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ADVANCES IN MODELLING OF THE INTEGRATED PRODUCTION LOGISTICS IN SUGARCANE HARVEST

ABSTRACT

The sugar-energy sector is extremely important to the Brazilian economy, with several other production chains derived from it, generating some of the main products linked to food and energy sources. This study proposes an integration model for sugarcane harvesting logistics processes, focusing on optimisation of industrial plant production capacity. Dynamic modelling has been applied to study a broad range of the productive phases of the sugar-energy chain. This paper proposes indicators to evaluate the degree of efficiency of the production logistics processes. Preliminary results showed that phase times in the production logistics processes can be significantly reduced in the harvest phase. When analysed as a coordination-oriented flow having chained activities, the production logistics processes optimise the speeds and travel times during the harvest phase. The developed model uses data set of the production and logistics processes phases of a sugarcane industry. A future study will focus on more detailed and complex stakeholder behaviours based on the model proposed.

KEYWORDS

modelling; logistics; sugar-energy production; energy; optimisation.

1. INTRODUCTION

The sugar-energy sector in Brazil comprises all agricultural and industrial activities related to the production of sugar, ethanol and bioelectricity. In Brazil, these products are mainly produced by processing sugarcane used for industrial purposes, and sugarcane is also used to produce animal feed and spirits. The sugarcane sector is extremely successful with high sustainable energy development and an integrated economic development strategy.

In Brazil, there are 421 ethanol and sugar industrial plants scattered throughout the country, with the greatest concentration in the region of São Paulo. The sugarcane-producing farms are greater in number being mainly concentrated around the regions of the sugar and ethanol industrial plants [1]. The level of technology is higher on industrial farms than on traditional farms. The industrial farms are integrated into an industrial chain requesting rapid response from decision makers in an increasingly demanding and changing market.

In order to maintain a competitive advantage in global and national markets, industrial farms must apply the latest technological innovations in various fields of knowledge. Regarding the optimisation of logistical and production processes, it is common to observe the industrial farms relying on a variety of tools for simulation and optimisation of sugar-energy processes and industrial plant management. Most of these tools have been implemented with a focus on steam, energy and processes. Furthermore, regarding the production of sugarcane, Brazil remains the world's largest producer of the crop. In particular, the state of São Paulo is responsible for 55% of the planted area for this crop in the country.

Consumer prices in the sugar-energy sector are subject to fluctuations due primarily to production competition between sugar and ethanol, global oil price fluctuations and, particularly, demand conditions. The sugarcane sector experiences problems including the lack of efficiency in the agricultural supply area and the lack of integration among plants increasing the transportation cost of raw material due to the long distances. Moreover, there has also been an increase in maintenance costs and idle production capacity. Since Brazil is one of the largest food producers in the world, there is competition between crops produced including for agricultural warehouses. Therefore, there are negative impacts for the supply chain because the resources are not only limited but also the industrial plants are usually closer to sugarcane producing regions. Moreover, producing farms are not integrated with each other reducing transport efficiency and increasing the vehicle maintenance costs due also to the poor condition of the roadways.

Brazil has several advantages for development in this sector including advances applying the latest-generation technology to acquire agricultural machinery and implements besides advances in inspection, monitoring and tracking of planted areas and harvests. The Brazilian sugarcane sector has also obtained data for the various information and communication systems. Despite the technology advancements, many Brazilian farms insist to use unoptimised and obsolete management models based on family tradition, especially in the context of production logistics processes of the cutting, loading and transport (CLT) system. However, there is no available statistical data to quantify these observations and the data applied are given by the researchers' farm visits being validated by the agricultural sector technicians.

The flows of the logistics processes of the CLT system in the sugarcane farms need then to be optimised. This study presents an approach to optimise these flows regardless the demand fluctuations. Furthermore, the developed model aims to improve the performance of the CLT system independent of the demand. Therefore, the research has the challenge of modelling the CLT system, enabling the synchronisation of the different operating cycles of the CLT system. The equipment and the harvest front team idle times and the costs involved must be minimised besides maximising the productivity of the entire system. The main objective of the modelling is to apply dynamic simulation to analyse viable scenarios allowing the selection of the best scenario based on a set of performance variables. The proposed model can then aid the management of these processes contributing to the decision-making of farm-industry managers.

This article is divided into five sections. The first section presents a brief introduction to the problem, objectives and importance of the work. The second section addresses the theoretical and bibliographic references. The steps of the proposed model are given in the third section. The fourth section describes the results of the dynamic model, and in the last section, a summary of the conclusions and recommendations for future research is presented.

2. APPLIED MODELS

There are several studies developed with a focus on specific models for the Brazilian sugar-energy production chain that focus primarily on stages within the farm, especially with regard to sugarcane production. Most of this research identified that the harvesting process entails the highest costs and that there is a need to efficiently coordinate the processes of mechanised cutting, loading and transport of sugarcane. However, there is not much emphasis on optimising this process, seeking to minimise costs and improve service. The literature presents logistic systems involving the integration and optimisation of information flow, distribution, resource allocation, packaging and material handling [2], but little research has been done on the harvesting process that is the focus of this work.

In logistics systems, working efficiently requires cost management, with the premise of costing all system activities. Costing information for all activities in the production chain is used to assess their efficiency and effectiveness, both upstream and downstream.

There are models to analyse maintenance activities at sugarcane industrial plants, in which the objective was to observe and determine the ideal intervals between shutdowns for maintenance of the industrial plant [3]. In 1995, another outstanding work was that of Lopes, who modelled a transport system, considering loading and towing, with the objective of identifying, categorising and analysing variables related to the cost of operations. *Table 1* presents other studies applied to the transport and the harvesting of sugarcane, and the most of these studies were applied to Brazil emphasising the operational processes of the sugarcane industries.

Linear programming models were used to study decisions related to the transport and storage of sugar and alcohol [4]. Iannoni and Morabito developed a system focused on the reception of the sugarcane using discrete simulation for analysing sugarcane transport in 2002 [5]. Several studies have been published presenting models and optimisation methods related to the integration and the scheduling of cane cutting taking into account the raw material from field to the industrial plant [6–9].

