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Modeling waste management in a bioethanol supply chain: A system dynamics approach

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Abstract
This paper presents a model and simulations, which was built with a System Dynamics methodology applied to waste management in the bioethanol supply chain in Colombia. The stages of the supply chain used were cane planting, production and the distribution process. The residues taken into account were bagasse and vinasse. Moreover, four simulation scenarios were performed in which the values of variables modified management strategies. The installed bioethanol production capacity was increased to observe the evolution of increased waste generation evaluated. The initial conditions for the simulation were modified to represent a production of about 2,500,000 liters / day. This leads to an increased generation of vinasse of over 400 million liters on average in a month and around more than 1 million tones of bagasse. The results are used to estimate the impact of management strategies on the amount of waste generated in the production of bioethanol.

Keywords: manuscript formatting; camera-ready manuscript.

Modelamiento de la gestión de residuos en la cadena de suministro de bioetanol, enfoque con dinámica de sistemas

Resumen
En este artículo se presenta un modelo y sus simulaciones, construido con la metodología de Dinámica de Sistemas, aplicado a la gestión de residuos en la cadena de suministro de bioetanol en Colombia. Las etapas de la cadena de suministro utilizadas fueron siembra de caña, proceso de producción y distribución. Los residuos que se tuvieron en cuenta fueron el bagazo de caña y las vinazas. Se realizó la simulación de cuatro escenarios en los que se modificó los valores de las variables denominadas estrategias de gestión. Se aumentó la capacidad instalada de producción de bioetanol para ver la evolución temporal del aumento de la generación de los residuos evaluados. Las condiciones iniciales para la simulación fueron modificadas para representar una producción de 2,500,000 litros/día. Esto permite que se incremente la generación de vinazas por encima de 400 millones de litros en promedio en un mes y alrededor de más de 1 millón de toneladas de bagazo. Con los resultados se permite estimar el impacto de las estrategias de gestión en el número de los residuos generados en la producción de Bioetanol.

Palabras clave: Dinámica de sistemas, Modelamiento, Bioetanol, Residuos

1. Introduction

Supply chain management is a rather wide subject. Over recent years researchers have reviewed it from different points of view. [1]. The concept of sustainable supply chain is growing within supply chain management, which is characterized by the integration of environmental and social objectives that address the economic dimension of the chain [2]. The use of quantitative models for decision-making can be found in research conducted to link the social and environmental issues in the supply chain [3]. Models are either a simplified representation or abstraction of reality. They are based on a set of variables and causal relationships [4,5].

The use of models and simulations allows the inclusion of external issues such as environmental variables. These models are very useful in Green Supply Chain Management (GSCM). The GSCM can be defined by the inclusion of environmental thinking in the process. This ranges from the integration of product design, selection and provision of raw

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materials, production, distribution and delivery of the final product to consumers to the end of the products' life cycle and reverse logistics [6]. In order to accomplish a green supply chain it is necessary to minimize, or preferably, eliminate the negative effects that the supply chain generates on the environment. This requires the use of environmentally friendly materials and minimizes waste generated. One of the environmental aspects to be considered in the area of sustainability is the management of wastes that are generated in production processes.

Agro-industrial waste management has gained attention in different countries due to improper handling and final disposal in the environment [7]. While handling of waste is defined in terms of reuse and exploitation, this does not reach 100% of the generated waste. As a result, increasing the production of bioethanol (EtOH) will also directly increase the generation of waste, and the problem of waste management.

According to the above, we propose a hypothesis which uses modeling and simulation tools, such as system dynamics, that can be associated with external factors, such as environmental variables, specifically waste management in the supply chain.

The model developed in this study focuses on the fields of biofuels, specifically bioethanol. The residues that were taken into account to build the model were: sugarcane bagasse and vinasses.

2. Description of the system to study

Bioethanol is a type of biofuel produced from the alcohol fermentation of sugars in agricultural crops or crop residues. This is by far the most technologically mature biofuel derived from microorganisms and is a good candidate to replace fossil fuels [8]. In Colombia, bioethanol is produced from sugar cane. The production of this type of plant is well established in the country and has greater energy efficiency compared to other raw materials from which the bioethanol is produced. Its production in Colombia is carried out mainly in the Cauca River Valley, primarily in the departments of Cauca, Valle, Risaralda and Caldas, which encompass 47 municipalities [9].

Information on Colombian installed capacity for bioethanol production (1,250,000 liters/day) was taken as the basis of this study. Variables associated with the supply chain were also considered, as well as the number of planted sugarcane hectares intended for bioethanol, the milling capacity, the performance of cane per hectare, the inventory of bioethanol in factories, bagasse generation, vinasse generation, and the inventory of bioethanol for wholesale, among others.

