

Research Article

Assessing the Impact of a Vinasse Pilot Plant Scale-Up on the Key Processes of the Ethanol Supply Chain

Rocio Ramos-Hernández,¹ Dulce Rocio Mota-López,¹ Cuauhtémoc Sánchez-Ramírez,¹ Giner Alor-Hernández,¹ Jorge Luis García-Alcaraz,² and Galo Rafael Urrea-García¹

¹Division of Research and Postgraduate Studies, Instituto Tecnológico de Orizaba, Avenida Oriente 9, 852 Colonia Emiliano Zapata, 94320 Orizaba, VER, Mexico

²Department of Industrial and Manufacturing Engineering, Universidad Autónoma de Ciudad Juárez, Avenida del Charro, 450 Norte, Colonia Partido Romero, 32310 Ciudad Juárez, CHIH, Mexico

Correspondence should be addressed to Cuauhtémoc Sánchez-Ramírez; cuauhtemoc.sanchezr@gmail.com

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One of the byproducts generated in the cane sugar production is molasses, which is used for ethanol distillation. However, one of the problems of distilleries is vinasse. Vinasse is highly water pollutant and is dumped untreated in lakes or rivers and damages the environment. The company FALA developed a pilot plant that uses vinasse to produce a type of livestock feed called MD60. In this paper, the impact of the pilot plant's scale-up in the key processes of the company's supply chain is analyzed. With the help of a sensitivity analysis, this study finds the values that would allow the company to improve its order fulfillment indicator and to increase profits, assuming an expected demand by the introduction of this new product into the market. The results show that (1) the pilot plant fulfills 32% of the orders, (2) according to the current vinasse storage capacity, it is possible to fulfill up to 77% of the orders by scaling up the pilot plant, (3) to satisfy 100% of the orders, it is necessary to use all the vinasse generated, and (4) the highest profit is reached by processing all the vinasse and by considering the upper sale price.

1. Introduction

The sugar industry is one of the most important in the world due to the products and byproducts generated from its production. These become raw material for many supply chains, including ethanol, biofuels, beverages, and pharmaceutical products. According to OECD/FAO [1], trends in sugar production indicate that, by 2023, 86% of the sugar globally produced will be obtained from sugar cane, and only a small portion will be extracted from sugar beet.

One of the products generated by the sugar industry is molasses, also called black treacle. The thick fluid is similar to honey but darker. According to experts, the darker it is, the more flavor and nutrients it has. For the international market, cane molasses have four main uses: (1) livestock feed, due to their concentration of calcium, chloride, and magnesium; (2) ethanol production; (3) reprocessing for sugar production;

and (4) production of yeast, citric acid, and lysine, among others [2].

When molasses are used for ethanol production, the new byproduct or wastewater called vinasse is generated. Vinasse is a liquid residue remaining from the fermentation and distillation of alcoholic liquors. It has a dark, red color, ranging from crimson to almost black. Similarly, it has a strong odor, moderately acidic pH, temperature close to 85°C, and a biochemical oxygen demand (BOD) between 70 and 80 g/L. Vinasse is also composed of 93% water, 2% inorganic compounds (potassium, calcium, sulfates, chlorides, nitrogen, phosphorus, etc.), and 5% organic compounds that volatilize when heated at 650°C [3].

Vinasse from the ethanol industry is one of the major environmental pollutants. According to Moraes et al. [4], for every liter of produced ethanol, between 10 and 18 liters of vinasse are also generated, depending on the distilling

process. Moreover, vinasse is usually discharged untreated into bodies of water, and it consequently pollutes surface water and groundwater [5]. Furthermore, the growing ethanol production from cane juices and molasses to use it as automotive fuel [6] greatly increases the risk of further pollution if technologies that help reduce pollutants are not implemented.

According to CONADESUCA [7], Mexico produces 190 million liters of ethanol each year, and, considering the aforementioned ethanol-vinasse relationship, this equals 1,900 million liters of vinasse, also per year. Undoubtedly, this is a major issue, not only due to the progressive deterioration of the environment, but also because this is economically ineffective since costs for collection, transport, and disposal of vinasse are constantly increasing [8]. However, if it is properly treated, vinasse can reduce its environmental impact, not to mention that it can become a continuous source of energy and raw materials with high added value [9].