Table 1 – Models applied to the transport and harvesting of sugarcane

Author, year	Place/Institution	Models	Applications
Lopes, 1995	Escola Superior de Agricultura Luiz de Queiroz	Linear programming	Transport system in the production of sugar cane
Oiticica, 2009	Universidade Federal de São Carlos	Mathematical programming and optimization	Sugarcane plants
Bastos, 2009	Universidade Federal de Goiás	Dynamic simulation	Sugarcane harvest
Silva et al., 2011	Universidade Estadual Paulista	Operational research	Sugarcane plants
Morabito, 2002	Universidade Federal de São Carlos	Operational research	Sugarcane plants
Silva et al., 2013, 2015	Universidade Estadual Paulista	Binary goal programming	Sugarcane harvest
Marins, 2013	Universidade Estadual Paulista	Multi-objective models	Sugarcane plants
Castilho, 2013	Universidade Federal da Grande Dourados	Dynamic simulation	Sugar cane harvest
Chankov et al., 2014	Jacobs University Bremen	Logistic synchronization	Transport in manufacturing systems
Perá et al., 2014	Escola Superior de Agricultura Luiz de Queiroz	Operational research	Sugarcane plants
Sotolani, 2015	Universidade Federal da Grande Dourados	Operational research	Sugarcane plants
Chankov et al., 2016	School of Industrial Engineering, Purdue University - USA	Synchronization of logistics processes	Transport in manufacturing systems

Marins et al. [10] proposed a mixed-binary goal programming model to optimise aggregate production and distribution planning in the sugar-energy sector in Brazil. The model addressed the sugar and alcohol production processes, and the agricultural, industrial and distribution stages, allowing decisions to be taken on a weekly planning horizon, including the harvest and off-season. Bastos [11] developed a dynamic model to the transport processes in the sugarcane harvest. This study was applied in one of the largest Brazilian Midwest plants where the displacement, loading and unloading times of the equipment in the planting zones were evaluated.

The described models do not consider the production planning to depend on the demand, decreasing then the efficiency and the competitiveness of the logistic-production chain from upstream of the farm to downstream [12]. Demand forecasting allows a better planning not only of the production size and the logistics capacity but also the development of strategic policies and investment decisions related to the production, storage and transport infrastructure of the whole sugarcane system [13].

Dynamic simulation models have already been applied to the sugar-energy sector to study all phases of the sugar-energy production chain. They aim to optimise the processes within the farm and in the industrial plants. In the literature review, the case studies published had a limited context, without addressing the complexity of an entire harvesting/cutting, loading and transport (CLT) system in large farms.

There is a lack of research addressing the scale of the principal operating equipment at the farms, and the secondary equipment such as tanks, pumps, tubes and valves, integrating all elements of the CLT system to enable development of advanced process control strategies. Dynamic modelling contributes to the cost-benefit analysis of the process routes, the cost reduction by scaling activities according to the demand, and mainly to the bottleneck optimisation.

3. METHODOLOGY

The flowchart in *Figure 1* shows the five steps of the research methodology. Step five shows the three phases in which the model validation is performed and outlines the steps followed within each phase to achieve the objectives. At the bottom of the figure, the flowchart of the simulation model applied to obtain the results is presented, which is part of step 5 and phase F1.

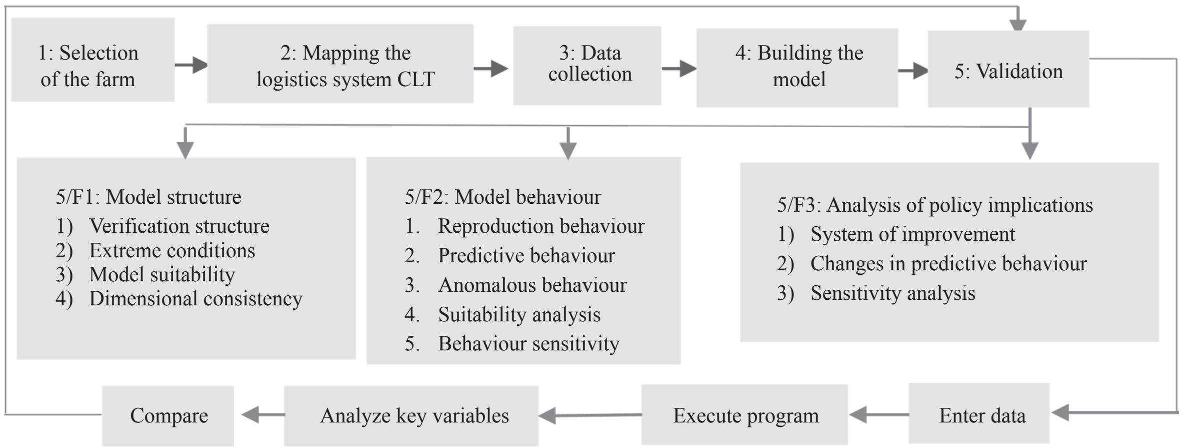

Figure 1 – Research methodology flowchart

3.1 Selection of the plant for the case study

The selected industrial plant was founded in 2008 being part of the portfolio of plants owned by Petrobras Biocombustível. The analysed plant has 2,601 employees and its harvesting is 100% mechanised. The total area of the farm covers 1.7 industrial plantation square meters, with 23 thousand square meters of built area, and a modular layout with planning for expansion of operations. It has an industrial operations centre commanding and checking the real-time status of all industrial operations. The plant's processing capacity is 4.5 industrial plantation tonnes of sugarcane per year being capable to produce 385,000 cubic meters of ethanol per year. It is considered an industrial farm due to its size and processing capacity.

3.2 Mapping of the CLT logistics system

The first stage of modelling consisted of mapping the logistics system for harvesting/cutting, loading and transport of the sugarcane to the industrial plant. This entire process is mechanised and programmed in advance by the agricultural mechanisation department. The purpose of this mapping is to define the variables involved in the CLT system measuring the time spent on each activity. In this case, the logistics system for planting is not included, due to the long period of time between the executions of both systems. It is important to emphasise that good planning for the second system (CLT) depends on the planning of the first one (Planting). Therefore, the planning of the planting area includes an important variable being the division of this area into plots, separated by paths through which the equipment planned for both planting and harvesting will circulate. These plots depend on the size of this equipment and vice versa.

Another important factor in the planning of the CLT system is the definition of the harvest fronts (HF), since the number of HFs needed for the entire harvest depends on the industrial planting capacity of the plant, the geographical distribution of the planting area, as well as the size of the farm and location of the plant. The harvest fronts are worked by a team operating a separate set of equipment suitable for this type of the harvesting process. Besides stating the number of the harvest fronts required for the CLT system, the boundaries of the areas that each team will service must also be determined, since the HFs work simultaneously throughout the harvest period.

