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SYSTEM DYNAMICS AND VIABILITY THEORY FOR SUSTAINABILITY ASSESSMENT, APPLICATION FOR BIOETHANOL PRODUCTION IN COLOMBIA

DINÁMICA DE SISTEMAS Y TEORÍA DE LA VIABILIDAD PARA LA EVALUACIÓN DE LA SOSTENIBILIDAD, APLICACIÓN PARA LA PRODUCCIÓN DE BIOETANOL EN COLOMBIA

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ABSTRACT

Contextualization: This paper has a framework for prospective assessment of sustainability in bioethanol in a dynamical way, this is important as a tool for policymakers in Colombia.

Knowledge gap: No dynamic models have been developed with the formulation of viable or desired scenarios. The evaluation of environmental aspects and sustainability is always carried out with past information and historical data, it is rarely carried out with prospective models and no restrictions or unwanted scenarios are linked. A general bioethanol supply chain must be modeled, connecting variables that represent sustainability indicators. The modeled indicators were proposed by the Global Bioenergy Partnership (GBEP).

Purpose: A model is built to evaluate sustainability indicators and know if the trend behavior of the system evolves through the desired regions that would correspond to the sustainability objectives and goals of the sector.

Methodology: A model is developed with System Dynamics and to integrate the modeling with the evaluation of sustainability, the concept of constraints, developed in the Viability Theory, is used; Here, the desired regions of the system state are suggested and defined as desired, alert, and undesired scenarios.

Results and conclusions: The model have been tested with the information of a bioethanol production chain from sugarcane in Colombia with an installed capacity of 450 million liters per year, using two sustainability indicators that were designed and simulated using the constraint regions. These indicators are water consumption and jobs in bioethanol production. The results show important findings for modeling, monitoring, and assessing sustainability in the biofuels sector, using indicators and providing a method of implementing the best practices for sustainability using defined desired regions of the systems.

Keywords: Sustainability, Modeling, System Dynamics, Viability Theory, Bioethanol.

RESUMEN

Contextualización: en este artículo se desarrolló un marco referencial para la evaluación dinámica y prospectiva de la sostenibilidad del bioetanol de caña, como herramienta para los tomadores de decisiones en Colombia.

Vacío de conocimiento: no se han desarrollado modelos dinámicos con la formulación de escenarios viables o deseados. La evaluación de aspectos ambientales y sostenibilidad siempre se realiza con información pasada y datos históricos, pocas veces se hace con modelos prospectivos y no se vinculan restricciones o escenarios no deseados. Así, se debe modelar una cadena de suministro general de bioetanol, conectando variables que representen indicadores de sostenibilidad. Los indicadores modelados fueron propuestos por Global Bioenergy Partnership (GBEP).

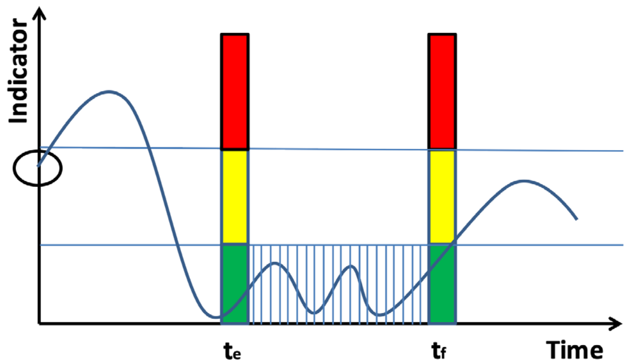
Propósito: se construye un modelo para la evaluación de indicadores de sostenibilidad y saber si el comportamiento del sistema evoluciona por las regiones deseadas, que corresponderían a los objetivos del sector y metas de sostenibilidad.

Metodología: se desarrolla un modelo con dinámica de sistemas y, para la integración de la modelación con la evaluación de la sostenibilidad, se utiliza el concepto de restricciones desarrollado en la teoría de la viabilidad; aquí las regiones deseadas del estado del sistema se sugieren y se definen como escenarios deseados, de alerta y no deseados.

Resultados y conclusiones: este modelo ha sido probado con la información de una cadena productiva de bioetanol a partir de caña de azúcar en Colombia con una capacidad instalada de 450 millones de litros al año, utilizando dos indicadores de sostenibilidad que fueron diseñados y simulados, junto con la evaluación de estrategias de mejora. Estos indicadores son el consumo de agua y el empleo en la producción de bioetanol. Los resultados muestran hallazgos importantes para modelar, monitorear y evaluar la sostenibilidad en el sector de los biocombustibles, utilizando indicadores y brindando un método para implementar las mejores prácticas para la sostenibilidad utilizando regiones deseadas definidas de los sistemas.

Palabras claves: bioetanol, dinámica de sistemas, modelamiento, sostenibilidad, teoría de viabilidad

GRAPHICAL ABSTRACT



Source: Authors.

Graphical abstract: Behavior of sustainability indicators in several regions in a prospective evaluation. The figure shows 3 scenarios: desired scenario in green, alert scenario in yellow, and undesired scenario in red. The figure shows the evolution of an indicator of sustainability from an initial condition in the alert scenario. Note that from some evaluation time until a final time , the indicator state is in the region of the desired scenario (hatched area)

1 INTRODUCTION

The application of sustainability measurement is currently an important topic in scientific community research and government programs in several countries in the world (Nabavi et al., 2017). The biofuels sector (Bioethanol, biodiesel, and Biogas) is one sector where sustainability is implemented and evaluated. Bioethanol is a biofuel produced from a biochemical process named fermentation of sugars, that sugars are obtained from crops or biomass of cropses. It is a promising energy source because it has advantages over gasoline in terms of energy efficiency and emissions reduction. (Nigam and Singh, 2011; Zabed et al., 2017) Bioethanol production policies are currently focused on creating projects and sustainability standards, which is encouraging many countries to explore the use of biofuels in their energy systems. Biofuels have the potential to partially replace fossil fuels, reduce greenhouse gas emissions, increase the diversity of the energy mix, create jobs, and promote rural development. However, there are concerns about the potential environmental and economic impacts of biofuel production (Valencia and Cardona, 2014).

Bioethanol is the most technologically mature biofuel derived from microorganisms and a good candidate to replace fossil fuels (Zerva et al., 2014). Bioethanol is recognized as a promising energy source compared to gasoline because it has advantages in terms of energy efficiency and reduction of emissions. According to Nigam and Singh (2011), one liter of ethanol can contribute 66% of the energy provided by one liter of gasoline, but bioethanol has a higher-octane rating than gasoline. This improves the gas mileage when they are mixed in fuel for transportation. By blending bioethanol with gasoline, we can also oxygenate the fuel mixture so that it burns more completely and reduces polluting emissions (Zabed et al., 2017). That is why it is used as an additive in gasoline.

Biofuel production policies are currently focused on creating a production with sustainability standards. This is urging several nations to explore, implement, or consider the opportunity to introduce the production of biofuels from different feedstocks in their national energy systems (Pacini et al., 2013). "All of this is also encouraged because biofuels have been considered as an option for partially replacing fossil fuels" (Mata et al., 2013) and for reducing emissions of greenhouse gases, increasing the diversity of the energy mix, creating jobs, and promoting rural development (Scarlat and Dallemand, 2011). "However, concerns remain about the potential direct and indirect impacts for sustainable development, especially the contribution to greenhouse gases, food safety, environmental effects, and economic development, which are still discussed in different contexts" (Valencia and Cardona, 2014).

Thus, the search for sustainable development as an adaptive process of learning by doing may be more comprehensible from the formulation and application of sustainability indicators (Dale et al. (2013); Pupphachai and Zuidema (2017); Evans et al. (2009)). Ahi and Searcy (2015) and Banos-González (2016) suggest that more research is needed to identify specific indicators that can be used to measure sustainability. In response to this need, sets of indicators have been developed to assess sustainability in biofuels production. One such set of indicators was proposed by the Global Bioenergy Partnership (GBEP) in 2011. This set consists of 24 indicators that can be used to assess and monitor bioenergy sustainability at the national level. "This was the first global consensus of governments to assess sustainability in the use of bioenergy through indicators. These indicators are based on the three pillars of sustainability: economic sustainability, social sustainability, and environmental sustainability". The GBEP indicators focus on the national and/or regional market level and consider biofuel throughout its lifecycle (Hayashi, Ierland, and Zhu, 2014). The use of these indicators provides a tool for generating and analyzing information. They are useful for sharing and comparing and for facilitating decision-making by different stakeholders in building sustainability policies in different contexts (Díaz-Chávez, 2011).

However, the assessment and monitoring of these indicators are done based on historical data and present and past behaviors. This is useful for learning the current states of the system but does not enable the visualization of the evolution of the system or its future behavior. Thus, this paper proposes an approach that strengthens current methods by including System Dynamics to better describe future states of a system through simulations and defining desired regions of sustainability.