Since bioethanol in the country was first produced, the generation of waste or by-products such as bagasse and vinasse has been identified. Vinasse is the wastewater generated from the production of ethanol, either from sugar cane, corn, wheat, yucca, or lignocellulosic residues. These are associated with the amount of bioethanol produced. The ratio of generation is on average between 10 and 15 liters per each liter of bioethanol, depending on each factory equipment [10]. Moreover, another by-product of this process that is involved in this system is the bagasse that is generated in the milling of juice production. Bagasse can be used as formation of animal food or as an element for energy cogeneration, and therefore, reduces energy costs [11].

Table 1.
Basic Scenario Simulation.

PARAMETERS	VALUES
Hectares	35000 Ha
Crop Yield	80 Ton/Ha
Milling Yield	70 L/Ton
Bagasse Generation	28,60%
Vinasse Generation	8 L/L ethanol
Sowing Time	11 months

Source: The author

The two main residues, vinasse and bagasse, were considered. Scenarios with different input values obtained from the Federation of Biofuels reports in 2014 [12] were established for these residues. Table 1 shows the information on the basic parameters of the simulation. The simulation time limit is one hundred and fifty days (150), i.e. five months of production.

The following are the main attributes that were identified in obtaining and delimiting the system under study. They describe the component parts of the bioethanol supply chain, which has the most impact on waste generation.

- Hectares of Cane: The number of sugarcane planted hectares that are intended for the production of bioethanol.
- Planting Cane: The planting of the required sugarcane for bioethanol production.
- Cane harvest: The number of hectares harvested and intended for the production of bioethanol.
- Milling to get Juice: Milling process of harvested cane.
- Cane Bagasse: Bagasse quantity generated in the milling stage.
- Fermentable Juice: Quantity of cane juice intended for fermentation.
- Bioethanol Production (EtOH): Production process according to production rate of fermentable juice.
- Bioethanol Inventory: Accumulation in liters of produced EtOH.
- Vinasse Generation: Quantity of vinasse generated in EtOH production.

3. System Modeling

The modeling was undertaken using the System Dynamics methodology. The steps proposed by Forrester [13-14], and Aracil & Gordillo [15] were followed in the process. It also took into account the methodology followed by Callejas et al [16]. Therefore, we started by building a causal loop diagram, and then moved on to the formulation of a Levels and Flow diagram in order to obtain equations representing the model. Finally, the simulation was carried out. We used the Vensim Ple [17] in this study.

3.1. System Dynamics

System Dynamics is a methodology for analysis and problem solving. It was developed by Jay Forrester at the