For all these reasons, the company FALA (this name was given for confidentiality reasons) has designed a pilot plant for vinasse treatment, which, as a result, produces MD60, a type of livestock feed. Unfortunately, the plant does not have enough capacity to process 100% of the generated vinasse. Therefore, this paper analyzes the impact of the company's pilot plant scale-up in the key processes of its supply chain. Systems Dynamics (SD) is used to carry out this analysis.

The remainder of this paper is organized as follows: Section 2 briefly discusses previous works reporting vinasse use and treatment, and it explains the concept of industrial scale-up and study cases. Then, Section 3 describes the methodology employed to analyze pilot plant scale-up in FALA, while Section 4 presents and discusses the obtained results. Finally, Section 5 includes conclusions and recommendations for future work.

2. Literature Review

2.1. Vinasse Treatment to Reduce Its Environmental Impact. As previously mentioned, the chemicals contained in vinasse make it highly hazardous for the environment. However, if properly treated, it can be used as an energy source, livestock feed, or fertilizer [8] or for many other purposes. For instance, vinasse has been widely used to generate biogas from anaerobic digestion [4, 9, 10]. Similarly, it has been employed as a fertilizer for sugar cane fields, although the main problem with this is that a portion of vinasse may infiltrate into the soil and damage aquifers [11–16]. In addition, Colin et al. [17] and Sankaran et al. [18] used bacteria to retrieve effluents generated from the ethanol industry, while Akram et al. [10] assessed the potential of vinasse for biofuels production. Another use of the vinasses is the production of livestock feed [5, 19–22].

2.2. Industrial Scale-Up. Industrial scale-up aims at implementing, at a full scale, innovations or new technologies already tested in laboratories or pilot plants in order to improve the performance of industrial processes [23].

The literature has reported several innovations in industrial processes, such as biogas generation from industrial waste and residues [24–26], and the utilization of vinasse generated from distilling processes [27]. Similarly, other works have assessed the effectiveness of new technologies in improving the characteristics of heavy crude oil [28], reducing the environmental impact caused by the textile dyeing process [29], treating wastewater from a polyvinyl chloride production plant [30], and obtaining value-added products through biorefineries whose raw materials include biomass [31] and waste and residues [32, 33]. However, despite their success, most of these innovations have been tested only in laboratories or pilot plants. However, in some cases, their economic feasibility is analyzed and suggestions are provided for their implementation on a large scale.

Only few studies have implemented their proposed innovations and new technologies in the industry. Some of these implementations include a brand-new range of products from a steel company [34], performance improvement of activated sludge reactors [35], and the use of special equipment to control odors in a wastewater treatment plant [36]. In addition to reporting results from both a pilot plant and a full-scale industrial plant, these studies have highlighted the problems that arise from implementing the technologies at the large scale. Some of these problems include installation issues, failures in operational stability, and excessive economic costs, among others. Unfortunately, none of the works found reports scale-up in pilot plants that use vinasse for the production of livestock feed.

2.3. Use of Systems Dynamics for Industrial Scale-Up. To facilitate industrial scale-up, certain tools must be employed to assess the impact on production processes, as well as the problems, costs, and benefits that would be brought by the implementation of innovations and new technologies into the plant. Simulation, especially System Dynamics (SD), is a tool that enables assessing these variables. SD is based on a holistic system analysis, which is why simulation models designed through it demonstrate the behavior that would emerge in the system if any of its components are modified [37–39]. This is the main reason why SD has been widely employed to analyze and test different alternatives that modify the performance of many industrial sectors, including the cement industry [40–42], the steel industry [43, 44], the oil industry [45], and the automotive industry, and supply chains [46, 47].

None of the articles found to support this work report the use of SD to simulate the large-scale implementation of innovations and technologies previously tested in a laboratory or in pilot plants. However, one particular study developed a simulation model that analyzed increased vinasse generation as the result of a surge in bioethanol production [48].