In this line, a tool, a way or a method for modeling systems that allow the study of chance and necessity is required, as well as a method that shows emergent behaviors demonstrating the existence of adaptation. These concepts are developed in Viability Theory.

In Viability Theory, chance is a choice (ordinary differential equation) between the possibilities given by an evolutionary engine (differential inclusion) and necessity is a condition on the system states. In this way, each evolutionary path of the system (opportunity) represents an adaptation made by the system because of the environmental constraints (necessity). A change of a system is the same as the concept of chance in Viability Theory. Thus, aim objective of this study is to make an original contribution to the biofuels sector, developing a tool that involves the ideas of chance, necessity, and adaptation, developed in the context of System Dynamics methodology and Viability Theory to prospectively evaluate the sustainability indicators established by the GBEP.

The proposal of this work for sustainability assessment in biofuel sector is presented with a specific example of bioethanol production from sugarcane in Colombia, where constraint conditions were defined for the state variables, giving, as result, delimited prospective regions (desired, undesired, and alert) that must be included for sustainability assessment in all contexts.

The paper is organized as follows: Section 1 presents the introduction with background information of the bioethanol sector in Colombia. Section 2 presents the methodology for the assessment of sustainability. Section 3 presents the results with a case study supply chain of bioethanol production from sugarcane in Colombia and the whole process of modeling, linking the GBEP indicators. After that, presents the results, discussion, and some suggestions for future work, and Section 4 presents the conclusions and directions for the modeling and assessment of sustainability indicators for biofuels.

MATERIALS AND METHODS 2

Supply chains are dynamic and complex, and modeling is an important tool for their analysis and design. System Dynamics is a modeling and simulation methodology used for dynamic problems. "It provides a set of conceptual and quantitative methods that can be used to represent, explore, and simulate the complex feedback and non-linear interactions among system elements" (Forrester (1961); Sterman (2000)). In System Dynamics, the main parts of a system are defined and represented as the causal interactions among attributes that describe it. A systemic representation is built, named a causal loop diagram. Consequently, a mathematical model and stock and flow diagram are then used for simulation purposes, followed by a testing phase (Ibarra and Redondo (2015); After the tests, it is possible to evaluate several prospective scenarios, making a variation of parameters, this can represent strategies or policies that can improve the behavior of the system based on the desired objectives. Ahmad et al. (2016).

System Dynamics is particularly useful for analyzing supply chains for biofuels such as sugarcane bioethanol due to their dynamic nature and complexity of production processes. It attempts to simulate the behavior of systems over time. This methodology can help in the analysis and problem solving of supply chain management (Tako and Robinson, 2012). Several studies have used System Dynamics to assess sustainability in different sectors, including the biofuels sector (Nabavi et al. (2017); Zhang et al. (2017); Dace et al. (2015)). Specifically in the biodiesel and bioethanol sector, it has also been used to obtain prospective scenarios for environmental and social impacts (Musango et al. (2012), Robalino-López et al. (2014), Demczuk and Padula (2017)).

After obtaining the model, it is necessary to determine whether the system evolves through desired states that correspond with the sustainability objectives of the sector. To achieve this, some basics of Viability Theory such as Chance, Necessity, and Adaptation have been linked.

The concept of Chance is included in this evaluation of sustainability indicators in the biofuel sector because production systems are constantly changing over time due to market dynamics and the energy transition policies. Therefore, changes in the production chain cannot be ignored when evaluating sustainability indicators.

The Necessity concept is included because any changes in the system may not necessarily meet the desired goals from different business model and sustainability trend. It is important that the state of the system meets certain restrictions to ensure that business continuity and sustainability goals are achieved (Aubin, 1992).

The Adaptation concept is important in this context because the systemic constitution of any productive sector, including biofuels, occurs as an adaptive response of the sector to remain in the market. Adaptation is the direct response of the systems to the concepts of Chance and Necessity (Aubin et al., 2011). Therefore, there is a need for a method of representing systems that would allow the study of Chance and Necessity and that would also show emergent behaviors demonstrating the existence of Adaptation.

The systematic organization of the methodological framework developed to evaluate sustainability indicators in the biofuel sector is described below in Figure 1.

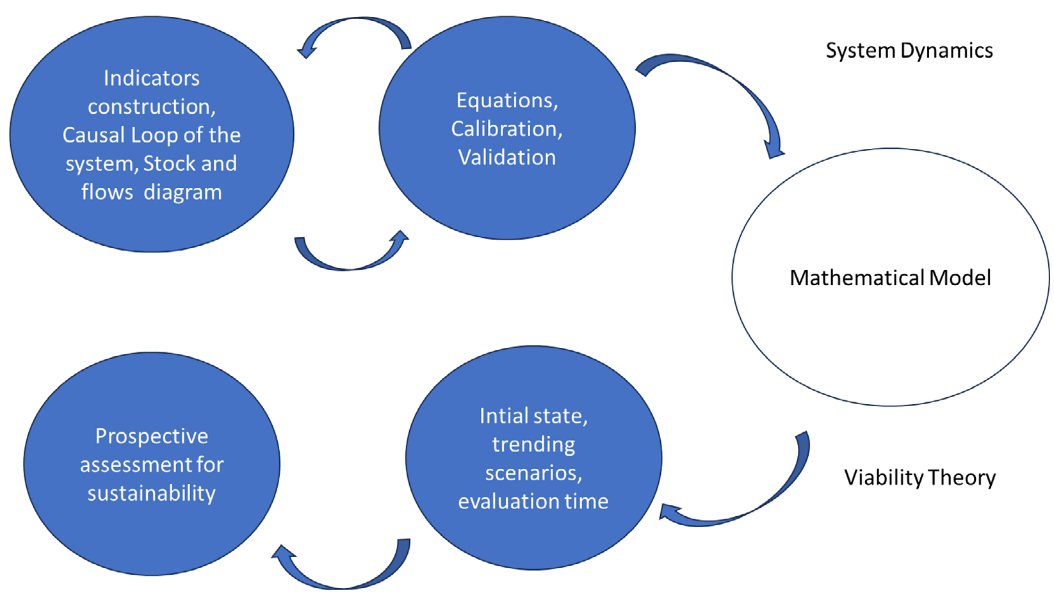


Figure 1. Framework for the assessment of sustainability in biofuels. This propose was developed using system dynamics and viability theory

Source: Authors made from Sterman (2000); Walters et al. (2016); Ziemele et al. (2017); Ibarra-Vega (2017).

Modeling with System Dynamics

One of the methods commonly used for the representation of production systems is System Dynamics methodology (Aracil and Gordillo, (1997); Sterman, (2000)). This systemic representation methodology is based on the establishment of causal relationships between attributes of the represented system, which will be considered as state variables, rates of change, auxiliary variables, and parameters, resulting in a deterministic mathematical model of the system.

The first step is to model the system under study. Thus, we start by building a model of the biofuel supply chain to be evaluated. Specifically, as is widely known, System Dynamics consists of three main phases: conceptualization, formulation of the model, and model evaluation (Aracil and Gordillo (1997); Sterman, (2000)).

System Dynamics methodology is a commonly used method for representing production systems (Aracil and Gordillo, 1997; Sterman, 2000). This methodology is based on the establishment of causal relationships between attributes of the represented system, which will be considered as state variables, rates of change, auxiliary variables, and parameters, resulting in a deterministic mathematical model of the system. The first step in using this methodology is to model the system under study. Specifically, System Dynamics consists of three main phases: conceptualization, formulation of the model, and model evaluation (Aracil and Gordillo, 1997). In this case, we start by building a model of the biofuel supply chain to be evaluated.

The aim of the conceptualization phase is to understand and become immersed in the problem being studied. Here, we need to do what is usual in the scientific method, such as a review of the state of art. This allows a clearer view of what is to be modeled so that we can identify some parts of the system of interest and their interrelationships, which leads us to build a dynamic hypothesis and a causal diagram with feedback structures.

Once the causal diagram is built, based on the attributes of interest identified in the system, we find the formulation phase, in which we can carry out a redrafting of this diagram in the formal language used in System Dynamics, which is the stock and flow diagram. With this diagram, the mathematical model representing the system is built. These equations can be introduced into simulation software, which in the case of this paper was Vensim Ple.

After programing the mathematical model in the simulation software, we proceed to make model runs, which, through graphic behavior of the variables, make it possible to see whether there is a consistent relationship between the dynamic hypothesis and the formulated model. This is done in order to know whether the model is potentially useful. Continuing with the evaluation, it is important to determine the sensitivity of the model in relation to its parameters.