The implementation of the CLT system begins with the mechanised harvesting and cutting of the sugarcane, which is uninterrupted (*Figure 2*). This first phase is carried out with harvesting machines (harvesters) (phase 1) that work 24 hours a day. The harvester cuts the cane, chops it and dumps it into a forwarder (phase 2). This equipment is similar to a semi-trailer being coupled to the forwarder tractor, so one tractor can haul several forwarder units. Once the forwarder (F) is full, the tractor goes to the threshing machine (area where the trucks are parked) and positions itself beside the semi-trailer truck (phase 3). This forwarder has its own mechanism allowing it to lift the container. The operator then activates some hydraulic pistons and the forwarder rises, transferring the load to the trucks. After this procedure, the tractor returns the empty

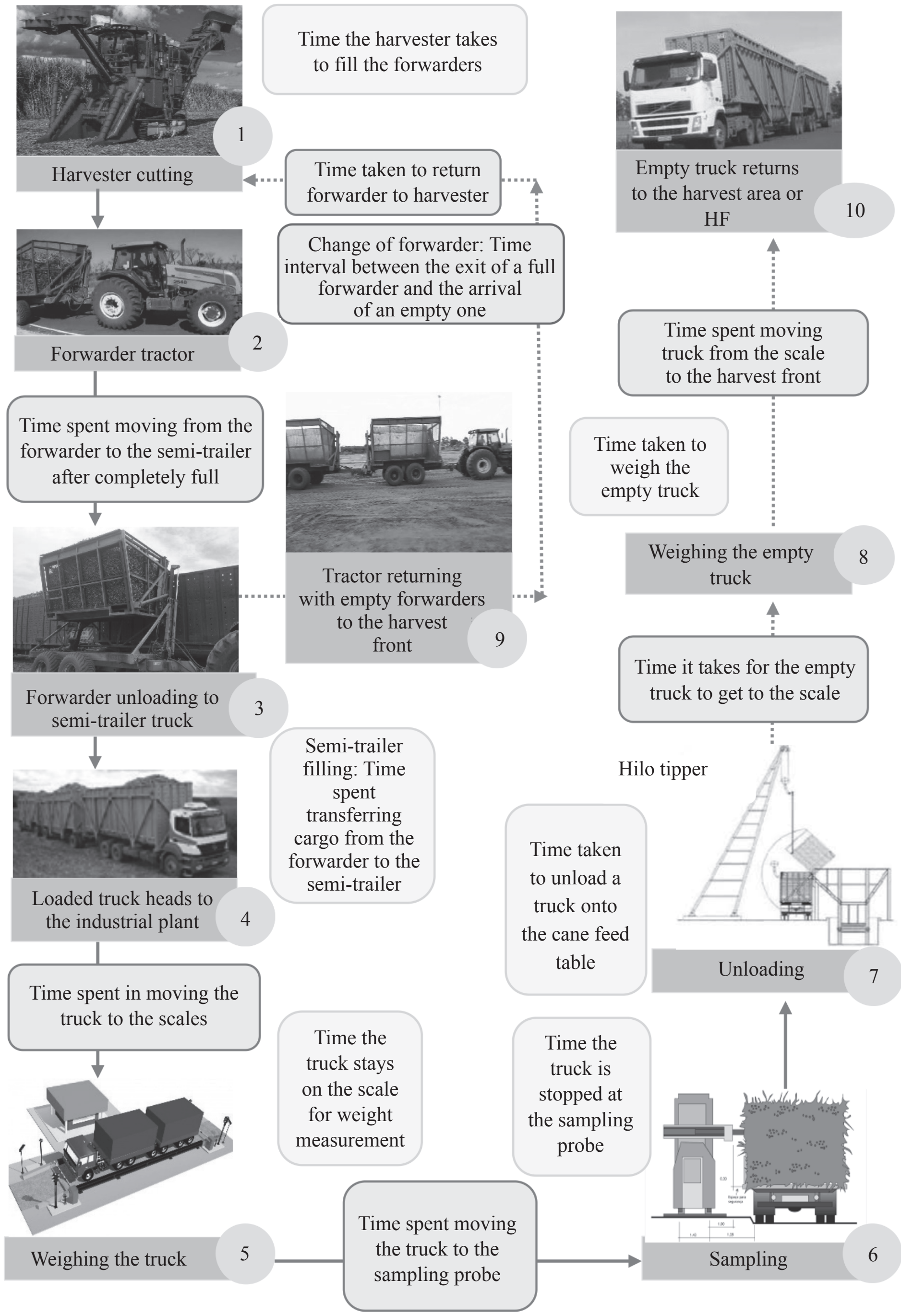

Figure 2 – CLT Logistics SystemSource: Photos from phases 1 to 4 and 9 and 10 are by the author; photo from phase 5 of setcesp.org.br; photo of phase 6 of stab.org.br; photo of phase 7 of the Embrapa Information Agency; photo of phase 10 of mundobrasileiro.com

forwarder to the harvest front (phase 9) to receive the cane being cut. This activity is performed by a tractor called the forwarder tractor (FT).

When the semi-trailer truck C-ST completes the load, the driver goes to the plant (phase 4). Upon reaching the plant, the semi-trailer truck C-ST is weighed (phase 5). The driver then heads to the sampling area where an operator takes a sample using a probe (phase 6). Soon, the driver parks the semi-trailer truck C-ST next to the hilo cane tipper (HT) where it is operated by coupling the truck's cables or chains to the tipper hooks. The HT winch lifts the load from the truck C-ST through a mechanical drive, dropping it onto a cane feed table (phase 7). After this operating cycle, the empty semi-trailer truck C-ST goes to the scale again for weighing (phase 8) and returns to the harvest front (phase 10).

For the entire operating cycle of the CLT logistics system to work seamlessly without stopping, it is necessary to synchronise all processes and activities from the first phase of the process to the last phase, as shown in *Figure 2*. The main challenge of this research is the synchronisation of operating times and movement of all equipment, so that the cut cane arrives at the industrial plant at the right time without stopping the process of the plant. The processes were mapped for a cane industrial plant in the Centre-West region of Brazil. The mapping showed that there are two important decisions in the management of the CLT logistics system which are related to the two operating cycles of the system. The feasibility and the synchronisation of these two cycles depends on the scale of the equipment and the plant capacity.

