supplied with chopped sugarcane.

The aggregate measures of scenario 2 are: Q = 599.4 tons (a 17.9% increase over the original scenario) and R = 34,223.1 tons per day (0.6%); note that the first is worse than the original. This means that a change in the fleet mix can yield larger amounts of sugarcane waiting for the grinding process, due to the limited capacity of the mills. The utilization rates of mills A, B and C are 94.9%, 95.6% and 93.4%, respectively. This scenario shows that, in considering alterations on the fleet mix to increase the amount of raw material transported per truck trip, the logistics managers may face the limited capacity of processors and equipment in the agricultural and industrial area. As mentioned before, for the agro industries with continuous processes, the queues of trucks affect the synchronization between agricultural and industrial area due to the limited processors capacity. For example, the congestion of vehicles in the processing plant reception area may also cause the idleness of equipment in the agricultural area.

5.3. Scenario 3

Some agro industries may be interested in the opportunities and tendencies on the market to establish the mix of products to be processed. In other cases, the decisions related to this mix depend on new technologies implemented by the agricultural or industrial area. As different types of raw material may require specific types of trucks, the agro industries may also consider accomplishing alterations on the fleet mix, as was shown in scenario 2. The scenarios considering such complex and expensive alterations can easily be investigated by a simulation model without real interferences to the system.

For the sugarcane plant of the present case study, the tendency is the replacement of whole stalk sugarcane by chopped sugarcane, as a consequence of improvements in its harvesting systems through the use of more mechanization. Similar to scenario 2, the objective of scenario 3 is to analyze the effects of a 50% increase of *rodotrem* trucks (from 8 to 12 trucks), followed by a proportional decrease of *romeu-julieta* trucks (to compensate for the increase in the amount of sugarcane transported by the larger number of *rodotrem*). It should be noted, however, that unlike scenario 2, instead of chopped sugarcane trucks (*treminhão*), this scenario replaces whole stalk sugarcane trucks (*romeu-julieta*) by chopped sugarcane trucks (*rodotrem*). It also includes a dedicated unloading line (installed at mill A) to absorb, partially, the increase sugarcane supplied by *rodotrem* trucks.

As in scenario 2, a new distribution of unloading lines is considered so that the mean amount of sugarcane unloaded in each mill reaches its capacity. The priority list is also changed so that *rodotrem* trucks lose their unloading priority over the *treminhão* form 2 (unit truck). Thus, the configuration of unloading lines is as follows: mill A is supplied by lines A_1, A_2 and A_3 (where A_3 is an unloading line dedicated to *rodotrem*), mill B is supplied by lines B_5, B_6 and B_7, and mill C is supplied by lines C_{10}, C_{11} and C_{12}.

Table 8 shows that the mean waiting time of *rodotrem* trucks increases 18.5% due to the increase in the number of these vehicles and their priority loss to *treminhão* form 2. Moreover, the increase of unloaded chopped sugarcane results in a longer waiting time for the *treminhão* form 3 (34.9%), since other vehicles such as the *treminhão* form 2 and *rodotrems* maintain their priority over the two trailers. As expected, the mean waiting times with *romeu-julieta* trucks (with whole stalk sugarcane) and *toco* reduce to 15.7% and 25.8%, respectively. Note also in Table 8 the reduction of 90.5% in the average arrival rate of *treminhão* form 1 and the increase of 60.8% in the average arrival rates of the *treminhão* form 2 (unit truck) and form 3 (two trailers). These results occur because with the increase in chopped sugarcane within the reception area, it is not necessary

Table 8
Results from scenario 3 compared to the results of original scenario

Type of truck, i	Mean waiting time, W_i (min)	Deviation (%)	Mean arrival rate, λ_i (trucks/min)	Deviation (%)	Mean amount of sugarcane p/trip, q_i (tons)	Amount of sugarcane waiting, Q_i (tons)
Rodotrem	15.4	18.5	0.096	62.7	65	96.1
Treminhão form 1	18.3	−8.0	0.009	−90.5	45	7.4
Treminhão form 2	14.7	−21.0	0.238	60.8	15	52.5
Treminhão form 3	39.0	34.9	0.238	60.8	30	278.4
Romeu-julieta (whole stalk)	19.3	−15.7	0.208	−19.4	25	100.4
Romeu-julieta (chopped)	20.3	−12.1	0.069	−19.8	25	35.0
Toco	16.4	−25.8	0.020	5.3	15	4.9
Total (Q)						574.7
Average amount of sugarcane unloaded, tons/day (R)						34,428.9

to dispatch a *treminhão* form 1 to supply the mills. Consequently, the *treminhão* trucks more frequently unload in the intermediary storage, splitting in *treminhão* form 2 and 3 whereas the arrival rate of these trucks tends to increase.

