Dynamic Model for Evaluation of Sustainability of Brazilian Ethanol Production: Elements for Modeling

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Abstract

System dynamics is an approach to analyze the behavior of complex systems, such as the productive chains, strictly considering the inherent characteristics. This approach is based on mathematical concepts of nonlinear processes developed in mathematics and physics and consolidated in engineering. The concepts inherent in this approach assists in creating a mathematical model which represents a production chain by using computer simulation. Thus, the main objective of this paper is to present the formalization of the dynamic model of assessing the sustainability of Brazilian ethanol production, its borders (external environment) and the scenarios needed for a deeper understanding of relation of cause and effect, causal loops and diagrams of flows and stocks as a result of the awareness stage, with regard to understanding the problems involved, the survey methodology known as design science.

Keywords: *ethanol, system dynamics, sustainability*

1. Introduction

1.1. Ethanol Production in Brazil

The Brazilian supply of ethanol grew in the period 1994-1998 when a crisis period began due to high inventory levels and drop in the domestic market. During this period the price of sugar in the international market has increased and consequently the supply of ethanol in the domestic market plummeted. With the fall in demand, the share of ethanol-powered vehicles decreased from 75.5% in 1985 to 0.06% in 1997, with high financial and tax costs. This picture has reversed since 2001, when ethanol engines began to be produced again. This trend has given rise to the emergence of a new ethanol industry since 2003 when entered the scene with flexible fuel engines.

Brazilian sugar and ethanol industry gathered in the biennium 2012/2013, 602 million tons of sugarcane by 8.5 million hectares. Production accounted for 38.8 million tons of sugar and 23.9 billion liters of ethanol. This represents a share of 41.8% in the total world production of ethanol, estimated at 49 billion liters. It is expected that Brazil bend the growing area of sugarcane in the next twenty years reaching a production of 40 billion liters of ethanol.

Despite the picture above, the ethanol produced from sugarcane has turned recently the subject of intense attacks by European authorities. They see the expansion of biofuel production around the world the reason for a rise in food inflation. The United Nations (UN) sentenced the biofuels, with the Special Rapporteur statement to the High Commissioner for Human Rights, that mass production is a crime against humanity for its impact on world food prices. According to Oliveira (2009), through the expansion of biofuels remains follow in question: what are the consequences for food production in Brazil with the expansion of the sugarcane crop in the next 20 years?

Data from the Brazilian Institute of Geography and Statistics (IBGE), between 1990 and 2012, show that the reduction of food production, imposed by the expansion of planted area of sugarcane, grew in this period, more than 2.7 million hectares. Taking the municipalities that had the expansion of more than 500 hectares of sugarcane in that period verify that there was reduction of 261 thousand hectares of beans and 340 thousand hectares of rice. This reduced area could produce 400,000 tons of beans, ie 12% of national production, and a million tons of rice, equivalent to 9% of the country's total. In addition, in these municipalities the milk production was reduced to 460 million liters and the amount of cattle was reduced by more than 4.5 million.

Despite the production of ethanol is being studied in various universities, research institutions, government agencies and the private sector, regional production and distribution characteristics have not been sufficiently addressed in research, but are essential to assess the risks and the consequences of such expansion in the environment and in food production.

The picture above associated with the fact that the simulations make it possible to observe the risk factors more clearly than it is possible in real scale, given the complexity of the production-distribution processes, justifies the development of a dynamic model of production based on dynamic ethanol system. In this simulated microcosm becomes possible to isolate the effects and causes more easily than when engaged by the complexities of the real world. (WARREN, 2008).

1.2. Application of system dynamics to sustainability studies

The system dynamics is an approach to analyze the behavior of complex systems, such as supply chains, strictly considering the inherent characteristics. This approach is based on mathematical concepts of nonlinear processes developed in mathematics and physics and consolidated in engineering. The concepts inherent to the methodology aid in the creation of mathematical models representing the productive chain may diagnose problematic points in chain structure using computer simulations employing an easy to understand representation.

Agarwal and Shankar (2008) argue that due to the causal relationship, existing in the production system, the approach of dynamic systems is well suited to capture the impact of the dynamic performance of the variables on the integration and responsiveness of the production system in a given time interval.