Prospective evaluation and viability

The second step is to determine whether the system evolves through desired regions that correspond to the objectives of the sector and sustainability goals.

In this sense, the ideas of chance, necessity, and adaptation developed in the context of the methodology of System Dynamics and Viability Theory are involved.

From the systemic and mathematical representation achieved with System Dynamics methodology, we can perform different types of analysis of the orbits of the system. For example, a study of the invariant sets of the system and the changes that may occur in these sets when the parameters are varied could be performed, through applying the Theory of Nonlinear Dynamical Systems. But, the purpose of this paper is to determine how the orbits evolve in near time periods, that is, to study the transient behavior and to determine whether, when they evolve, they do so in the desired regions. To find out whether the system evolves through desired regions that correspond to the objectives of the sector and sustainability goals, Viability Theory (Aubin et al., 2011) has been used.

Viability Theory is used to design and develop mathematical and algorithmic methods to investigate the adaptation of the states of complex systems to their viable evolution sets (Aubin, 1992). The purpose of Viability Theory is to attempt to directly answer the question of dynamic adaptation of uncertain evolutionary systems to environments defined by constraints (Aubin et al., 2011).

Viability theory makes it possible to determine whether these thresholds (i.e., viability constraints) can be satisfied, and, if so, for what states of the system (Domenech et al., 2014). These constraints can be named sustainability regions.

Thus, the methodology performed seeks to establish whether future states of the productive system, that is, its indicators, are desired states. We call this: the prospective evaluation of sustainability indicators.

The development of the methodology proposed for carrying out the prospective evaluation of sustainability indicators begins with the presentation of the following elements:

- ***Initial system state or baseline $x(t_o)$***. The initial state is the state that describes the first condition of the system. If is the vector representing the system state for any time t then the initial state is represented as $x(t_0) \in \Omega \quad R^n$, where Ω is the space of all possible states that could be adopted by the system.

- ***Assessment time t_e***. This is the time when the evaluation of the system indicators will be done; thus, it is expected that if $t = t_0$ defines the time of the initial state of the system, the evaluation time $t_E \quad R_+$ will be greater than the time of the initial state, that is to say, $t_e > t_o$.

- ***Trending scenarios A_i***. Trending scenarios A_i are partitions of the state of spaces of the form $A_i=\{x \quad \Omega \quad R^n: a_i \leq x_i \leq b_i, i=1,\dots,n\}$ that satisfy two conditions: 1) the intersection of the scenarios must be empty ($A_i \cap A_j = \phi$)) and 2) the union of the scenarios must be the space of possible states for the application ($A_i=\Omega \quad R^n$).

For the assessment of sustainability in the biofuels sector, we have defined the following three scenarios:

1. Desired scenario A_D
2. Alert scenario A_A
3. Undesired scenario A_N

Thereore, the system has the desired values for the time of evaluation when for the time of evaluation and any future value after it in a well-defined time interval, the system is in the region of the desired scenario (t $[t_e,t_f]$ $x(t)$ A_D), (Figure 2).

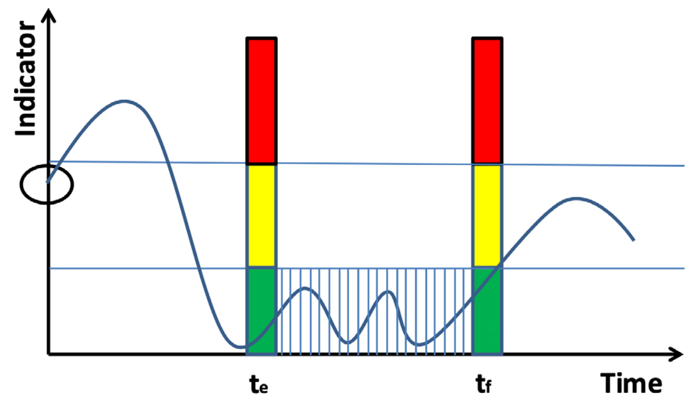


Figure 2. Prospective evaluation of sustainability indicators. The figure shows three scenarios: desired scenario in green, alert scenario in yellow, and undesired scenario in red. We also see the evolution of an indicator of sustainability from a certain initial condition in the alert scenario. Note that from some evaluation time t_e until a final time t_f, the indicator is in the region of the desired scenario (hatched area)

Source: Ibarra-Vega (2017).

Therefore, behaviors such as those presented in Figure 3 do not comply with the mentioned conditions because, although the system is in the region of the desired scenario for one of the evaluation times, its later condition evolves in the region of other scenario; that is, $x(t_e)$ A_D but $x(t)$ A_D, $\forall t \in (t_e,t_f]$ (Figure 3).

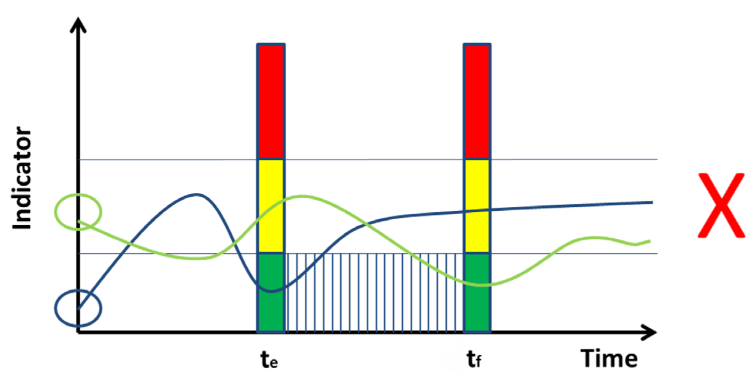


Figure 3. The orbit of the indicator reaches the desired scenario at the evaluation time but evolves into other scenarios

Source: Authors.

The purpose of the prospective evaluation is for the decision makers to know whether they will reach the goals set for the indicators or whether they should apply some types of actions that will allow them to achieve these goals and to experience these actions through simulation before implementing them.

Now, it may also occur that, $x(t_e)$ A_D, but for time values after the evaluation time, x A_D. Then, what we can assume is that the evaluation time has been inadequately established or that the evaluation time is too early for the fulfillment of the goals to be reached.

Statistics analysis

For the simulation of the model and to generate real trend scenarios with behaviors that represent reality, statistical analyzes of behavior validation were carried out, for this, parameter values were obtained based on the existing information, in this way, the calculation of the parameters was carried out, associated with the growth of sugarcane cultivation and bioethanol production using multi-year growth averages.

$$\%\text{Increase}= \left(\frac{\textit{Final Value}-\textit{Initial Value}}{\textit{Initial Value}}\right)*100$$

And,

$$\%\textit{Increase prom} = \frac{\sum_{i=1}^{n} Xi}{n}$$

To review the trend behavior, the *MAPE*, the Average Absolute Percentage Error of three main variables of the bioethanol supply chain, was calculated. The formula used is the following:

$$MAPE = \frac{100\ \%}{n}\sum_{i=1}^{n}\left|\frac{Real_i - Simulated\ i}{Real\ i}\right.$$

In System Dynamics, it is allowed to have MAPE of up to 15% depending on the object of the model. It should be noted that from the methodological point of view, these models are perceived as models of trend behavior and not predictive models. Once the bioethanol supply chain model has been simulated, it is necessary to carry out statistical tests for validation and to relate the dynamic hypothesis, the structure of the model, and its behavior (Cárdenas, 2015). In System Dynamics models, exist different validation criteria or techniques established by (Barlas, 1989) where, mainly, the validation of the structure and behavior is required.

To validate the behavior, the Monte Carlo method, also known as multiple probability simulation, was employed. In system dynamics, sensitivity analysis using Monte Carlo is a technique that allows us to assess how variations in model parameters influence the model's behavior. This is achieved by iteratively running the model with different randomly generated parameter values. This allows the modeler to see how the model's output varies over a range of possible parameter values. Section 3.1 presents the results of the statistical analyzes described here.

RESULTS AND DISCUSSION 3

RESULTS

For implementation of the proposed framework, a supply chain of bioethanol from sugarcane was modeled, as shown in the Figure 4.