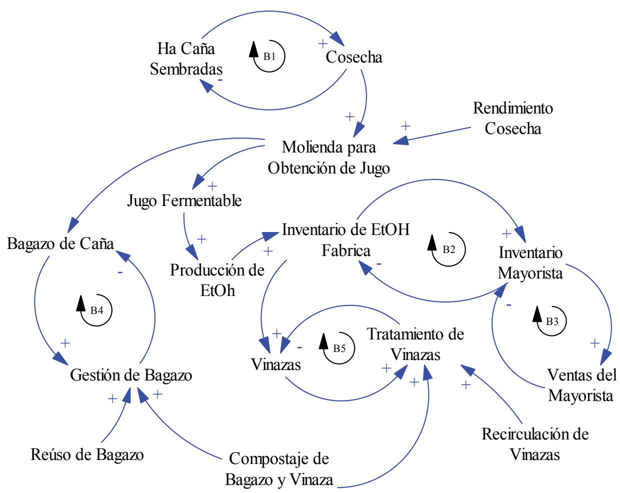

Figure 1 Causal loop Diagram of the Problem.
Source: The author

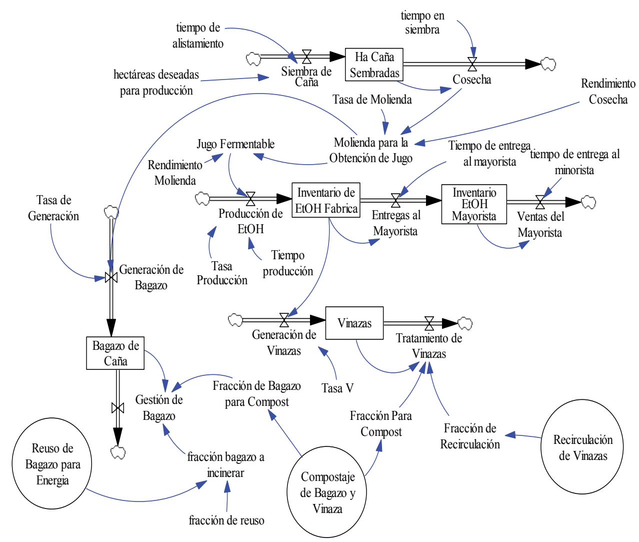

Figure 2. Levels and Flow Diagram of the problem.
Source: The author

Massachusetts Institute of Technology (MIT). He presented this methodology in his research [13-14]. It facilitates the of learning complex systems through formal models and simulation methods [18]. In System Dynamics, any aspect of the world is conceived as a causal interaction between attributes that describe it. Thus, systemic representations with arrows and dots, called causal loop diagrams, are built. They capture all the hypotheses proposed by the modeler. From these hypotheses we can learn about the system in order to take part in the decision making. Subsequently, the Levels and Flow diagram is obtained, in which a quantification of the causal loop diagram is undertaken. We can later obtain a set of equations that allow the decision maker to see the system of interest's behavior through specialized software simulations [19].

It should be noted that the background to this research reveals a growing interest in environmental issues in recent years and, in particular, an interest in environmental issues applied to supply chains management [20].

3.2. System conceptualization

In this stage, causal relationships that can be identified in each one of the problem's attributes are described. Fig. 1 shows the results in the causal loop diagram.

Fig. 1 shows the conceptualization of the problem expressed with feedback loops, which demonstrates the structure of the system.

B1 represents the following relationship: if more hectares of sugarcane are planted there are more hectares harvested; if more are harvested, fewer hectares of sugarcane are planted.

In turn, more harvested cane that signifies more raw materials for the production of juice by milling, which increases the fermentable juice to produce bioethanol (EtOH).

B2 represents EtOH inventory increasing with the production of EtOH. Given the dynamics of this market in Colombia, it is assumed that everything that is produced goes directly to the wholesale inventory.

In B3, a constant sale of EtOH is assumed. Therefore, it can be understood that if there is a higher wholesale inventory, there will be more wholesale sale.

B4 represents cane bagasse generation. This comes from the milling stage in order to obtain juice. It is stated that the more milling there is to obtain juice the higher the production of cane bagasse. Therefore, if there is more bagasse generated, there is a requirement for more management; if there is more management, there will be a lesser quantity of bagasse generated.

B5 represents vinasse generation. It is obtained in the production process and it is associated with the number of liters of EtOH produced. This vinasse requires treatment because of its high pollutant content. The more vinasse that is treated the less the quantity of untreated vinasse.

3.3. Formulation

In this phase, the causal loop diagram shown in Fig. 1 is reworked and it becomes a Levels and Flow diagram, which is known as "the language" of the system dynamics simulation. Fig. 2 shows the model developed in Vensim.

The generation of waste in the production process of bioethanol is one of the most important environmental aspects when considering sustainability. While it is true that these residues are susceptible to use and treat, it is necessary to evaluate what will happen to the amount of waste that is generated when the Colombian government continues to increase the amount of bioethanol in the country.

In Table 2 and Table 2.1 the model equations and arithmetic relations that were considered for the simulations and management strategies are presented.

4. Model Behavior

In this study, four different scenarios which enabled the understanding of the system behavior were established. The scenarios were constructed by changing the values of bagasse reuse strategies for energy and composting bagasse and vinasse (0-1). Similarly, the bioethanol production capacity was increased to twice the current production (installed capacity 1,250,000 liters / day) and the behavior of the amount of managed and unmanaged waste was observed.

Initially, the model was validated with real data, the current bioethanol production capacity in the country and also with an initial simulation for this capacity. As shown in Fig. 3, the Y axis displays the amount of liters of ethanol generated, and the X axis shows the time expressed in 6 months.

In Figs. 4, 5, 6, and 7 the simulation results of the generation and management of the main waste produced in the supply chain of bioethanol can be found. The Y axis is the number of liters of ethanol produced, the number of vinasses liters generated and the amount of cane bagasse in tonnes. The X axis is the simulation time in days.