Researches on systems dynamic applied to sustainability studies are divided into three major groups:

i. Researches that contribute to the construction of theories about sustainability;
ii. Researches using the system dynamics in solving sustainability problems;
iii. Researches working in the development and improvement of modeling tools in sustainability.

The research of Chichakly and Eberlein (2013) is a typical example of the use of systems dynamic in theory construction. Studying IT service industry Minis et al (2010) proposed a new theory for the virtuous and vicious cycles, using an exploratory causal model to describe the interrelationship of the key success factors.

Morecroft (2007) uses the dynamic systems to solve strategy problems by developing a strategy management model for simulating several scenarios. Cha, Pingry and Thatchen (2008) investigated the amplification of demand in supply chains.

Research on the development and improvement of modeling tools in dynamic systems are an example in the work of Howick and Eden (2004) that studied the nature of discontinuities in system dynamics modelling of disrupted project. Another paper on the line is Arango and Osorio (2009), which considers also the technical, organizational complexity inherent to the system dynamics model for the world coffee market.

1.3. Research aims

The main aims from this study are to:

1. Identify the main variables, flows and stocks and the causal relationships of sugarcane, sugar and ethanol production processes;
2. Explore how the production of ethanol in Brazil is increasing and how this production is impacting food production;
3. Apply the modeling and simulation in system dynamics in ethanol production system.

The knowledge generated by this study allows for a more thorough discussion of the ethanol production impacts both on the environment and on food production as well as being the basis for the development of the equations that describe the behavior of variables and stocks that are at the root of the simulation process. The study concluded that beginning with the identification and characterized the elements for modeling and working with different scenarios simulation is better to understand the degree of sustainability of ethanol production.

Thus, the main objective of this paper is to present the formalization of the dynamic model of assessing the sustainability of Brazilian ethanol production, its borders (external environment) and the scenarios needed for a deeper understanding of cause and effect, causal loops and diagrams of flows and stocks.

2. Methods

The methodological framework of a research comprise in the selection and justification of a method that is able to respond to the formulated research problem, to be evaluated by the scientific community and demonstrate procedures that make robust research results. These logical steps should not be seen as obstacles to the conduct of research, but as procedures necessary to ensure the impartiality, accuracy in work driving and the reliability of results. Thus, this research adopts the methodology the science design. As this research seeks to develop an artifact (dynamic model) to design science proved to be an appropriate methodology, not only dealing with the construction of an artifact but also requiring the application of rigorous methods, both in construction and in the evaluation of the artifact design. Accuracy is often measured by the adherence of the research to an appropriate collection of data and the correct technical analysis.

To identify the variables to the model and the causal relationships, was conducted an interview during the months August and September of 2014, with a group of ethanol producers of local productive arrangement of alcohol (APLA) in Piracicaba, SP. The analysis of these interviews has concluded awareness stage with regard to the understanding of the problems involved, according to the science design methodology. Romme and Damen (2007) argue that it may be necessary to understand the issues from a broader perspective, in which systems thinking (Andrade et al., 2006), for example, could bring a significant contribution.

3. Results and Discussion

In this section we discuss the overview of the model, the causal loop diagram, the diagram of stocks and flows of ethanol production and simulation scenarios. It is used to visual system dynamics modeling tool Vensim®, software provided by the company Ventana System Inc., which enables the analyst to link words with arrows representing relations between the variables as causal relationships. The stock diagram and flow in Vensim® consists of auxiliary or constant, cash variables that represent actions or accumulations. This information is used by the equation editor to complete the modeling process.

3.1. Overview of the model

In the model, sugarcane production is considered as the most important production source, while the production of ethanol and sugar is the second level and the generation of solid waste and wastewater is the third level. The figure 1 is a schematic representation of product flows and inventory information associated with ethanol production. The model doesn't include the second-generation ethanol production, from sugarcane bagasse, because the amount of ethanol produced with this technology is small and doesn't influence the data for simulation.