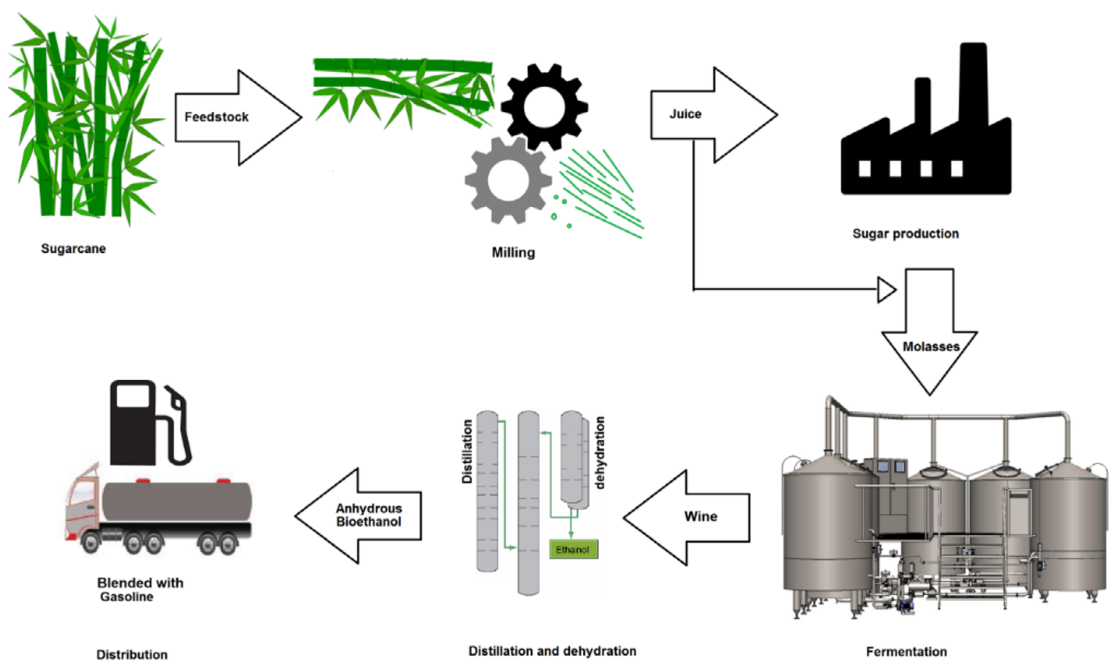


Figure 4. Limit of the supply chain of bioethanol used in this study

Source: Authors.

Description and modeling of the system

In Colombia, bioethanol is produced from sugarcane, due to the production of this type of plant is widely consolidated in the country and this crop has higher energy efficiency compared to other raw materials from which bioethanol can be produced. In Colombia the crops of sugarcane take place mainly in the Cauca River Valley, in the departments of Valle , Cauca, Risaralda(CUE- Consortium, 2012).

For this paper, we took as base a bioethanol supply chain of sugarcane, presented in CUE- Consortium (2012) and Valencia and Cardona (2014). The main links in the chain of bioethanol are producing sugarcane (hectares of sugarcane), processing of raw materials, production, and transportation (Ibarra-Vega, 2016). Below the key attributes that were identified to obtain and define the system to be studied and that describe the parts of the supply chain of bioethanol are shown and defined.

- Sugarcane area: Refers to the total of hectares of sugarcane planted for the production of bioethanol.
- Net increase: Refers to the rate of increase in the value of hectares for sugarcane production.
- Harvested: Refers to the amount of hectares harvested that are conconducted for the production of bioethanol.
- Preparation of sugarcane: Refers to the cleaning and grinding process of harvested sugarcane
- Installed capacity: Refers to the bbioethanol maximum production of bioethanol in liters, in the country.
- Sugarcane juice: Refers to the number of liters of sugarcane juice obtained for fermentation.
- Bioethanol production: Refers to the production process in function of production rate of fermentable juice and installed capacity
- Produced bioethanol: Refers to the accumulation of produced bioethanol, in liters
- Distribution: Refers to the total volume of bioethanol for blending with gasoline.
- Productivity: Refers to an indicator that shows the volume of bioethanol produced per hectare of sugarcane.

After identifying the main variables, of the sugarcane supply chain, it is possibly create a basic causal diagram. Reinforcing loops are represented by the letter "R" and balancing loops are represented by the letter "B". There are four balancing loops (B1-B4) and two reinforcing loops (R1, R2). The causal loop diagram is the base to obtain the stock and flows diagram (Figure 6).

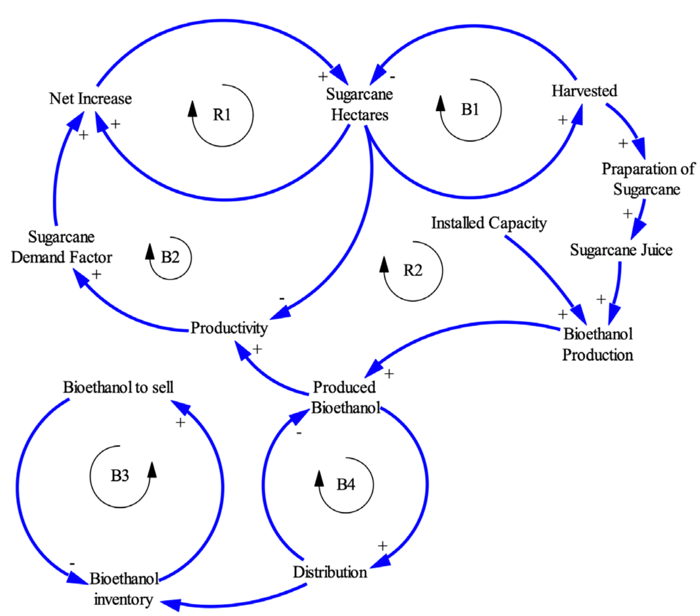


Figure 5. Causal loop diagram of the studied system of bioethanol

Source: Authors.

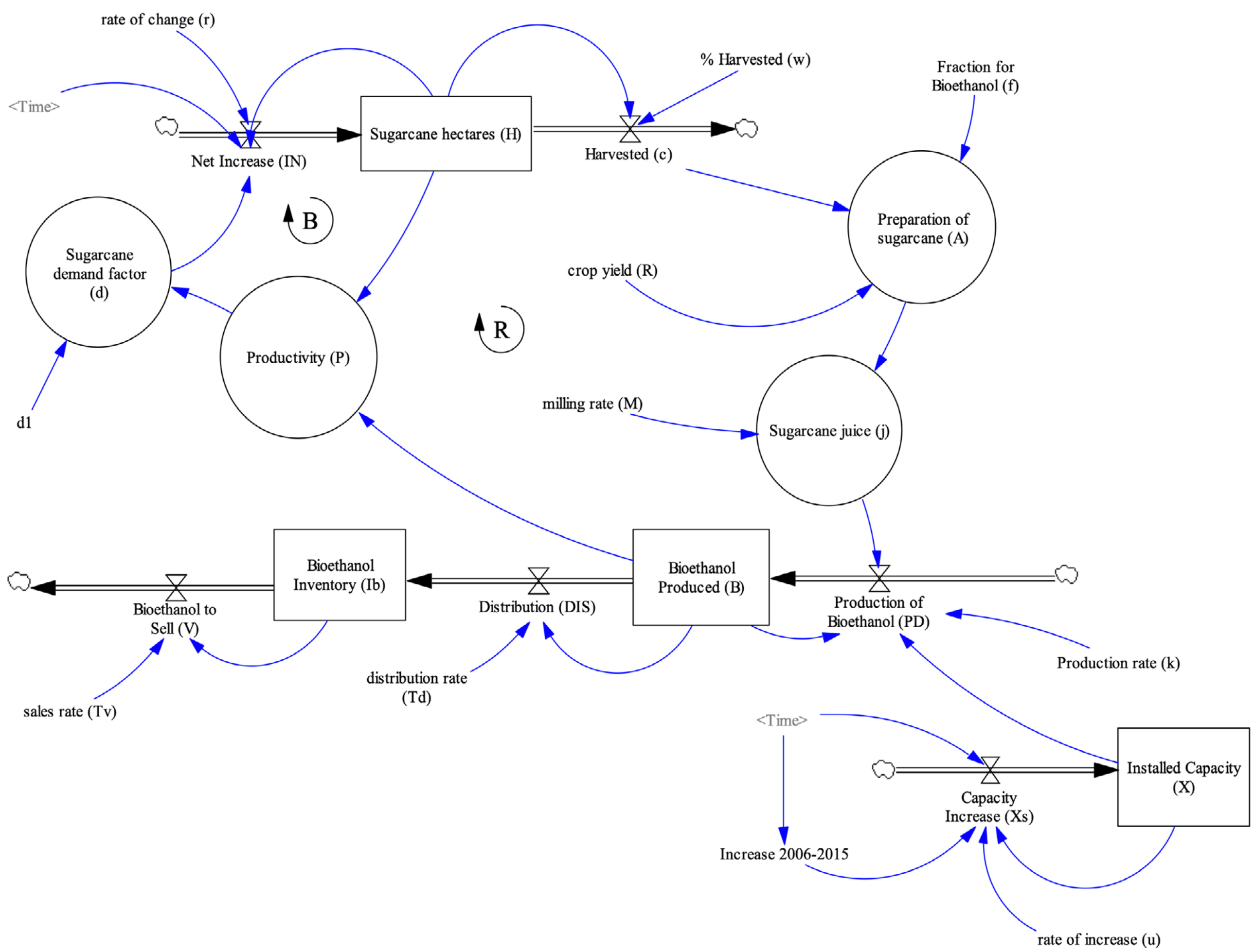


Figure 6. Stock and flows diagram of of the studied system of bioethanol

Source: Authors.