The first operating cycle refers to the harvester versus semi-trailer truck C-ST synchronisation, and the second cycle to the semi-trailer truck C-ST versus industrial plant synchronisation. Regarding the first cycle, it is essential to obtain the quantity and the capacity of the forwarder units (F) and forwarder tractors (FT). These two machineries maintain the continuous flow of cargo between the harvester and the semi-trailer truck, ensuring that the harvester does not stop at any time. In the second case, the number of the semi-trailer trucks C-STs and their capacities are required to model the studied problem. The purpose in this case is to always keep a truck or semi-trailer at the threshing machine or forwarder cargo point so that the first flow is not interrupted. The other vehicle will then have enough time to deliver the cane to the industrial plant repeating the whole process in the second operating cycle of the CLT system.

The logistical planning for the CLT system depends on the objectives and strategies of each sugarcane company. These strategies are based on the product's market price, demand, the company's capital and financial capacity, costs and benefits, market positioning, limitations, etc. The sizing of the area to be planted, as well as the sizing of equipment, in terms of number and quantity, are decisions that can be considered both strategic, tactical and operational.

It is important then to analyse the adoption of any logistical plan, always seeking to achieve optimisation and synchronisation of the system's operating cycles. There are many scenarios being implemented by business owners. In the case of the first operating cycle, some farms prefer to use one forwarder per tractor providing greater flexibility in the loading and unloading process. However, there is the cost of the equipment, as more tractors and forwarders are needed to serve the harvester while the other forwarder tractors travel to the semi-trailer truck to unload. Other farms adopt few tractors with more forwarder units attached to them, that is, each tractor hauling more forwarders. However, an analysis must be made of the manoeuvring time of the forwarder convoy for loading and unloading to know the costs and understand the advantages of this process phase. Whichever scenario is applied, a simulation and an economics feasibility study is applied to ensure the best solution for the studied scenario.

The second operating cycle process is similar to that for forwarder tractors and forward units, except that this cycle is dependent on the previous one. In this operating cycle, it is important to define the geographical position of the truck at the harvest front. This position defines not only the times from the forwarder tractor and forwarder to the semi-trailer tractor C-ST but also the travel time from the semi-trailer tractor C-ST to the plant, going through phases 5, 6, 7 and 8 until it returns to its new position at the harvest front (HF). This information will determine whether another semi-trailer or trailer truck is needed to meet the demand of the tractor and forwarder and, therefore, the harvester.

The study of this type of problem requires the construction of several solution scenarios to determine the best choice. The implemented scenarios can generate many solutions due to the combinatorial process taking place with the number of variables involved in the model. The best method to study this type of problem is simulation, and therefore this method is addressed in this study.

3.3 Data collection for productive logistics processes at harvest

The data collection was carried out taking care not to include mistaken or biased evidence, which might influence the results and conclusions. Therefore, the entire process of cutting, loading and transporting the sugarcane to the industrial plant was personally monitored. The following data were collected.

a) Quantity and types of equipment in the CLT process.
b) Time spent on activities and equipment movements throughout all phases of the logistics system as illustrated in *Figure 2*. These phases are

related to the loading of the forwarder by the harvester, transfer of these forwarders by the tractors to the threshing machine, unloading of the forwarder to the semi-trailer truck, transfer of the forwarder to the harvest fronts, movement of the full semi-trailer truck, C-ST to the plant and its return to the HF.

c) Geographic location of the plots, of the harvest fronts for positioning the semi-trailer truck C-STs in the threshing machine, the weighing station, the sample analysis point, and the HT area, among others. The movement times were then obtained, and when added to the time spent in each activity, it enabled the calculation of the total time for each operation cycle.

d) Coupling and uncoupling times for semi-trailers to/from trucks and forwarder units to/from tractors.

e) Average speed of equipment. These data were collected daily from the on-board system of the equipment used on the farm.

f) Equipment efficiency levels. These parameters were obtained evaluating the indicators described in *Table 2*.

3.4 Presentation of the sugarcane harvest model

The dynamic systems methodology was used to build the model to understand the structural causes of the system behaviour. The study includes a set of independent elements having interactions among them. The dynamic system behaviour shows the consequences of interactions among its components, making the system phenomena observable, measurable and reproducible.

The model was developed taking into account the sugarcane production processes of a large sugarcane plant having several cutting fronts spread around a radius of 250 kilometres (about 160 miles). The processes were mapped, and the times for the loading, unloading and machinery displacement phases were collected. The model and simulations were carried out with the computer program ISEE System Stella 10. This software works with four screens, interface, model map and model equations, shown in *Figure 3*.

The dynamic systems technique employs four types of variables including the stock, the flow, the converter and the connector variables. In the

Table 2 – Efficiency indicators

Indicators	Description
Operating time(1)	Productive hours x downtime hours. Evaluates effect of maintenance functions on operation.
Availability(2)	Indicates availability of equipment for work. Equipment under maintenance is considered unavailable.
Utilization(3)	Hours used x hours available. Evaluates the effect of lost hours on equipment performance.
Effectiveness	It deals with the programming of the equipment's workday. Measured by the time portion of the day occupied by the equipment.
Efficiency(4)	Product of the other indicators mentioned above

(1) Refers to fuel and lubricant supplies, implement adjustments and calibrations, headland manoeuvres, field change with its own displacement, and cleanings. (2) When this indicator presents low efficiency, there is a direct association with high equipment breakage rates. (3) Very low levels indicate a lot of lost hours per day. (4) Reveals the time that the equipment actually fulfils its productive function.