Table 2. Model equations

Variable Name	Type	Formula	Unit
Sugarcane sown Hectares	Levels	Sugarcane planting – Harvest	Hectares
EtOH Inventory -Factory		EtOH Production –Deliveries to Wholesale	Liters
EtOH Inventory - Wholesale		Deliveries to Wholesale – Sales to Wholesale	Liters
Bagasse		Bagasse Generation – Bagasse Management	Tons
Vinasse		Vinasse Generation – Vinasse Treatment	Liters
Sugarcane planting	Flows	Hectares desired for Production / Induction time	Hectares
Harvest		Sugarcane sown Hectares / Sowing Time	Hectares
EtOH Production (Bioethanol)		Fermentable Juice * Production Rate/Production Time	Liters
Deliveries to Wholesale		EtOH Inventory –Factory /Delivery Times to Wholesale	Liters
Sales to Wholesales		Wholesale EtOH Inventory/Delivery Times to Retail	Liters
Vinasse Generation		Factory EtOH Inventory *V Rate	Liters
Vinasse Treatment		Vinasse*(Recirculation Fraction + Fraction for Compost)	Liters
Bagasse Generation		Milling to Obtain Juice *Generation Rate	Tons
Bagasse Management		Bagasse *(Bagasse for Incineration Fraction + Fraction of bagasse for Compost)	Tons
Hectares desired for Production	Parameter	External Data	Hectares
Induction time		External Data	Months
Sowing Time		External Data	Months
Crop Performance		External Data	Ton / Hectare
Milling Performance		External Data	Liter / Ton
Production Time		External Data	day
Production Rate		External Data	Dimensionless
Delivery Times		External Data	day
V Rate (Vinasse Generation Rate)		External Data	Liters of Vinasse /Liter of EtOH
Milling to Obtain Juice	Auxiliar y	Crop Performance * Crop)* Milling Rate	Tons
Fermentable Juice		Milling to Obtain Juice * Milling Performance	Liters

Source: The author

Table 2.1.
Equations of Management Strategies

Variable Name	Type	Formula	Unit
Reuse of bagasse for energy	Auxiliary	0= Do not implement, 1= Implementation	Dimensionless
Fraction of bagasse to incinerate	Auxiliary	Reuse fraction * Reuse of bagasse for energy	%
Bagasse and Vinasse Compost	Auxiliary	0= Do not implement, 1= Implementation	Dimensionless
Fraction of Vinasse for compost	Auxiliary	(Bagasse and Vinasse compost)*0.3	%
Fraction of Compost to reuse	Parameters	External Data	%
Reuse Fraction	Parameters	External Data	%

Source: The author

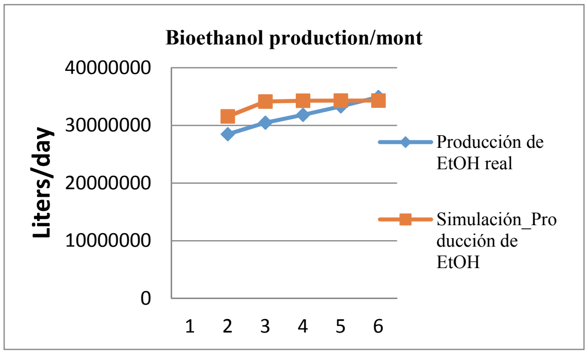

Figure 3. Model validation with historical production data.
Source: The author

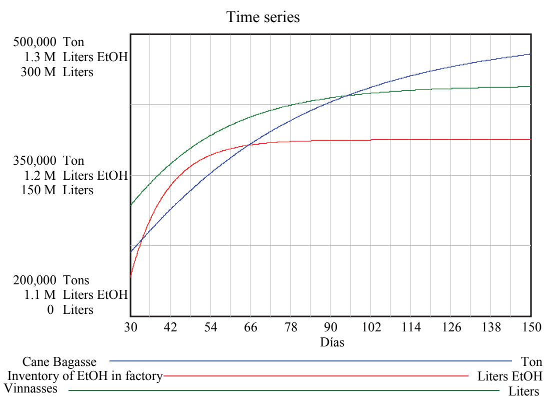

Figure 4. Scenario 1: initial conditions
Source: The author

4.1. Behavior Analysis

Fig. 4 shows that the amount of waste generated is actually much higher compared with the production of bioethanol in an average month. This first scenario shows a simulation with no management strategies for cane bagasse reuse, composting of bagasse and cane, and vinasses recirculation to the process. These strategies had an initial value = 0.

Fig. 5 shows a simulation with the initial conditions of the first scenario, but with waste management strategies having been implemented. These had a value = 1; this is shown in Table 2.

Behavior shows waste reduction, of both vinasse and bagasse. The proportion of bagasse to be incinerated is 70% as the other 30% can be destined to marketing.