From the stock and flow diagram the responding differential equations of the system are obtained, those represent the evolution in time of the state variables of the system (Sterman, 2000). Thus, it can say that the number of hectares of sugarcane planted is given by:

$$\frac{dH}{dt} = IN - C, \text{ (Equation 1)}$$

where IN is the net increase given by changing a demand factor, *d*, in relation to the time and number of hectares of planted sugarcane and is defined by a piecewise function. *r* is a parameter to increase the number of hectares of sugarcane according to historical data from sugarcane crops in Colombia; this is related to the time steps ti and tj.

$$IN = \begin{cases} H + (H \cdot r) \; if \; t < ti \\ H + (H \cdot r) \cdot d \; if \; t \geq tj. \end{cases} \text{ (Equation 2)}$$

The harvested flow variable, C, is the number of hectares of sugarcane that are harvested per a fraction of the number of hectares, w. This is given by:

$$C = Ha \cdot w \text{ (Equation 3)}$$

The flow variables IN and C are measured in hectares of sugarcane, ha.

The amount of bioethanol produced is estimated annually; it accumulates in bioethanol produced variable, B, which is given by the difference between the production of bioethanol, PD, and distribution, DIS.

$$\frac{dB}{dt} = PD - DIS \text{ (Equation 4)}$$

the production of bioethanol is modeled as a piecewise function:

$$PD = \begin{cases} x \text{ if } B \geq x \\ j.k \text{ if } B < x \end{cases} \text{ (Equation 5)}$$

In turn, the sugarcane juice j is defined by the product of the efficiency R and the auxiliary variable sugarcane preparation, A, which is a function of the crop yield, R, the milling rate, M, and the fraction for bioethanol, f, expressed as follows:

$$j = A \cdot M, \text{ where}, A = (R \cdot C) \cdot f \text{ (Equation 6)}$$

k is the percentage production rate parameter. The installed capacity x in this model is represented by a capacity increase as a Table function $f(x)$ and a rate of increase, u, as follows:

$$\frac{dX}{dt} = \{f(x), X \cdot u\} \text{ (Equation 7)}$$

The variable flow distribution, *DIS*, is given by the product of bioethanol produced and a distribution rate, Td

$$DIS = B \cdot Td \text{ (Equation 8)}$$

The amount of inventory of bioethanol, Ib, is represented by the difference between what is distributed, *DIS*, *to* stock and what is sold, V:

$$\frac{dIb}{dt} = DIS - V \text{ (Equation 9)}$$

Sales relate to a constant sale rate Tv:

$$V = Ib/Tv \text{ (Equation 10)}$$

To estimate the net increase, it is associated with a demand factor, d, which is modeled as a piecewise function of the productivity, P. A parameter threshold for increasing the demand factor is defined as n. In this way, the productivity P is defined by the amount of bioethanol produced B in the number of hectares of sugarcane aimed at production, ha, as follows:

$$P = \mathrm{B/H} \text{ (Equation 11)}$$

$$d = \begin{cases} d_1 \text{ if } P \geq n \\ d_2 \text{ if } P < n \end{cases} \text{ (Equation 12)}$$

Statistics analysis and validation

For the validation of the structure, the estimation of the parameters began, with this, it seeks to justify the value of the parameters of the model with the historical information (Cárdenas, 2015), in this case, with the information of the actual production of bioethanol from sugarcane in Colombia. The parameters that were considered in the supply chain model are presented in Table 1. The estimation of the most important parameters, such as the net increase in sugarcane cultivation and the increase in bioethanol production, are presented in Table 2 and Table 3. For the net increase of cane and the increase in installed capacity, the validation consisted mainly of finding the average values of annual production of bioethanol and the installed capacity from 2006 to 2015, based on this it was estimated the rate of net annual production increase of bioethanol and was included in the model. In Figure 7, a comparison of behaviour between bioethanol production historical data and simulation data is presented. Figure 8 shows the behavior validation correlation between the real values and the simulated values of the area planted with sugarcane.

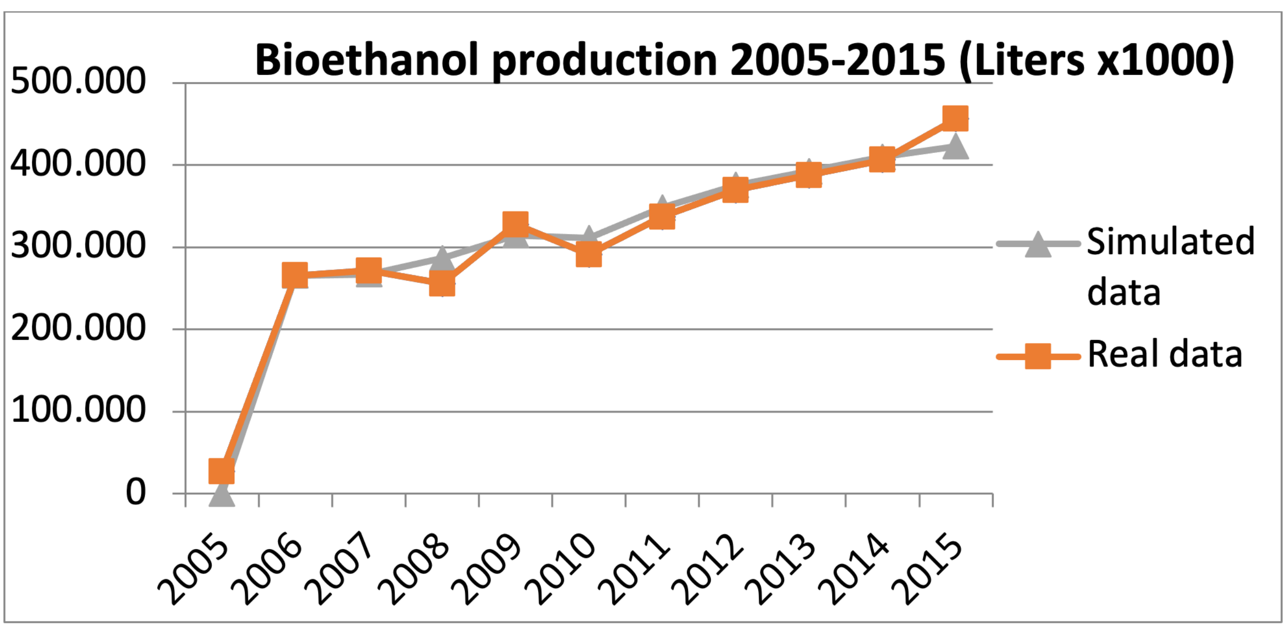


Figure 7. Comparison between bioethanol production historical data and simulation data

Source: Authors.

Table 1. Initial conditions

Parameter or initial condition	value	units	source
Harvest yield	118	Ton/Ha	CUE, 2012
Milling yield juice	70	Liters/Ton	CUE, 2012
Net increase of sugarcane area	Prom of 2006-2015	Percentaje	Asocaña, 2016
Increase capacity	Prom estimated 2006-2015	Percentaje	Asocaña, 2016
sugarcane area (Net)	203.184	Ha	Asocaña, 2012
Bioethanol produced	265.684	Thousands of liters	FedeBiocombustibles, 2015

Source: Ibarra-Vega (2016; 2017); CUE- Consortium (2012).

Table 2. Estimated rate of increase in sugarcane cultivation

Year	Net area planted National (hectares)	Net Increase (Calculated)
2006	203.184	NA
2007	202.926	-0,1270
2008	205.664	1,3493
2009	208.254	1,2593
2010	218.311	4,8292
2011	223.905	2,5624
2012	227.748	1,7164
2013	225.560	-0,9607
2014	230.303	2,1028
2015	232.070	0,7673
	Average	1,499

Source: Authors.

Table 3. Estimate of rate of increase in Bioethanol Production

Year	Production (Thousands of liters).	Production (Simulation)	Net increase (%)
2006	265.684	146.000	NA
2007	271.773	284.223	2,29
2008	255.584	304.196	-5,96
2009	327.705	322.045	28,22
2010	291.286	343.088	-11,11
2011	337.398	362.915	15,83
2012	369.722	385.776	9,58
2013	387.859	409.477	4,91
2014	406.468	431.624	4,80
2015	456.403	444.329	12,29
		Increase average	6,760

Source: Authors.