2.4. Complex Supply Chains. The structure of *supply chains* is complex due to the quantity of suppliers and customers involved [49, 50]. For this reason, different tools and techniques have been developed for their analysis, evaluation, and decision-making; one of these techniques is simulation. Considering its strengths, compared with mathematical programming methods or stochastic models, simulation

especially through SD enables the user to find, analyze, and learn about the dynamic behaviors of the system studied, which is helpful in the decision-making process [51].

SD has been used to analyze the complexity of different types of supply chains [52, 53]. For example, Kumar and Kumar [54] study the effects of the lack of suppliers in healthcare supply chains for rural communities, caused by their geographical location, Lee and Chung [55] assess the coordination among the links of perishable food supply chains, since it is critical to guarantee the freshness of their products. Sagardi et al. [6] evaluate the feasibility of the biofuel supply chain in Mexico analyzing the ethanol production and three key variables were identified to develop this sector: the availability of raw materials, the production capacity, and the reduction of carbon dioxide emissions. Peng et al. [56] simulate the behavior of a postseismic relief supply chain, produced by information delay and damaged road infrastructure. Cannella et al. [53] tested the effect of inventory record inaccuracy in an information supply chain, finding that it causes instability among the links of the supply chain.

However, the analysis of the state of the art indicates that none of the research works found (1) addresses the impact of industrial scale-up of vinasse treatment over a supply chain and (2) uses SD to assess industrial scale-up. These are two aspects fully analyzed in this work.

To analyze the complexity of FALA's supply chain, the use of a simulation tool as SD is necessary.

3. Materials and Methods

The company FALA was used to assess the impact of pilot plant scale-up in the key processes of an ethanol supply chain. This company is located in the South of Mexico, and it is a national pioneer in the use of vinasse to produce livestock feed in a pilot plant that was developed by its research department. Figure 1 shows the supply chain of the company.

The supply chain begins with the harvest of sugar cane, which is taken to the mills for sugar production. A residue that is generated in this process is molasses, and although they are commonly used as cattle feed, in this case they serve as raw material for FALA's production process. That is, the company uses molasses to produce ethanol, which is later used in various products, such as makeup, drugs, beverages, and biofuel.

In its distilling process, FALA generates around 11 liters of vinasse for every liter of ethanol. This type of residue is usually dumped untreated into water bodies, thus damaging the flora and fauna, because it diminishes the oxygen concentration of these water bodies.

FALA perceived this problem and the serious environmental implications. It therefore decided to set up a pilot plant for vinasse treatment, obtaining MD60 as a result, which is a type of livestock feed. However, this pilot plant has the capacity to process only 2% of the daily-generated vinasse. The remainder is stored in holding tanks, but the storage generates additional costs. This paper therefore presents a SD model that assesses different scenarios in order to analyze the impact of the scale-up of the vinasse pilot plant in the key

processes of the company's supply chain. The best alternative will be chosen based on results of two key performance indicators (KPIs). The following section describes the use of SD to develop the evaluation model.

3.1. Causal Diagram. A causal diagram is a graphical tool that helps represent the behavior of a system and the different interactions among its variables. Causal diagrams consist of variables connected through arrows that indicate cause-effect relationships ($A \rightarrow B$). These relationships can be either positive or negative. If a relationship is positive, an increase in the cause will produce an increase in the effect, or a decrease in the cause will produce a decrease in the effect. Nevertheless, if the relationship is negative, any increase in the cause will produce a decrease in the effect, or any decrease in the cause will produce an increase in the effect.

Figure 2 depicts the causal diagram used to study industrial scale-up in the vinasse pilot plant. Some of the variables identified include master production schedule, molasses tank, ethanol production, ethanol production capacity, MD60 production capacity, and finished product inventory.