The availability of land for planting is treated as being shared between sugarcane and food production, that is, it is considered a finite availability of land so that an increase in planting sugarcane implies the reduction in food crops. These increases and decreases are influenced by the planted crop productivity level. The amount of ethanol to be produced is influenced by the production of sugar, which competes in the consumption of sugar and productive resources, as well as by the level of consumption of other types of fuel such as gasoline and vehicular natural gas, in addition to suffering influence of investments in production and distribution infrastructure.

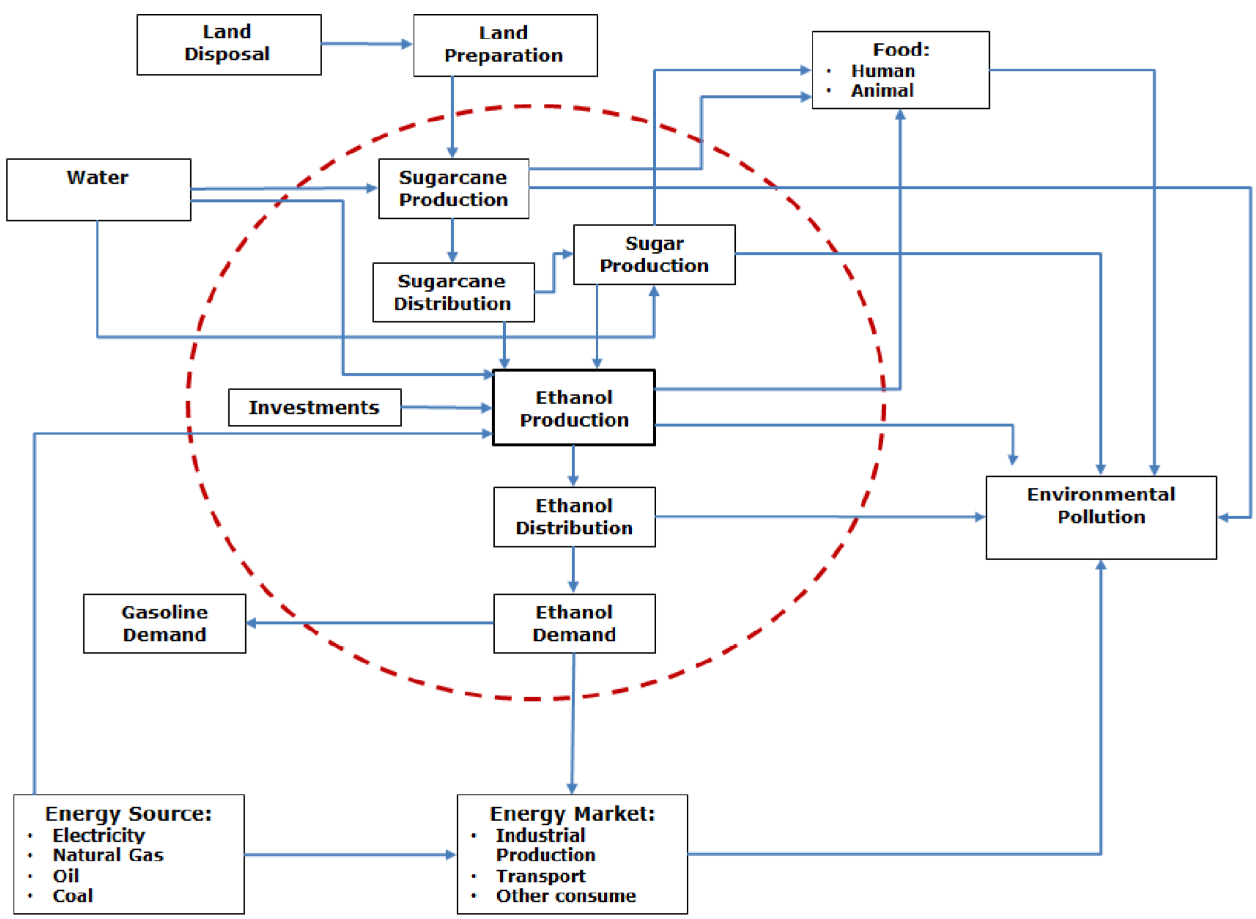

Fig. 1. Overview of the ethanol production model

3.2 Modeling

Modeling a system using the system dynamics is interactive and it's an ongoing process of formulating hypotheses, testing and review of formal mental models. According Sterman (2000), in modeling process a few steps should be considered, such as:

1) Problem Articulation - What's the problem? Why this problem? What are the key variables and concepts that should be considered? What time to be considered to the future? What is the historical behavior of the concepts and key variables?