Table 4. Milled sugar cane and Hectares of planted sugar cane

Year	Milled sugarcane (Tons)	Milled sugarcane (Tons) (Simulation)	Net area planted National (hectares)	Net area planted National (hect-ares) (Simulation)
2006	22.019.933	21.907.400	203.184	203.184
2007	21.090.203	22.250.100	202.926	206.297
2008	19.207.728	22.587.400	205.664	209.424
2009	23.588.646	22.929.800	208.254	212.599
2010	20.272.594	23.277.400	218.311	215.822
2011	22.728.758	23.630.300	223.905	219.094
2012	20.823.629	23.988.600	227.748	222.416
2013	21.568.243	24.352.200	225.560	225.788
2014	24.283.248	24.721.400	230.303	229.211
2015	24.205.089	25.096.200	232.070	232.685

Source: Authors.

As a complement to the validation of the behavior, the calculation of the Average Absolute Percentage Error (MAPE) was used, which calculates the accuracy of the model trend, defining a MAPE up to 30% as valid (Barlas, 1989, Bautista, 2016). The MAPE synthesis is presented in table 5, was calculated using the information presented in table 4, for Milled Cane, Planted Cane Area, and Produced Bioethanol (The most important for the supply chain), the values generated by the model were compared with the historical values collected between 2006 and 2015.

Table 5. MAPE simulation of three main variables

Variable	MAPE 2006-2015 %
Ground cane	7.217
Net area planted National	0,016
Bioethanol Produced	6,742

Source: Authors.

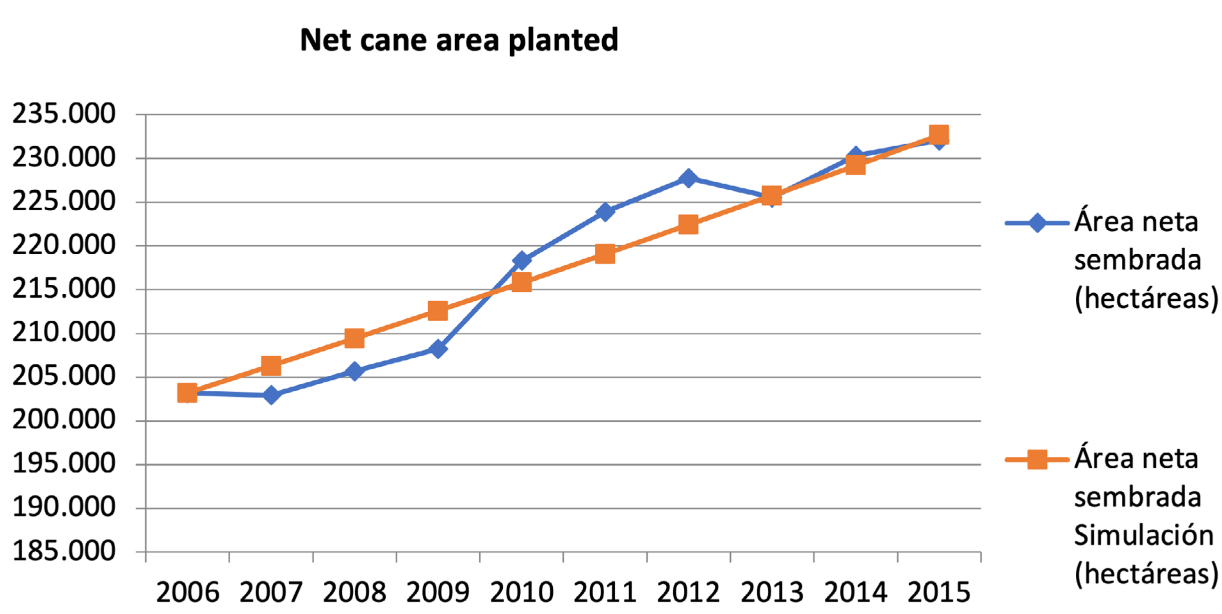


Figure 8. Comparison between historical data of sugarcane hectares and simulation data

Source: Authors.

Sensitive analysis with Montecarlo in Vensim

Sensitivity analysis is a technique used to assess how the uncertainty in the output of a model or system can be divided and allocated to different sources of uncertainty in its inputs. It is a what-if analysis that helps you understand how changes in the input variables of a model will affect the output.

The results of the numerical sensitivity analysis that were performed on the initial model are shown below. Numerical sensitivity exists when changes in the assumptions change the numerical results (Valencia, 2017). This test was performed using Vensim Plus software. This software can do repeated simulations in which the selected model parameters are modified, for each simulation. This can be very useful for understanding the behavior limits of a model. For the variables Produced Bioethanol, Sugarcane area planted, and productivity, it is possible to see the evolution with modifications in the demand growth rate (d1) with values (0.4 to 1.05), the initial value of the demand is 1. The behavior of the variables shows a possible reduction of up to 60% and a slight increase, above the current demand. This allows us to see the great sensitivity that the model must market demand.

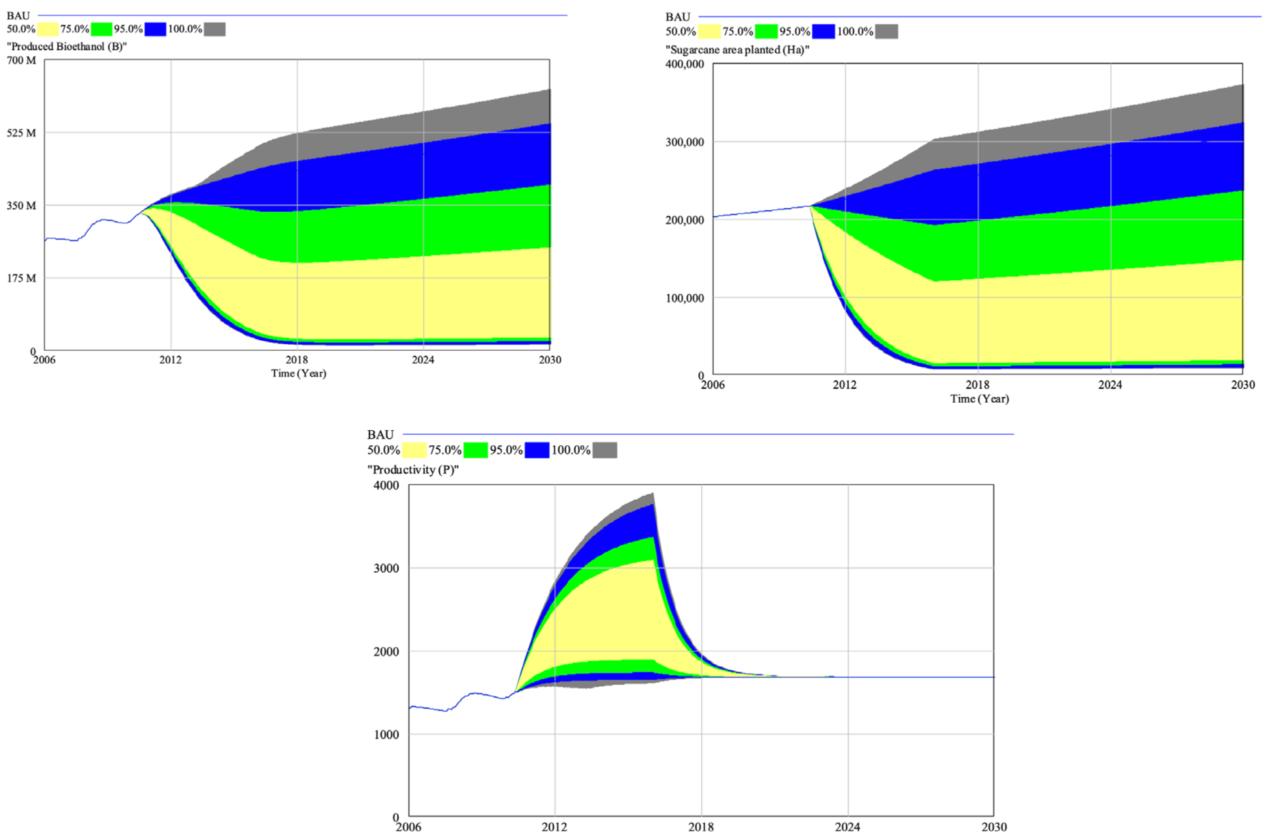


Figure 9. Numerical sensitivity analysis, Montecarlo method with Vensim, for three variables

Source: Authors.

Indicators

Once the mathematical model of the supply chain has been defined and validated, we proceed to link the social and environmental variables, considering the causal diagram constructed (Figure 5). Thus, a connection to environmental and social indicators generated from the supply chain is displayed.