The feedback loops of the causal diagram are described as follows:

- (i) Loop B1: it has a positive impact on the amount of orders requested from the supplier. However, if the amount of order increases, the molasses inventory of the supplier decreases or vice versa.
- (ii) Loop B2: if the molasses inventory increases, the ethanol production may also increase, and when the ethanol production increases, the molasses inventory will decrease. Similarly, the ethanol production depends on the production capacity of the plant.
- (iii) Loop B3: when vinasse inventory increases, MD60 production also rises. An increase in MD60 production causes a decrease in vinasse inventory, which limits MD60 production.
- (iv) Loop B4: if the variable MD60 production increases, the finished product inventory will also increase. If there are high levels of finished product inventory, MD60 production decreases.

3.2. Equations. This section describes the equations from the simulation model that correspond to the key processes of the supply chain:

Orders from Supplier. FALA receives daily orders from the supplier (DOS) depending on the condition shown by (1). Thus, during harvest season, the company daily receives between 25 and 30 shipments with 30 tons of molasses. However, when it is not harvest season, the company receives maximum 8 shipments, although sometimes there is no daily supply:

$$\text{DOS} = \begin{cases} \text{With harvest,} & 25 \leq \text{DOS} \leq 30, \\ \text{Without harvest,} & 0 \leq \text{DOS} \leq 8. \end{cases} \quad (1)$$

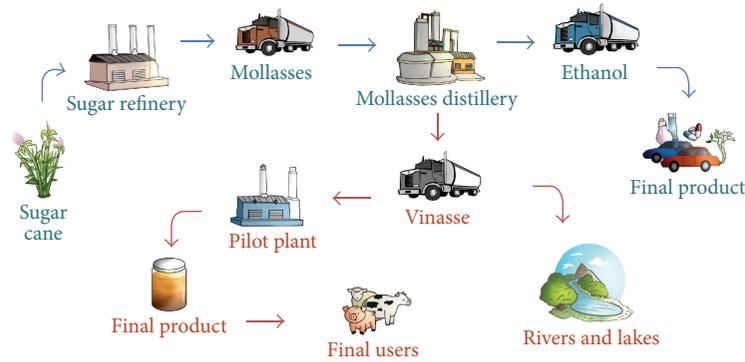


FIGURE 1: Supply chain of FALA.

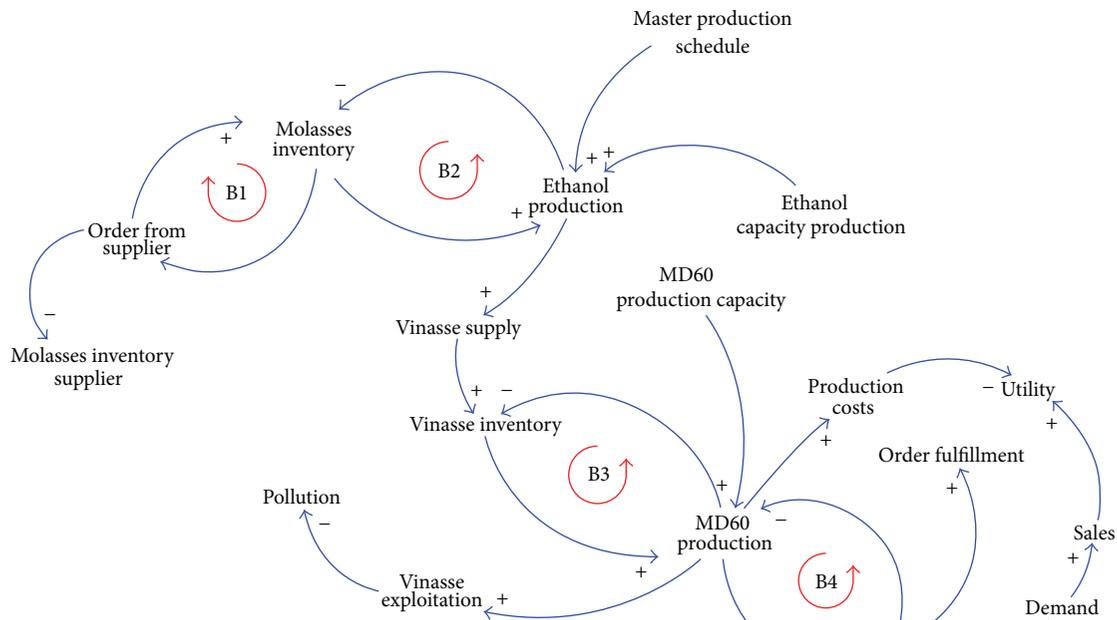


FIGURE 2: Causal loop diagram of the scale-up of plant pilot of vinasse.