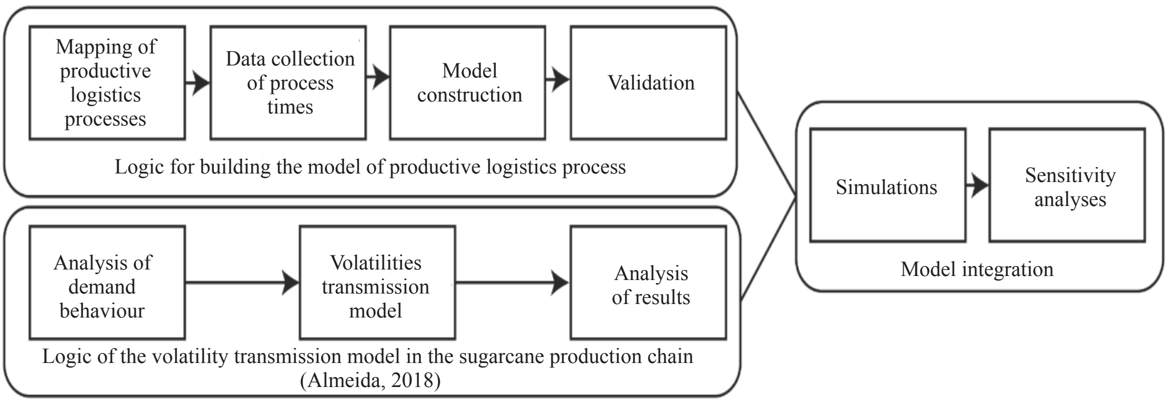

Figure 3 – Logical steps for building the model

flowchart shown in *Figure 4*, the stock or the level variables are the elements showing the status of the model. Therefore, they have an accumulation of values varying as a function of the elements called flows. The variables having this accumulation or stock behaviour are the sugarcane and the semi-trailer trucks C-ST taking part in the processes of mechanised harvesting and ethanol production.

The flow variables will always be connected to a stock variable. The stock flow can be connected either as an input flow or as an output flow, and these two flows can be bidirectional. The connectors establish the relationships between two components when building the model.

The developed model is a very complex one due to the size of the planted area requiring several harvest fronts and involving several key variables for modelling the CLT system that supplies the industrial plant. This model was structured in three modules including two mechanised harvest fronts and one industrial plant module. When implementing the harvest fronts modules, the flow of the harvest has four harvester machines and their respective loading times in the forwarders were used. The developed model included the productivity of the field efficiency, the capacity of the forwarders, the average speed of the forwarder tractors, the forwarder loading and unloading times, the movement time to the semi-trailer trucks C-STs, the semi-trailer truck C-ST loading time, the coupling and the decoupling times, the displacement time to the industrial plant and the average weight of sugarcane loads (*Figures 4 and 5*).

The plant module then considered the following variables related to the reception of the sugarcane from the harvest fronts, time to the weighing scale, the sampling time, travel time to the hilo tipper, the time for the semi-trailer trucks C-STs to unload to the feed table and the return of the semi-trailer trucks C-STs. The model is inserted into the plant module and connected to the production outputs, *Figure 5*. In the layout of the model's control interface, each variable can be controlled and several simulations performed.

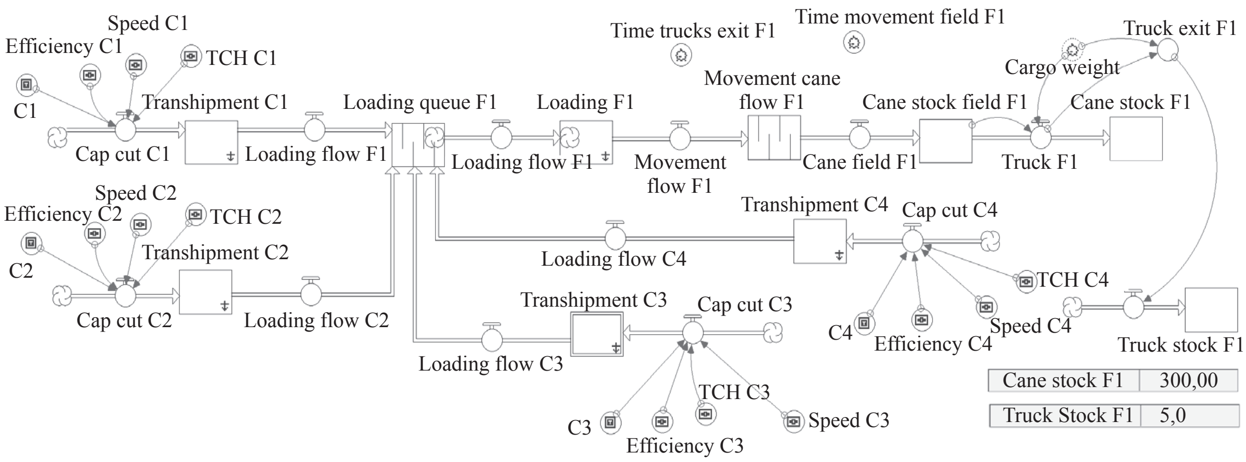

Figure 4 - Modelling the principal harvest front

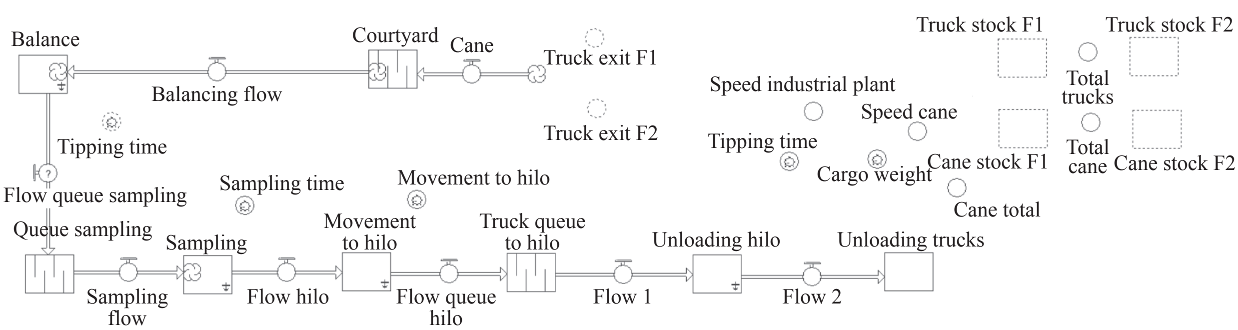

Figure 5 - Modelling industrial plant

3.5 Validation of the sugarcane harvest model

The approach of Forrester et al. (1990) was selected to validate the model showing that the validation process begins with the analysis of the construction of the model, evaluating whether its behaviour is in accordance with the objective for which it was developed, also known as the structure verification test. The model is validated by the following phases, including its structure, behaviour and analysis of policy implications (*Figure 1*). In the first validation phase, the model is implemented and the model variables are stressed to verify the outputs. The results are then compared with the field observations at the plant determining if the model is viable. The second and third phases followed the steps shown in *Figure 1* in the process of development.