For this paper, two indicators were chosen from those proposed by GBEP (2011): one from the environmental pillar and the other from the social pillar. The environmental indicator is water consumption, and the social indicator is jobs in the whole of the supply chain. Later, the indicators must be represented in a stock and flow diagram to obtain the equations representing the temporal evolution.

Once the model of the bioethanol production chain has been built, we proceed to model the indicators to be evaluated. When modeling these indicators, we considered the information of a production chain of 450 million liters of bioethanol per year in Colombia.

Use and water efficiency indicator

This indicator can measure the volume of water withdrawn from a watershed for the production and processing of bioenergy feedstocks per unit of bioenergy output (GBEP, 2011). In this case, the indicator was modeled considering the estimated water consumption for growing sugarcane intended to produce bioethanol. The amount of water consumed is a function of the number of hectares of sugarcane planted.

The stock and flow diagram in Figure 9 complements the one in Figure 6. It shows the dynamics of the water consumption indicator. The stock represents the amount of water consumed, and the flow represents the rate at which water is consumed. The rate of water consumption is a function of the number of hectares of sugarcane planted.

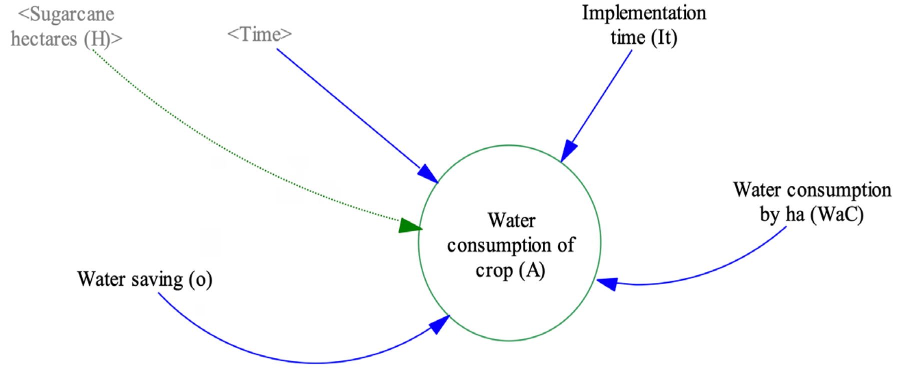


Figure 9. Water indicator int the stock and flow diagram

Source: Authors.

The initial conditions defined for the simulation of the model with the indicator of water consumption are presented in the Table 6.

The simulation model shows that the annual water consumption variable without any intervention is in the undesired scenario in 2020. This is because the amount of water consumed is not within the desired range of 1.25 billion cubic meters. Therefore, a strategy or policy is needed to move the indicator state to the desired region. We implemented water saving strategies for sugarcane cultivation, which is the activity with the highest water consumption. These strategies seek savings of 20%, 30%, and 60% in water consumption, with the combination of improved irrigation techniques.

Table 6. Water saving techniques

Saving strategy	Technical description of savings	Irrigation per hectare per year	Percentage savings
NA	BAU (Business As Usual)	9000 m^3	NA
Savings 1	ACI (Administrative Control of Irrigation)	7200 m^3	20
Savings 2	ACI and alternating groove	6300 m^3	30
Savings 3	ACI, alternating groove, and pipe with gate	3600 m^3	60

Source: CUE- Consortium (2012).

The assessment of the water consumption indicator (Annual behavior) reveals that implementing savings strategies would enhance the situation and steer the system towards the desired area. However, this improvement is only observed in the system that incorporates savings strategies 2 and 3 (refer to Figure 10). As a result of its temporal evolution, it is in the region of the desired scenario at $t_e = 2020$ and $t_f = 2025$, satisfying the proposal of this paper.

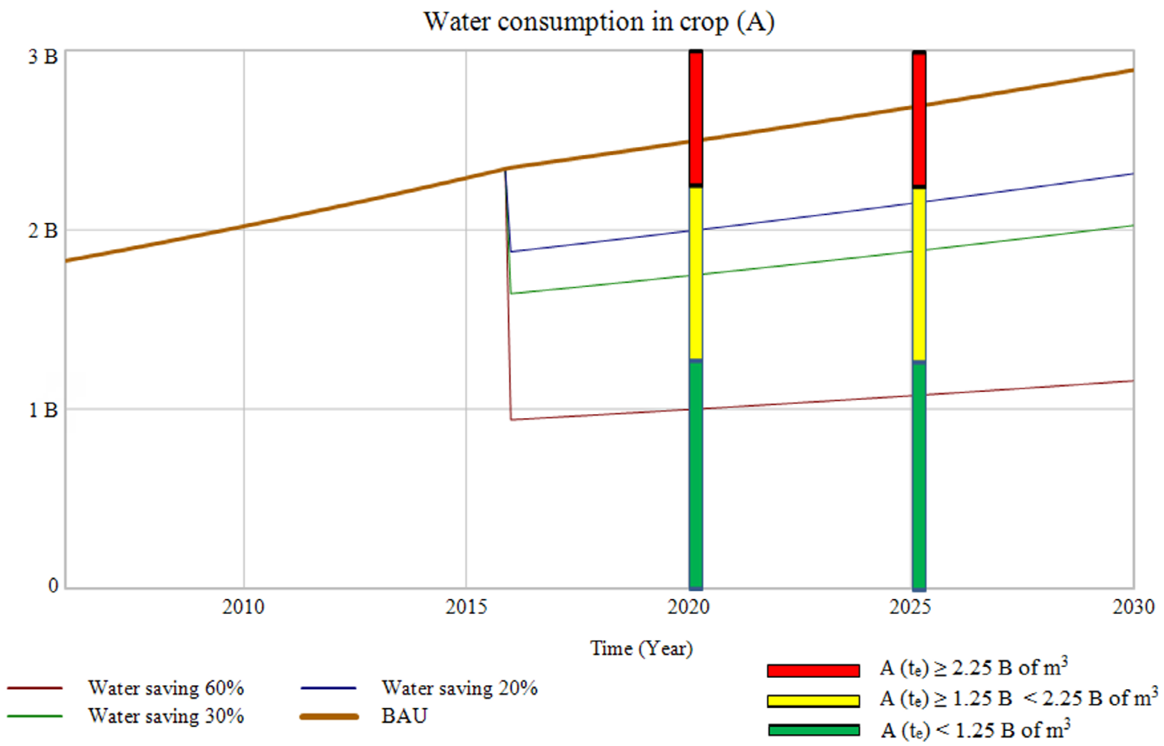


Figure 10. Prospective behavior for assessment water consumption (A) with water savings strategies

Source: Authors.

Employment generation indicator

This indicator is defined by GBEP as net job creation because of the production and use of bioenergy. We used this employment indicator in this paper, measuring it as the number of jobs generated throughout the production chain of bioethanol presented in figures 5 and 6.

The GBEP defines this indicator as the net number of jobs created due to the production and use of bioenergy. In this paper, we used this employment indicator to measure the number of jobs generated throughout the production chain of bioethanol. The causal diagram in Figure (11a) shows the link between the indicator of the number of jobs and the other variables in the model. The stock and flow diagram in Figure (11b) can model the indicator itself.

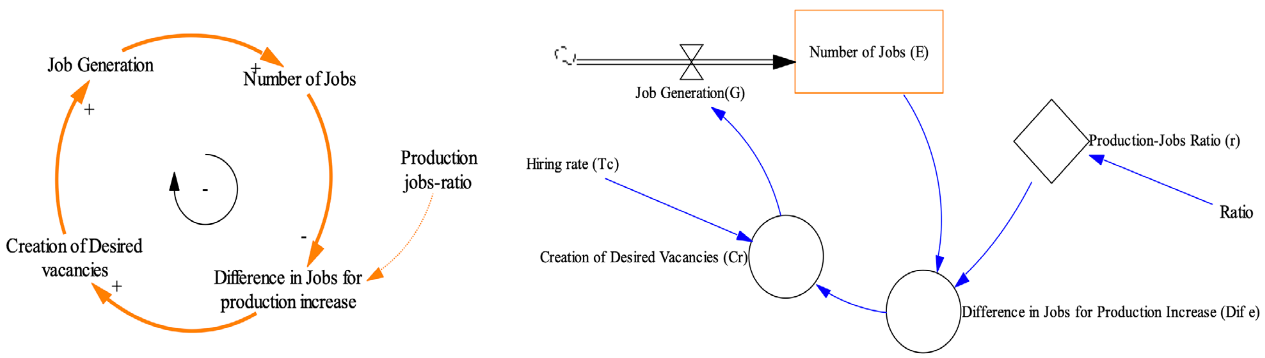


Figure 11. (a) Causal diagram of jobs indicator; (b) Stock and flow diagram of the job's indicator

Source: Authors.