FALA uses the distillation method for ethanol production (EP). Therefore, the amount of ethanol obtained per ton of molasses can vary. To represent this variability, the RANDOM function is used, which generates a random value from a range of preestablished values. In this case, and according to historical data, the minimum and maximum values were 235,118 and 292,397 liters of ethanol:

$$EP = \text{RANDOM}(235.118, 292.397). \quad (2)$$

Vinasse (V) is the raw material of FALA’s pilot plant, and it depends on EP. Every liter of produced ethanol generates around 11 liters of vinasse (os). This relationship is expressed by

$$V = EP * os. \quad (3)$$

Due to the great amount of vinasse that is generated, FALA reuses it as its raw material. Its supply policy depends on the demand of the livestock feed, MD60. That is, if there is a high demand of MD60, vinasse is treated; otherwise, it is sent to holding tanks as expressed by

$$VHT = DOV - VP. \quad (4)$$

In this equation, VHT stands for the vinasse that is sent to the holding tanks. It is the difference between the daily-obtained vinasse (DOV) and the vinasse that is temporarily stored in a pit (VP) for its further treatment. The amount of vinasse in VP_{t+1} is determined by the condition expressed by

$$VP_{t+1} = \begin{cases} \text{If } DOV \leq CVP - FP_t, & \text{Then } DOV, \\ \text{else,} & CVP - FP_t. \end{cases} \quad (5)$$

If the amount of daily-obtained vinasse (DOV) is smaller than the difference between the capacity of the pit (CVP) and the amount stored in VP_t (in time t), DOV is then stored in VP_{t+1} ; otherwise, the amount stored is only what results from this difference.

The pilot plant has a batch production system (BPS) for MD60 production. This system works as expressed in

$$\text{BPS} = 2\text{PR} (L_1 + 4L_2). \quad (6)$$

In this equation, PR is the percentage of vinasse retrieved and L_1 is the initial load added, while L_2 stands for four additional loads with different values which are added throughout the MD60 production process.

As regards industrial scale-up, MD60 production in the full-scale industrial plant (IP) follows the behavior described in

$$\text{IP} = \sum_{i=1}^n \text{PR} (\text{CF}_h), \quad (7)$$

where CF_h is the continuous flow per hour and n represents the number of work hours in a day.

Both plants have PR that behaves as a normal distribution (see (8)) with a mean of 11.58% and a standard deviation of 1.8%:

$$\text{PR} = N(11.58, 1.8). \quad (8)$$

The Company's Inventories. Inventory of MD60 (IMD), inventory of vinasse (IV), and inventory of molasses (IM) behave as expressed in (8), (9), and (10), respectively:

$$\text{IMD} = \text{IMD}|_{t=0} + \int_0^t (V * \text{PR} - s), \quad (9)$$

$$\text{IV} = \text{IV}|_{t=0} + \int_0^t (m * r_{\text{molasses}} * \text{OS} - V), \quad (10)$$

$$\text{IM} = \text{IM}|_{t=0} + \int_0^t (a * Q_{\text{molasses}} - m). \quad (11)$$

In these equations, s represents the effective sales of MD60, m is the amount of molasses to be processed, r_{molasses} is the yield of molasses per ton of ethanol, a is the amount of orders requested from the molasses supplier, and Q_{molasses} is the amount of molasses that is ordered. The company's molasses inventory is considered in the model, since MD60 depends on ethanol production, which in turn could not be achieved with a molasses inventory that is low or inexistent.