4. RESULTS

4.1 Field research results

The results obtained from the field research are presented in three categories corresponding to the 2017/2018 harvest. In the first and second categories, the times spent per event/activity was obtained from the 13 observations. In the third category, the speeds recorded for the on-board systems of the equipment used in the farm-industry are presented.

4.2 Sugarcane harvest front time analysis

In the analysis of the 13 observations taken, variations in the displacement times of the semi-trailer trucks returning to the harvest fronts were recorded, as shown in *Table 3* and *Figure 6*. In the case of the semi-trailer trucks leaving the thresher to the weighing scales, the variation in travel times exhibits a stochastic behaviour (*Figure 6*), and the average of these values is higher than the average of the times of the first event (*Table 3*). In both cases, these differences are due to the positioning of the equipment on the harvest fronts varying with the advances in the harvest area even though the routes are predefined in advance.

When analysing the set of all of the semi-trailer truck C-ST displacements from all harvest fronts to the weigher scale, there is a large variation in times, due to the difference between teams, the yield of each harvester, the formation of queues during loading and the movement of the trucks on the roads. Of the 13 analyses carried out in the primary HF module, an average time of 87 minutes and a standard deviation of 26 minutes were obtained. In the secondary HF module, with 14 observations, the obtained mean time reached was much higher, 139 minutes, and the standard deviation was 44. It must be emphasised again that the size of the analysed plant is quite huge covering an area of about 250 km of radius (about 150 miles). Moreover, the availability of the data set is very scarce, not only for the studied plant but also for the other existing ones in Brazil. It is believed that there must be as many as 40 other plants in Brazil with similar capacity, and if their data set is available in the future, they could be considered to improve the data set accuracy.

The coupling and decoupling times had a more linear behaviour having a lower standard deviation, 0.22 (*Table 3*) since it is a standard procedure. Therefore, the coupling and the decoupling times will only increase in exceptional cases when there is a mechanical-operational problem. Considering areas with similar productivity, the forwarder loading times were measured, the average was 12.97 minutes (*Table 3*). These values depend on the productivity per square meters of the sugarcane changes.

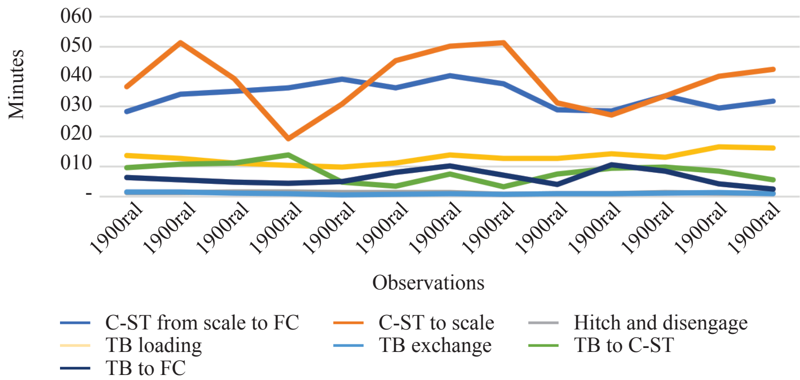

Figure 6 – Average times per observation per event

The forwarder changeover time is not considered a relevant activity in the process. However, some bottlenecks such as queues when unloading the forwarders to the semi-trailer trucks C-ST and the lack of operator training can increase the forwarder changeover times being relevant in some observations (*Table 3*). Delays in the forwarder changeover result in long delays when returning them to the harvester, and the system is hampered because the harvester is idle. The displacement activity from the forwarder to the semi-trailer truck C-ST tends to have a high standard deviation (*Table 3*) because it depends a priori on the distance between the loading and the harvesters that are in operation.

The filling time for the semi-trailer trucks C-ST showed low variation because it is a standard procedure, i.e. the hydraulic lifting of the equipment resulting in the average time of 3.621 minutes and standard deviation of 1.478. The travel time of the forwarder tractor to the harvester showed a high standard deviation in some samples again because of the distance from the loading front to the location of the harvesters (line 7 of *Table 3*).

4.3 Analysis of times within the plant area

The average time for weighing on the scale had several peaks due to the formation of queues, even with an automated system that tends to generate standardised time (*Table 4*). As the scale cannot be duplicated in the system because of the long queues, some ethanol plants use the normal average weight releasing the semi-trailer trucks C-Rs to continue to the next phase without having to weigh.

The travel time of the semi-trailer truck C-ST to the sampling location where the sugarcane test is performed resulted in high values. Nevertheless, it must be said that only 30% of the trucks CR are subject to this process, decreasing the travel time average value to 5.781 minutes and standard deviation of 1.077. The displacement of the truck C-R to the hilo tipper was less than one minute, with a standard deviation of 0.121, having a low representation in the system as a whole. The tipping time depends on the industrial planting process inside the plant, thus, there were some oscillations in the observations made, as shown in *Figure 7* and in *Table 4*. The displacement time to empty the truck CR from the hilo tipper to the scale showed some significant variations having an average of 0.787 minutes but this procedure depends on the vehicle performances and the driver performances.

4.4 Speed of sugarcane harvesting equipment

The average speeds for the studied observations did not show large oscillations, with an average of 40.02 km/h in the plant-field direction, and 31.32 km/h in the field-plant direction, as shown in *Table 5* and *Figure 8*.

The average speed of the forwarder units shown in *Table 6* refers to a sample of 20 tractors at the plant, covering only productive time periods, and excluding refuelling time, transit speed and cleaning, for instance. The speed varied from 4.38 to 6.87 km/h averaging 5.83 km/h.