The aggregate measures of this scenario are: $Q = 574.7$ tons (13.1%) and $R = 34{,}428.9$ tons per day (1.2%); note that the first is worse than the original. As in scenario 2, this means that a change in the fleet mix can yield larger amounts of sugarcane waiting for the grinding process, due to the limited capacity of the mills. The utilization rates of mills A, B and C are 94.5%, 95.9% and 97%, respectively, showing that mill C, which processes the largest proportion of chopped sugarcane, presents higher utilization rate than the other two.

Table 9 presents a summary of the performance measures obtained from the original configuration and scenario 1 (all *treminhão* trucks release their two trailers in the intermediary storage of the reception area), scenario 2 (50% increase of *rodotrem* trucks and a proportional reduction of *treminhão* trucks) and scenario 3 (50% increase of *rodotrem* trucks and a proportional reduction of *romeu-julieta* trucks). It is worth observing that:

Table 9
Summary of performance measures to scenarios 1–3

Scenario	Average amount of sugarcane waiting, $Q = \sum_i Q_i$ (tons)	Deviation to original (%)	Average amount of sugarcane unloaded, Q_t (tons)	Deviation to original (%)
Original	508.2		34,009.7	
Scenario 1	439.5	−13.5	34,392.4	1.1
Scenario 2	599.4	17.9	34,223.1	0.6
Scenario 3	574.7	13.1	34,428.9	1.2

1. Scenario 1 presents significant improvements with respect to the original system. In other words, a reduction of 13.5% in the mean amount of sugarcane waiting in queues in the reception area (*Q*), and an increase (although small) of 1.1% in the amount of unloaded sugarcane (*R*).
2. Scenario 2 shows that, in spite of the proportional changes in the number of *rodotrem* and *treminhão* trucks, higher traffic jams and longer waiting times for sugarcane (*Q*) are expected in the reception area than in the original scenario (17.9%). This occurs because *rodotrem* trucks (whose numbers were increased) and *treminhão* trucks (whose numbers were reduced) have higher priority than other types of trucks and compete for the same mill, since they service different lines that supply the same mill. However, the average amount of sugarcane unloaded (*R*) increases 0.6% (Table 9) with respect to the original scenario.
3. Scenario 3, similar to scenario 2, shows that in spite of the proportional changes in the number of *romeu-julieta* and *rodotrem* trucks, higher traffic jams and larger amounts of waiting sugarcane (*Q*) are expected in the reception area (13.1%). However, scenario 3 presents slightly better results than scenario 2 with respect to the average amount of sugarcane unloaded (*R*), which increases by 1.2% (Table 9) with respect to the original scenario. The interpretation of these results is similar to those discussed for scenario 2.

Therefore, from the point of view of the performance measures analyzed, scenario 1 presents the most effective alternative and, therefore, it could be used to replace the original configuration. Although scenarios 2 and 3 both present an increase in the average amount of sugarcane unloaded in the mills (with respect to the original configuration), they significantly increase the average amount of sugarcane waiting in the reception area and require changes in the mix of the truck fleet. Thus, they appear to be less promising. Other scenarios could also be considered and analyzed in a similar manner as the scenarios presented in this section.

6. Conclusions

Studies have pointed out the importance of the coordinated logistic systems as one of the main sources of opportunities to increase the efficiency and competitiveness of Brazilian agro industries (Morabito et al., 2000). In the case of agro industries with continuous production, such as sugarcane, orange and wood industries, inbound logistics systems are fundamental to assure the required integration between agricultural and industrial operations. Using a case study of a sugarcane plant supply system, the present paper shows that simulation techniques can be efficiently used to model complex systems. In particular, it illustrates how simulations of different scenarios can detect efficiencies to be gained in the plant reception area processes. The analysis of the present study has wider applicability than just to sugarcane plants, such as orange and wood plants with similar supply systems.

To compare the alternatives, we used aggregated performance measures related to the mean unloading rate of sugarcane and the mean amount of sugarcane waiting in the queues of the plant reception area. The first depends on the mill's capacity and the available amount of sugarcane in the reception area, whereas the second takes into account the mean waiting times of the trucks in the queues. These measures are of major concern for logistics managers of agro industries, since shortages of raw material can disrupt the uniformity of the agricultural and industrial operations. The simulation results show that by simply releasing the truck trailers in the intermediary storage, which does not require changes in the fleet of trucks, can bring about significant contributions to the supply system. Moreover, modifications on the fleet mix can face the limited capacity of the processors and equipment in the plant reception area, increasing the mean amount of raw material unloaded.

Logistics supply systems in agro industries represent a relevant topic for other studies. For instance, there are interesting problems related to the upstream link, involving the vehicle dispatching to the fields, the raw material harvesting, loading and transportation back to the plants, among others. Further studies could apply similar simulation models to analyze logistics systems of other agro industries considering the coordination between the rural and industrial areas.

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