Two performance indicators were considered to assess the impact of the pilot plant scale-up in the supply chain of the company FALA: order fulfillment of daily demand (OFDD) and profits (P) gained in 365 days. On one hand, OFDD is calculated by

$$\text{OFDD} = \frac{1}{j} \sum_{i=1}^j \frac{S_i}{D_i} * 100\%, \quad (12)$$

TABLE 1: Initial parameters of simulation.

Plant	Pilot	Scale-up
Capacity vinasse pit (L)	1,500,000	1,500,000
Vinasse production for day (L/d)	19,200	1,320,000
Percentage of vinasse retrieve (L)	11.58	11.58
Capacity storage MD60 (kg)	15,000	950,000
Order fulfillment (%)	32%	—
Profit (USD)	34,600	—

where j stands for the amount of days when there is product demand, D represents the amount of this demand, and S stands for the amount of effective sales.

On the other hand, profits (see (13)) are the difference between total earnings (TE) and total costs (TC):

$$P = \text{TE} - \text{TC}. \quad (13)$$

The next step in the methodology of SD is to develop the Forrester diagram considering the above equations.

4. Results and Discussion

The model simulation is run with software Stella® V10.0.4 during 52 weeks. $\text{DT} = 1$, and hours is the time unit employed. Demand of MD60 is represented by a normal distribution with a mean of 164,000 kg and a standard deviation of 10,000 kg. The warehouse used to store the finished product has a storage capacity for 950,000 kg of MD60. It is assumed that the industrial plant would work 24 hours every day from Monday to Sunday. However, in these 52 weeks, there are two weeks of production stoppage due to the maintenance of the ethanol distillery plant.

Table 1 shows the parameters from both the pilot plant and the full-scale industrial plant. The parameters *capacity vinasse pit*, *vinasse production for day*, and *capacity storage* were chosen according to the technical specifications of the pilot and scale-up plant. *Percentage of vinasse retrieve*, *order fulfillment*, and *profit* were obtained by historical data. As can be observed, OFDD in the pilot plant reaches only 32% and P equals 34,600 USD. An increase in both indicators is expected with the implementation of a full-scale industrial plant.

Due to the low percentage of OFDD obtained, a sensitivity analysis was performed to find the values that satisfy 100% of the orders.

4.1. Sensitivity Analysis. A low percentage in OFDD in the pilot plant reflects the company's inability to satisfy a high demand of MD60. Therefore, to increase the values of the two performance indicators, a sensitivity analysis is carried out by modifying the values of the following variables: capacity vinasse pit (CVP), which represents the full capacity of the pit; continuous flow per hour (CF_h), which is obtained by a previous sensitivity analysis and represents the range where the flow can be continuous without stopping the production; initial raw material inventory (IIRM) and maintenance time (MT), which are defined through the experience of the company's managers; and finally sale price (SP) per kilogram,

TABLE 2: Simulation output to achieve the maximum OFDD (%).

				CVP = 1500000								
				CF _h = 47000			CF _h = 48000			CF _h = 49000		
				IIRM			IIRM			IIRM		
				500000	1000000	1500000	500000	1000000	1500000	500000	1000000	1500000
SP	0.11	MT	15	38.81	53.39	50.44	58.84	55.13	57.11	59.47	65.28	64.51
			20	32.34	46.80	43.00	55.95	54.08	53.86	56.86	57.01	56.94
			25	25.47	43.10	38.85	55.43	50.86	54.27	57.27	56.23	57.04
SP	0.12	MT	15	52.51	55.85	54.60	56.28	54.61	60.13	63.17	68.29	60.10
			20	36.24	43.87	53.93	55.99	54.98	54.99	56.92	54.97	56.66
			25	32.27	40.04	47.03	54.76	55.03	54.18	57.11	50.22	56.79
SP	0.13	MT	15	45.99	47.70	47.67	55.72	56.09	55.85	60.26	77.90	74.98
			20	38.65	34.30	40.93	54.76	48.95	55.50	58.52	55.51	56.18
			25	37.51	27.57	26.95	53.97	42.83	55.48	57.22	57.70	53.99

TABLE 3: Simulation output to achieve the higher profits (million USD).