Table 7 then shows the average speed of 20 harvesters being 5.89 km/hour, and it was based only on productive time. Therefore, the time spent in transit away from the field, fuelling, cleaning and change of area were not included. The data variations are due

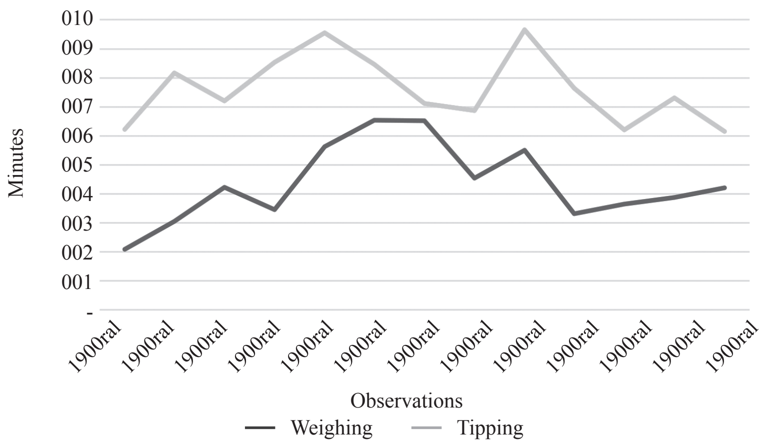

Figure 7 – Times per observation by event/activity

Table 3 – Time spent per observation by event/activity

Event	Time spent on each observation per event [min]													Average	Standard deviation
	1	2	3	4	5	6	7	8	9	10	11	12	13		
C-ST from scale to FC	28.32	34.14	35.16	36.18	39.15	36.21	40.26	37.54	29.00	28.60	33.52	29.61	31.81	33.81	3.92
C-ST to scale	36.72	51.26	39.33	19.25	30.85	45.25	50.22	51.23	31.22	27.22	33.54	40.21	42.51	38.37	9.46
Hitch and disengage	1.42	1.45	1.55	1.62	1.42	1.40	1.38	0.88	0.98	0.95	1.32	1.21	1.19	1.29	0.22
TB loading	13.72	12.74	11.12	10.45	9.84	11.12	13.92	12.84	12.74	14.21	13.21	16.51	16.22	12.97	1.95
TB exchange	1.55	1.62	1.16	1.02	0.55	0.89	0.98	0.87	1.03	1.05	1.10	1.33	1.00	1.09	0.27
TB to C-ST	9.68	10.77	11.12	13.96	4.82	3.52	7.62	3.24	7.56	9.54	9.77	8.54	5.69	8.14	3.04
TB to FC	6.44	5.57	4.85	4.45	5.06	8.08	10.2	7.08	4.09	10.55	8.44	4.33	2.44	6.28	2.37

Table 4 – Average time spent per observation by event/activity

Event	Average time spent on each observation per event [min]													Average	Standard deviation
	1	2	3	4	5	6	7	8	9	10	11	12	13		
Weighing	2.09	3.06	4.22	3.46	5.63	6.54	6.53	4.55	5.50	3.32	3.65	3.88	4.21	4.36	1.30
Tipping	6.23	8.16	7.21	8.54	9.56	8.47	7.12	6.88	9.65	7.65	6.21	7.31	6.15	7.63	1.14

Table 5 – C-ST speed by observation by event/activity

Event	C-ST speed per event [km/h]													Average	Standard deviation
	1	2	3	4	5	6	7	8	9	10	11	12	13		
Field-Usine plant	40.10	42.30	39.40	37.60	40.00	37.30	36.20	37.40	42.30	42.00	43.50	39.20	43.00	40.02	2.34
Usine Plant-field	31.20	24.50	34.50	31.30	28.40	28.60	33.90	30.00	31.80	35.50	36.40	39.20	29.40	31.32	3.14

Table 6 – Average speed of TB by samples

Observations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average
Average [km/h]	5.94	6.13	5.15	4.90	6.11	6.47	4.38	5.57	6.30	6.04	4.77	5.47	5.17	6.44	9.01	5.16	5.77	5.76	6.87	5.38	5.83
Standard deviation	1.41	1.42	2.00	2.06	2.94	1.57	1.88	1.68	1.87	2.80	3.18	0.89	2.00	1.68	1.76	1.32	1.21	2.01	2.32	2.46	1.92

Table 7 – Average speed of sample harvesters

Observations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Average
Average [km/h]	5.91	6.14	5.22	4.90	5.18	6.46	7.38	6.58	4.30	6.03	5.78	5.56	5.37	6.74	6.21	5.46	6.72	5.74	6.87	5.38	5.89
Standard deviation	1.42	1.42	1.14	2.06	2.94	2.57	2.88	1.68	2.87	2.80	3.18	0.89	2.00	1.68	2.76	1.52	1.11	2.71	2.32	2.46	2.12

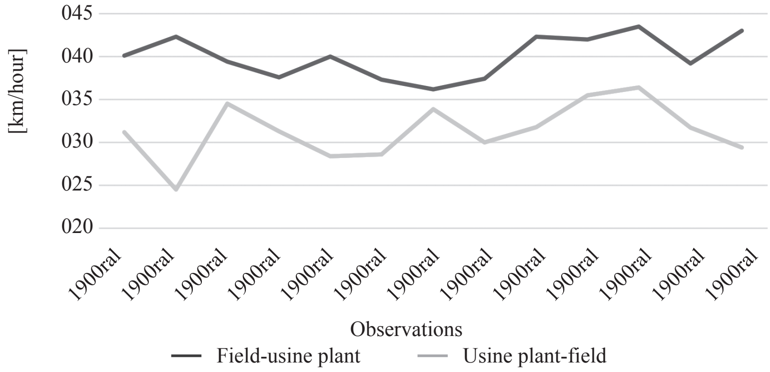

Figure 8 – C-ST speed by observation by event/activity

to different harvester models available, some with a track system, and others with an undercarriage of tires.

4.5 Model simulations and synchronised system performance

The model simulations were developed based on the sugarcane processing capacity, and the machinery speeds and the times of the current activities. A synchronised production plan is implemented based on the manufacturing capacity and the current stock levels besides the future forecasting demand [12–14].

The industrial plant processing capacity is 4.5 million tonnes per year operating currently with 78% of its total capacity. According to Almeida et al. in 2018 [15], there must be a Brazilian ethanol market expansion of almost 15% to satisfy the fleet of bi-fuel vehicles [15]. Two non-synchronised scenarios were then considered, with demand growth of 5% and 10%, and for the synchronised system, a growth of 15% was applied (*Figure 9*). Thus, the average of 500 observations performed in the simulations of the current system model was considered as a non-synchronised scenario with sensitivity analysis, and it was developed considering the plant's demand perspectives to simulate a scenario with synchrony between supply and demand.

The times in the synchronisation scenario are generally shorter (-13.31 min) being the exception the weighing time due to the limitation of the number of scales. Therefore, as there is an increase in the number of vehicles for the synchronised system, there will also be longer queues on the scales. Furthermore, with the increase in the production system, the agricultural sector optimises the harvesting processes, using the machinery in a more efficient way (*Table 8*).