2) Formulation Dynamics Hypothesis - Produce initial hypotheses, formulate hypotheses to explain the dynamics and consequences of endogenous feedback structure, develop maps of causal structures based on initial assumptions, key variables and other data available;

3) Formulation Simulation Model - Specification of the structure and decision rules, parameter estimation, behavioral relations and initial conditions, tests for stability with objectives and limits;

4) Testing – Does the model adequately reproduce the proposed behavior? Does the model behave realistically when subjected to extreme conditions? What is the sensitivity of the model?

5) New Policies and Evolution - What environmental conditions may arise? What new decisions, strategies and structures can be experienced in the real world? How can these new scenarios in the model be represented? What is the robustness of the recommended policies for different scenarios, considering the uncertainties? How policies interact? Are there any common actions or compensatory responses?

3.3. Simulation

From the perspective of system dynamics, any system natural or artificial, can be described through a language composed of four elements: stocks (levels), which represent accumulations of a resource; flows, which are the activities that produce growth or reduction of inventories; converters that process the information regarding the stocks and flows or represent sources of external information to the system; connectors which are coupling elements of information describing the relationship between stocks, flows and converters. In order to provide a simulation model behavior, it is sufficient to define the relationship and the value of each variable at time zero of the simulation, using for this the features available in the system dynamics software.

According to Agarwal & Shankar (2005), the performance of a supply chain depends on the integration of its trading partners and the ability to respond quickly to market changes. By simulating, the model for assessing sustainability of Brazilian ethanol production wants to evaluate the effect of integration and speed of response to changes in sustainability. The dynamics of interactions between the variables related to the integration of cause and effect and speed should show the importance of the behavior of sustainability in different ethanol production scenarios (represent market changes that require quick responses).

3.4. The causal loop diagram

This diagram shows the interactions and relationships between ethanol production, land use and water consumption, production of sugarcane and sugar. The figure 2 displays the causal loop diagram of the ethanol production system and the factors of influence. The diagram consists of multiple loops that show, for example, the production of sugarcane, sugarcane price, the government tax incentives, demand for ethanol and gasoline prices affect the production of ethanol.

Thus an increase in ethanol production influences reduction in the price which can increase the demand resulting in the increasing of the price. But an increase in the price reduces the demand for ethanol, hence the negative polarity of the link arrow. Once you have a reduction in the price of ethanol, there will be an increased demand for ethanol followed by the gap between the demand and supply of ethanol respectively. This can lead to both an increase of investment in ethanol and more allocation of sugarcane to produce. An arrow closes the cycle of positive polarity since an increase in the allocation of sugarcane to produce ethanol mean an increase in ethanol production. This cycle is an example of a positive self-reinforcing process.