Fig. 6 shows a third scenario following the country's interest in increasing production. Initial conditions for the simulation were modified to represent a production of about 2,500,000 liters / day. This leads to increased generation of vinasse of over 400 million liters on average per month and around more than 1 million tonnes of bagasse. In this scenario, management strategies had a value = 0. It is worth mentioning that the System Dynamics models are not used to forecast but to observe and evaluate behavioral tendencies. The major concern in this scenario what would happen if the vinasses that was generated was not treated. Where would it be discharged?

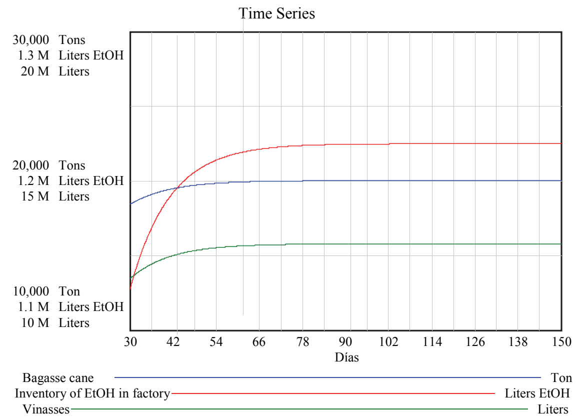

Figure 5. Scenario 2, Implementation of Management Strategies
Source: The author

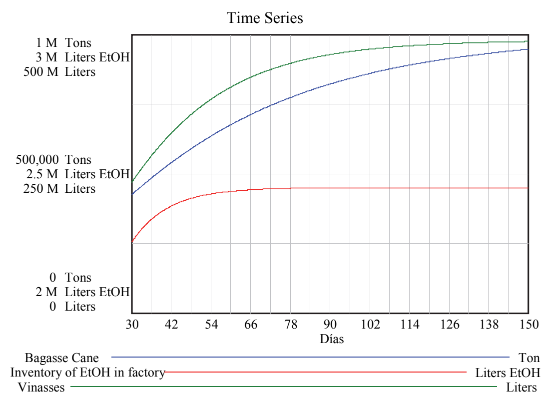

Figure 6. Scenario 3, increased hectares of sugarcane and bioethanol production.
Source: The author

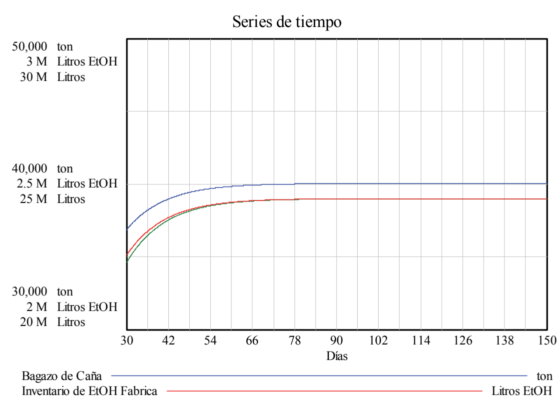

Figure 7. Scenario 4, implementation of strategies with a higher production of bioethanol.
Source: The author

Fig. 7 shows a simulation with the initial conditions of the third scenario. However, this time waste management strategies are employed. As in scenario 2, strategies have a value = 1. The trend shows a significant waste reduction in comparison to Fig. 6. However, there are still much untreated waste that may cause environmental hazards.

5. Conclusions and Future Work

Taking into consideration the Colombian policy of expanding the supply of biofuels, it is necessary to focus on the environmental importance of the bioethanol supply chain. The higher the production capacity the greater the environmental changes that would put pressure on the environment. The Colombian government is currently seeking the expansion of bioethanol production plants.

In bioethanol models, it is necessary to link the energy efficiency from the bagasse combustion process with its calorific value/ power and the performance of the steam generated. This is necessary in order to give the model more accuracy and to be able to evaluate more scenarios prospectively. Similarly, it is necessary to link other waste generated in the supply chain such as *chachaza* (the residue left after filtering the pressed cane juice)**,** with the oils used.

The model illustrates different scenarios or future trends in waste generation in the bioethanol industry. This is due to the change of parameters and the initial conditions that vary, depending on the information that is to be used in the model.

It was possible to vary the behavior of bioethanol production represented by the model with real information, which was taken from the Federation of Biofuels. Even though a correlation between the data is perceived, it is necessary to continue measuring the model to find a more accurate trend.

With the system dynamics methodology it is possible to create models that can be linked to environmental variables and simulate future scenarios of potential impacts. With his methodology, differential equations that show the behavior of the model variables are constructed. These equations can be integrated with other methodologies, such as Dynamical Systems, Life Cycle Analysis and Material and Energy Balances, in order to have a rigorous methodology to assess the sustainability of bioethanol supply chains or other biofuels.

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