4.6 Model implications

In the synchronised scenario, the model showed a reduction in the times of the sugarcane harvest activities, mainly in the gain of scale. When a greater demand is forecasted, the machinery used in the cutting fronts is increased reducing the overall times and then increasing the industrial plant productivity.

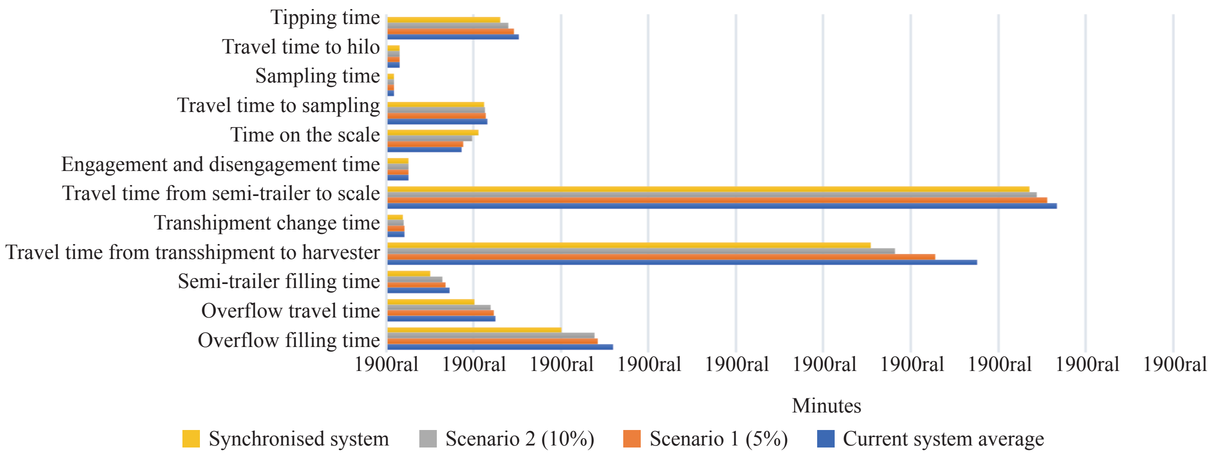

Figure 9 – Synchronised system results

Table 8 – Vehicle speed performance, and productivity

Variables	Current system average	Scenario 1 (5%)	Scenario 2 (10%)	Synchronised system	Variation
Cane weight on semi-trailer [t]	60.48	60.33	60.12	59.28	-1.2
Full truck speed [km/h]	31.32	31.3	30.87	30.13	-1.19
Empty truck speed [km/h]	40.02	40.02	40.02	40.02	0
Harvester speeds [km/h]	5.89	5.89	5.89	5.89	0
Efficiency of harvesters [%]	41.91	41.91	41.91	41.91	0
Sugarcane productivity [t/ha]	75.3	75.3	75.3	75.3	0

The developed model optimises the decision making processes for the machinery use besides increasing the system performance indicators including speed and processing times.

According to Almeida et al. [15], fluctuating market demand for sugar and ethanol products causes imbalances in the plant production systems. Logistics synchronisation has already been examined in other studies and it occurs when a flow-oriented coordination is present in the chain of the production-logistics process. This reduces the negative effects in the planning process of logistics activities in the harvest phase [15].

There is empirical evidence that all of the links in the sugar-energy chain transmit volatility to each other, both via shock and via volatility [15]. The series has co-movement characteristics and can possibly be called cointegrates. In the results of Almeida's study (2018), the presence of persistence of volatility in resellers was also presented, a common characteristic in more downstream links of the production chain.

Therefore, vehicles, teams, machinery and processes are optimised with a view to their more productive uses, reducing the time of production logistics processes in the main activities of the harvesting phase.

5. CONCLUSION

This study proposes a dynamic model that represents the functioning of the production logistics processes in the sugarcane harvest phase focused on ethanol fuel production. Unlike traditional models, this research assumes that harvesting equipment speeds are optimised when all of the production processes are systematised up to the industrial plant (production) phase, while activity times are optimised when taking into account ethanol and sugar demand forecasts.

It should be noted that this study assumes that the demand is adjusted to the potential productive capacity of the industrial plants. An interesting field for future study is to apply the model to determine the impact of the demand fluctuations on the production logistics processes.

The developed model showed that the systematisation of the harvesting logistical processes is important to collect the machinery data, making it also possible to confirm the idleness of the analysed industrial plant. Therefore, the studied industrial plant was non-optimised with the coordination of the activities across time and space a key concept for logistical efficiency. The entire analysed system became then a more efficient one when the processes were synchronised. This article defines a series of indicators (variables) for assessing the efficiency of machinery utilisation and processes within the farm.

The presented model can be considered a tool for decision-making and analysis of opportunities to improve the transport processes and the machinery use methods. Brazil has enormous financial difficulties due to the devaluation of the national currency impacting negatively the producers who buy productive inputs in dollars. The implemented model improves the performance of the production logistics processes in the harvest systems helping the producers to achieve better financial results.

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AVANÇOS NA MODELAGEM DA LOGÍSTICA DE PRODUÇÃO INTEGRADA NA COLHEITA DE CANA

RESUMO

O setor sucroenergético é de extrema importância para a economia brasileira, com diversas outras cadeias produtivas derivadas dele, gerando alguns dos principais produtos ligados a alimentos e fontes de energia. Este estudo propõe um modelo de integração dos processos logísticos de colheita da cana-de-açúcar, com foco na otimização da capacidade produtiva da planta industrial. A modelagem dinâmica tem sido aplicada para estudar uma ampla gama de fases produtivas da cadeia sucroenergética. Este artigo propõe indicadores para avaliar o grau de eficiência dos processos logísticos de produção. Os resultados preliminares mostraram que os tempos de fase nos processos logísticos de produção podem ser significativamente reduzidos na fase de colheita. Quando analisados como um fluxo coordenado e com atividades encadeadas, os processos logísticos de produção otimizam as velocidades e os tempos de deslocamento durante a fase de colheita. O modelo desenvolvido utiliza conjunto de dados das fases dos processos produtivos e logísticos de uma indústria sucroenergética. Um estudo futuro se concentrará em comportamentos mais detalhados e complexos das partes interessadas com base no modelo proposto.

PALAVRAS CHAVE

modelagem; logística; produção sucroenergética; energia; otimização.

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