				CVP = 1500000								
				CF _h = 47000			CF _h = 48000			CF _h = 49000		
				IIRM			IIRM			IIRM		
				500000	1000000	1500000	500000	1000000	1500000	500000	1000000	1500000
SP	0.11	MT	15	2.617	2.639	2.616	2.673	2.660	2.680	2.735	2.725	2.742
			20	2.597	2.585	2.596	2.648	2.628	2.630	2.685	2.690	2.677
			25	2.538	2.545	2.548	2.586	2.595	2.615	2.660	2.666	2.612
SP	0.12	MT	15	3.215	3.239	3.228	3.329	3.279	3.289	3.369	3.369	3.365
			20	3.185	3.189	3.175	3.266	3.232	3.264	3.287	3.270	3.308
			25	3.139	3.137	3.122	3.189	3.215	3.210	3.280	3.263	3.288
SP	0.13	MT	15	3.845	3.840	3.845	3.891	3.912	3.900	3.993	3.964	3.991
			20	3.782	3.789	3.765	3.846	3.894	3.843	3.936	3.951	3.919
			25	3.735	3.705	3.720	3.803	3.806	3.810	3.923	3.889	3.880

which is the range of the molasses' cost fluctuation, the biggest competitor of vinasses; all this is in order to improve performance indicators. Tables 2 and 3 present the results obtained of OFDD and P . 91 different scenarios were tested, considering the following values:

CVP (L): 1,500,000.

CF_h (L): 47,000, 48,000, and 49,000.

IIRM (L): 500,000, 1,000,000, and 1,500,000.

MT (days): 15, 20, and 25.

SP (USD): 0.11, 0.12, and 0.13.

In Table 2, there is a summary of the development of 91 scenarios to achieve 100% of OFDD, but the maximum value of OFDD achieved is 77.90%, obtained with the next combination CVP = 1,500,000 L, CF_h = 49,000 L, IIRM = 1,000,000 L, MT = 15 days, and SP = 0.13 USD. In the case of profit, Table 3 shows the result obtained and the major profits achieved are 3,993,269.00 USD with CVP = 1,500,000 L, CF_h = 49,000 L, IIRM = 1,000,000 L, MT = 15 days, and SP = 0.13 USD.

Results of the first sensitivity analysis still show inability to fully satisfy the product demand. Thus, a second analysis

is carried out, this time by considering that vinasse cannot be completely processed due to capacity constraints, which is why it is sent to holding tanks (Table 4). In this second case, the following values are analyzed:

CVP (L): 1,500,000.

CF_h (L): 47,000, 48,000, 49,000.

IIRM (L): 500,000, 1,000,000, and 1,500,000.

MT (days): 15, 20, and 25.

SP (USD): 0.11, 0.12, and 0.13.

Holding tank (L) = 15,000,000.

As shown in Table 4, three different scenarios allow obtaining 100% of OFDD; the combinations to achieve are shown in Table 5. However, different scenarios are close to 100%, as 99.99%, 99.90%, and others. This is because of uncertainty and variability in the following variables and processes: demand, production process of ethanol, percentage of recuperation of vinasse, and inventory of raw material.

Table 6 shows the scenario to obtain the higher profits (4,65,820 USD). This scenario has the following combination: CVP: 1,500,000 (L); CF_h: 49,000 (L); IIRM: 1,000,000 (L); MT: 15 (days); SP: 0.13 (USD); and holding tank = 15,000,000 (L).

TABLE 4: Simulation output to achieve 100% OFDD (%).