The initial parameters and conditions to simulate the model are the same that were presented in Table 1. For every 300 million liters of bioethanol produced annually, there is an employment relationship of 60,000 jobs.

The evaluation results of the job indicator, without intervention of government policies, indicate that the suggested initial conditions and with the scaled-up production of bioethanol, there will be a decrease in the number of jobs. This decline leads to the undesired region (Red) by te = 2020 in the temporal progression. Consequently, it becomes crucial for the government to implement sectoral policies aimed at increasing job opportunities in bioethanol production. Additionally, monitoring the correlation between ethanol production or production growth and the generation of new jobs is essential to achieve social benefits.

Therefore, theses results of the jobs indicator indicate an improvement in the time evolution of the indicator, given by the implementation of a policy that seeks to increase the number of jobs by 10 and 50% and to decrease the number of jobs by 20% at $t_e = 2025$ in the model. The desired scenario was defined as the existence of more than 120.000 jobs.

Figure 12 shows the evaluation with three different policies affecting the employment rate. Policies in E1 and E2 are proposed by the national government. It is concluded that the implementation of policies to increase employment by 60% (E2) would improve the outlook and bring the system within the desired region, because its evolution is within the region of the desired scenario at $t_e = 2020$ and $t_e \geq t_e$

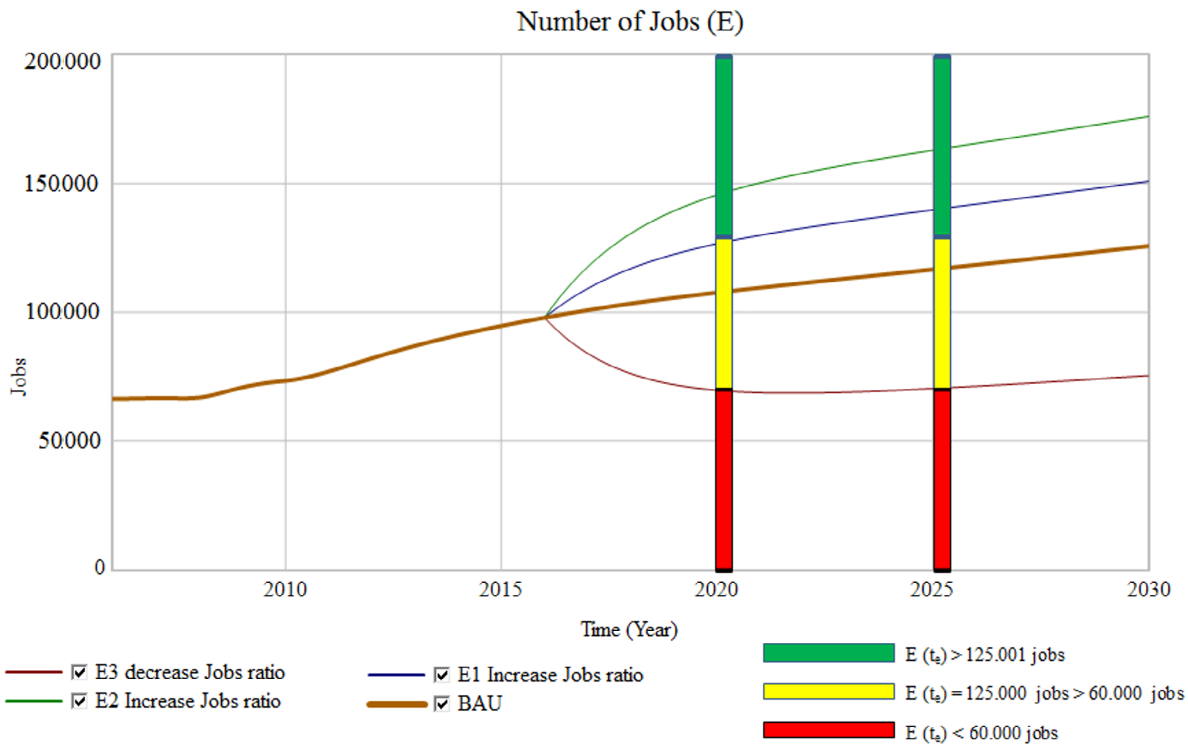


Figure 12. Prospective evaluation of number of jobs

Source: Authors.

DISCUSSION

This study created and verified the structure of a generic framework for assessing sustainability in biofuels using System Dynamics and Viability Theory. The model represents change over time through differential inclusion generated by System Dynamics modeling. The framework defines prospective regions (desired, undesired, and alert) based on constraint conditions defined on the indicators. Objective regions for the evolution of the system's states are defined as necessary. Adaptation refers to changes or parameter arrangements that represent decision rules for the system to define which satisfy viable constraints for an evaluation time interval. This perspective of Viability Theory inspires the methodology for sustainability assessment. The desired region is the same concept as the viable region.

This proposal for evaluating viable regions or the sustainability of the studied system is a good approximation under the conditions where the structure of a system intended for evaluation is known or clearly defined. The goal is that once the system is modeled, it can be identified the system's indicators or variables represent sustainability measures, allowing us to technically and prospectively define desired, alert, or undesired regions. Therefore, the initial step is to build the model that represents the problem or system under study. Without this preliminary step, the methodology proposed in this article would be restricted by lacking an adequate prospective representation.

The proposed approach can also be used as the basis for other studies of other biofuel production processes, since the integration of System Dynamics methodology and the concepts of Viability Theory performed in this paper seek to establish whether the future states of any productive system, that is, its sustainability indicators, are in the desired states. These desired states must be defined as trending scenarios of the behavior and evolution of each indicator that is going to be evaluated. Desired states should be obtained for each biofuel production assessment context, including the raw material, production scale, and supply limits. These results constitute an important level of novelty within the ongoing debate on sustainability assessment.

This paper proposes that when carrying out the prospective evaluation of sustainability indicators in biofuels production, it is necessary to consider the following general elements: the initial system state or baseline $x(t_0)$, the evaluation time t_e, and the trending scenarios A_i.

The authors have identified possible trends for further research. New considerations should be addressed to the following areas:

- Modeling additional sustainable indicators in order to increase the impact of this framework;
- Adding some policy measures;
- Including criteria to define the evaluation time;
- An accurate validation based on the structure of the system to be evaluated, historical data, and sensitivity analysis.

CONCLUSIONS 4

This paper presents a framework for sustainability-assessment indicators in the biofuel sector. The methodology involves the ideas of chance, necessity, and adaptation developed in the context of the Theory of Viability. These ideas were represented within a theoretical sugarcane bioethanol supply chain with an installed capacity of 450 million liters per year based on the methodology of System Dynamics.

This paper uses a qualitative approach to demonstrate that System Dynamics methodology can be used to represent the sugarcane bioethanol production sector or other biofuels from other sectors in Latin America and the world. The constraints, desired regions, and evaluation times of the indicators depend on the behavior of each biofuel market and on the local economy where this framework can be implemented.

The methodology developed in this research for sugarcane bioethanol in Colombia can evidence that it can be used to evaluate the future sustainability of the bioethanol and other bioufel production system. To do this, the production chain must be modeled by defining the raw material, installed production capacity, and annual increase in biofuel production. Sustainability indicators are also chosen and modeled for evaluation. After building the model, it is necessary to determine whether the system evolves through the desired regions by increasing the evaluation times and interval values according to the policies and interests of the context in which it is developed.

In the development of the research, it was possible to model and mathematically express biofuel sustainability indicators proposed by GBEP in a dynamic way, the indicators used show that it is possible to formulate dynamic indicators to carry out prospective evaluations and not static ones as they are normally formulated.

The production of biofuels is expected to increase and become a substantial part of the diversification of energy sources in Colombia, however, it is necessary to evaluate the sustainability of each market in order to explore its effects in different dimensions such as economic, social, and environmental. A framework can be used as a high-impact tool for assessing sustainability in present states and future states in economies with bioenergy production with different raw materials.

Our successful application demonstrates the framework potential to guide decision-making on biofuel development and ensure a balanced approach that prioritizes both energy security and food security. Future research could explore its applicability to other biofuels and further refine the indicators for tailored assessments.

The competition between sugarcane for ethanol production and crops for food requires clear and sustainable agricultural policies, particularly regarding water and soil nutrient consumption. Increased sugarcane planting can impact food security, especially in resource-limited areas. Therefore, we need models to find a balance between biofuel production and food production, thus ensuring a sustainable future where both energy and food needs are met for generations to come.

CONTRIBUCIÓN DE LA AUTORÍA

Danny Ibarra Vega: Research methodology, model formulation, model development, project administration, simulation, validadtion, manuscript draft, review and editing

Johan Manuel Redondo: Research methodology, model formulation, Viability Theory advisor.

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Conflicto de intereses
Los autores declaran no tener ningún conflicto de intereses.