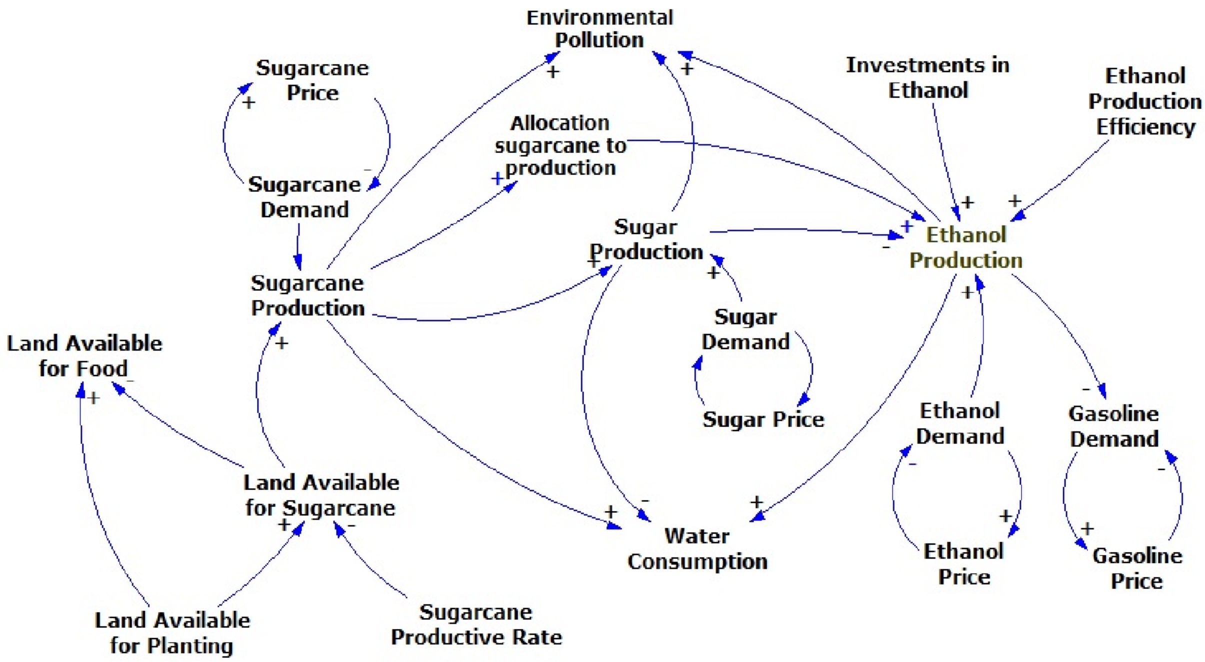

Fig. 2. Conceptual model of ethanol production

However, the cycle would be prevented from increasing the levels of each factor indefinitely because other factors beyond the loop, as the ethanol demand influence the price of ethanol. Gasoline demand also influence the demand for ethanol too.

Another example, an increase in yield obtained with the production and commercialization of ethanol positively affects new investments for the production of ethanol increases and the allocation of sugar for ethanol production. The effect of this is to increase ethanol production and decrease the price of ethanol by the forces of supply and demand. An ethanol lower price may reduce the profitability affecting investment levels. This subsystem tends to be inherently unstable if the acting forces do not take the self-regulation condition.

From the causal loop diagram is noticed that relevant factors for ethanol production level as investments in production, allocation of sugarcane production and profitability has a degree of dependence on production efficiency, the price of ethanol and sugar production, the availability of land for planting that can profoundly affect the needs for food and water production growth becoming unsustainable at expected levels.

3.5. Stocks and flows diagram

The equations that demonstrate the relationship between factors will be built on the basis of production data and investments of sugar and alcohol sector provided by the Department of Agriculture of the State of São Paulo, by the Council of sugarcane producers, sugar and Alcohol of the State of São Paulo and the Ministry of Agriculture.

The model is built considering four steps. The first step is the focal element ethanol and describes the dynamics of supply and demand, or deal with the production, storage and distribution of ethanol. The second stage, additional production, comes from sugar production model as a product substitute for ethanol production. The third step deals with the modeling of water consumption at various stages and land used for the production of sugarcane and food. The fourth step models the dynamics of capital, costs and investments. The forecast period begins from 2016 and extends until 2035. With this information it's possible not only to simulate the dynamic behavior of the production of ethanol, sugar and sugarcane as well as evaluate the impacts on the environment, water consumption and production foods, as illustrated in figure 3.

The flow diagram of inventory threats not only the direct demand for ethanol as well as indirect demand processes resulting mixture of ethanol and gasoline constituting a "pull" system in which the pulling is demand production. On the other hand, sugarcane harvesting system is modeled as a system "pushed" in which the sugarcane is harvested and destined for processing. In the case of the demand for sugar is less than the expected, there is no formation of a reserve stock for a short period of time to keep it in delaying the harvest field. If demand is greater than expected and the plants have available production capacities, as there is no training of reserve stocks, you can bring sugarcane from other states since the price and shipping cost offset. In this case, the availability of sugar would be the limiting factor for ethanol production.