				CVP = 1500000 + holding tank								
				CF _h = 47000			CF _h = 48000			CF _h = 49000		
				IIRM			IIRM			IIRM		
				500000	1000000	1500000	500000	1000000	1500000	500000	1000000	1500000
SP	0.11	MT	15	45.20	78.15	75.45	86.03	99.73	91.40	99.99	100.00	98.03
			20	38.99	50.66	54.86	63.81	88.59	77.14	97.03	99.92	81.97
			25	20.18	49.73	43.30	55.03	56.02	67.21	61.96	73.06	55.93
SP	0.12	MT	15	34.38	51.85	66.66	100.00	80.73	99.16	99.99	100.00	99.37
			20	23.81	41.23	45.66	86.00	76.73	75.49	97.17	99.92	76.71
			25	36.64	41.58	33.40	66.72	73.03	63.34	76.22	83.72	80.57
SP	0.13	MT	15	65.65	64.87	87.69	99.85	99.45	99.80	99.99	99.92	99.87
			20	42.30	43.60	61.01	72.72	65.29	96.05	86.42	99.90	88.36
			25	34.92	30.25	47.49	56.41	67.60	66.55	76.29	78.15	71.49

TABLE 5: Scenarios to achieve 100% OFDD.

Parameters	OFDD = 100%		
	Scenario 1	Scenario 2	Scenario 3
CVP (L)	1500000 + holding tank	1500000 + holding tank	1500000 + holding tank
CF _h (L)	48000	49000	49000
IIRM (L)	500000	1000000	1000000
MT (days)	15	15	15
SP (USD)	0.12	0.11	0.12

TABLE 6: Simulation output to achieve the higher profits (million USD).

				CVP = 1500000 + holding tank								
				CF _h = 47000			CF _h = 48000			CF _h = 49000		
				IIRM			IIRM			IIRM		
				500000	1000000	1500000	500000	1000000	1500000	500000	1000000	1500000
SP	0.11	MT	15	2.719	2.741	2.748	2.784	2.633	2.755	2.741	2.696	2.700
			20	2.727	2.718	2.740	2.741	2.764	2.770	2.730	2.679	2.783
			25	2.699	2.711	2.705	2.720	2.715	2.746	2.729	2.675	2.747
SP	0.12	MT	15	3.356	3.349	3.362	3.252	3.417	3.385	2.856	3.344	3.360
			20	3.344	3.341	3.360	3.409	2.767	3.386	2.838	3.332	3.412
			25	3.330	3.322	3.321	3.366	2.733	3.355	2.836	3.315	3.365
SP	0.13	MT	15	3.988	3.981	3.987	3.974	3.984	4.032	4.024	4.066	3.885
			20	4.000	3.998	3.996	4.030	4.012	4.013	4.015	4.034	4.046
			25	3.946	3.945	3.942	3.986	4.006	3.848	4.014	3.942	4.020

Although this scenario delivers the highest profit, it only achieves 99.92% of OFDD as shown in Table 4. This is due to the variability in the key process of the supply chain, which does not allow satisfying 100% of OFDD.

By using both the vinasse pit and the holding tank, the company could reach 100% of OFFD and obtain the highest profits. However, the use of the holding tank as storage will generate an extra cost that, given the improvement achieved for both OFFDD and P, is worth the investment.

Also, the sensitivity analysis shows a behavioral pattern among the set values, without missing the systems uncertainty and variability. In general, a larger MT decreases the OFDD and P. On the other hand, a larger inventory and a

larger CF_h increase the OFDD and P. These relations prove the logic described in the causal diagram.

5. Conclusions and Future Work

This paper evaluates the impact of pilot plant scale-up in the key processes of a supply chain. The pilot plant reuses vinasse generated in ethanol production to produce livestock feed. The major contribution of this research is the identification of those key processes from the company's supply chain that could be affected in the pilot plant scale-up process. A sensitivity analysis helps to find three scenarios to achieve 100% OFDD. One scenario allowed achieving the higher

profits. The key processes of the supply chain of FALA are procurement of vinasses and production of ethanol because the major variability and uncertainty are present here. As future work, it is necessary to assess, by means of sustainability indicators, the environmental benefits of the full-scale industrial plant. Likewise, the relationship cost-benefit must be evaluated by considering time dedicated and investments made to set up the full-scale plant. Finally, although this research considered only two performance indicators, a multicriteria analysis is recommended in order to improve decision-making.

Competing Interests

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

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