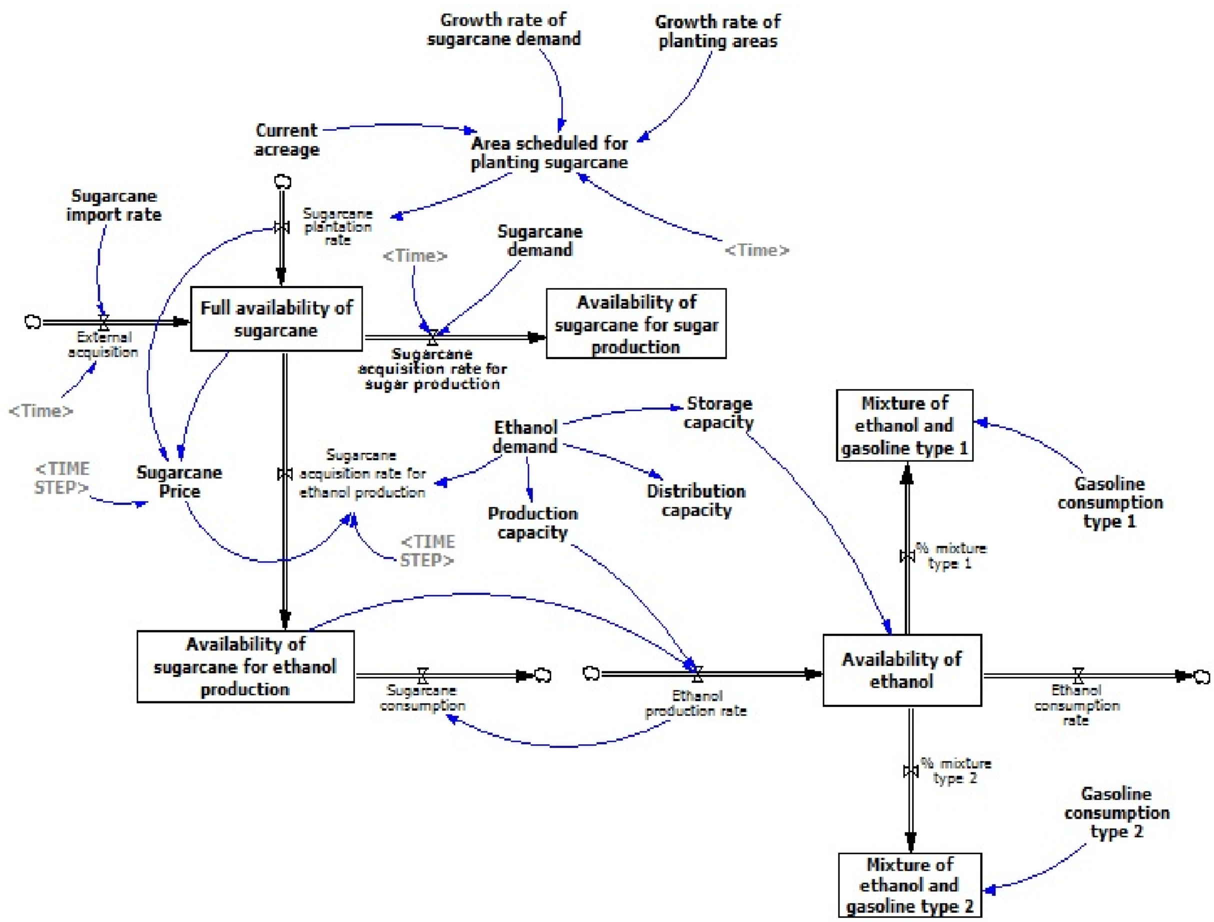

Fig. 3. Stocks and Flow Diagram

The demand of sugarcane for other purposes or sugar production and other industrial applications is shaped according to the projection. The sugarcane allocated to ethanol production depends on the demand, availability and price which in turn depend on the rate of acquisition of sugarcane for ethanol production. If the acquisition rate increases, the price rises and vice versa.

The diagram of stocks and flows also considers demand for ethanol and production capacity increase in the plants in proportion to the amount of sugarcane harvested, increasing the demand of growing areas, occupying spaces before intended for food crops such as rice, beans and corn. Investments in improvements in productivity to obtain the highest percentage of sucrose, exceeding 9% margin, allow the increase of ethanol production without an increase in the same proportion planted areas. This will appear in the diagram as a mitigating factor for consumption land available for planting.

One answer that is expected with this production simulation model is to evaluate how long production remains sustainable in the face of growing demand for ethanol.

3.6. Computational model

Once modeled in Vensim® the causal loop diagrams and charts of stocks and flows, the computer model will require the introduction of the equations that will govern the causal relationships of the different variables used and the definition of simulation parameters such as unit time to be used and the simulation horizon.

The simulation will work with a set of scenarios to assess the behavior of the variables and the sustainability of production. In the simulation three scenarios apply: an optimist, a pessimist and more likely. In the first scenario, it is assumed that the first period of 120 months, changes in demand and other factors have stable growth rates. In the second scenario, it's introduced changes in production capacity in the plants, oscillating demand for ethanol, water scarcity and fluctuations in the price of the final product, while the other factors remain unchanged. In the third, it's contemplated a scenario in which demand, production capacity, price and production of sugarcane tend to stabilize in the second half of the simulation time.

The computer model allows the interface with other tools such as geographic information systems to display the variations in plantation areas in the form of maps, as well as promote and export data for processing by other computational tools.

4. Limitations of Study

This article discusses the use of system dynamics modeling to model the problem of sustainability of the ethanol production system. The system dynamics modeling appears to be a useful tool for creating scenarios for such problems. However, this article considers some limitations to the use of this specific tool for modeling ethanol production. These limitations are highlighted by the ideas of system theory and by complex science (BOSSEL, 2007). There are also fundamental limitations to the correct prediction of the sustainability of ethanol production in the next twenty years, which are made clear by critics from of current production system (DeTOMBE, 1994) and chaos theory (GLEICK, 1987). These restrictions, however, do not set aside the importance of modeling and simulation tools as aid in understanding of dynamic phenomena such as sustainability.

5. Conclusion

As Mendonça (2007) pointed out: "Not long ago, biofuels were feted as an alternative to save the planet from carbon dioxide accumulation and excessive dependence on oil [...] were the synonym of a new era, the era clean and environmentally sound energy [...]". But, with so many contradictions, "[...] the wind shifted radically. Biofuels, almost overnight, is being considered the villain of the planet, responsible for the current food crisis, by soaring prices".

This article presented the step of formalizing the model for assessing the sustainability of ethanol production, its borders (external environment) and satisfactory solutions necessary to study the Brazilian ethanol production, its effects on the environment, food production and water consumption and future trends in three different simulation scenarios. The model considers that the importance of energy independence cannot be overestimated. Oil prices are expected to grow in coming years, as reserves are depleted and the remaining oil extraction process becomes more expensive. Ethanol is a biofuel which has an excellent history of use and relative ease of production as the basic raw material is sugarcane which can be easily cultivated. As a result, sugarcane production is expected to increase and more processing plants to be set up.

Improvements in farming technology are expected to increase productivity per hectare. However this increase can mitigate but not stopping the increase in sugarcane growing areas and hence bring significant reductions in food production with serious implications for the use of sugarcane as an alternative form of energy.

The use of modeling let to work with simulation scenarios and conditions where it is possible, given the initial conditions and the quality of the model, assess what would happen to the ethanol industry if ethanol prices float in response to the availability and supply of alternative energy sources for transportation or what would happen to food prices if ethanol demand continues to grow at an increasing rate. The model should be able to allow the situation of research that changes in planned production of sugarcane, the prices of sugarcane, capacity, demand and other factors relevant to the industry that can become business continuity unsustainable, either by lack of water resources or by the need of production and food for a growing population.

The models are as useful as the data used in their construction, understanding of the analysts and the inclusion of important and relevant factors. Brazil is the leading producer of large-scale biofuels and, maintaining this leadership depends on largely sustainability of ethanol production. As such, an evaluation model of sustainable production will be useful to explore the changes in market trends, assessment of impacts of new technologies of production and genetic improvement of sugarcane constituting a research instrument for the assessment of the future impacts of production biofuels in Brazil.

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