Invited Paper

FUZZY MULTI-OBJECTIVE OPTIMIZATION OF A MULTI-REGIONAL BIOETHANOL SUPPLY CHAIN

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Abstract

The onset of climate change has resulted in the development of strategies which try to mitigate the excessive generation of carbon dioxide (CO_2). The transport sector for example, which contributes more than 10% of the global CO_2 emission, is promoting the use of biofuels in order to improve a nation's energy security and to reduce the sector's carbon footprint. Biofuels which are sourced from agricultural feedstocks will require more water resources than their fossil fuel counterparts and with climate change affecting rainfall patterns, it is expected that water resources will become more scarce. A fuzzy multi-objective mathematical model for optimizing the biofuel supply chain in consideration of multiple regions is developed in this paper. The model seeks to identify how resources should be allocated in the presence of regional water constraints to satisfy the growing demand for biofuels. A case study on bioethanol produced from different indigenous feedstocks in three Asian countries is presented to demonstrate the capabilities of the model.

Keywords: Bioethanol, Biofuel Supply Chain, Optimization, Water Footprint

Introduction

The impact of human activities on the environment induces many global concerns such as climate change and global warming. This is increasingly threatened by the combustion of fossil fuels which release large amounts of carbon dioxide (CO_2) into the atmosphere. Therefore, it is necessary to find cleaner and more sustainable fuels. The use of bioenergy, such as bioethanol, is considered as a significant alternative because it is renewable. Furthermore, its net carbon emission is considered to be zero since it has absorbed atmospheric CO_2 during the photosynthetic process of biomass growth. In addition, the demand for bioethanol has increased in response to the upward trend in the prices of conventional gasoline. The production and use of bioethanol may provide additional benefits, such as improving energy security and decreasing dependence on imported fuels. Because of these benefits, several governments in many countries have been implementing policies which encourage, or even mandate, the partial replacement of gasoline by bioethanol at certain blending rates [1-3].

Despite the environmental and economic benefits which may be obtained from bioethanol production and use, there may also be significant disadvantages. One of them is the scarcity of freshwater resource. At present, the agricultural sector takes up 86% of worldwide freshwater use [4]. In many parts of the world, the use of water for agriculture competes with other uses, such as industrial supply and urban activities. According to recent statistical data, about one third of the world's population experiences a shortage of freshwater for their daily needs [5], and yet increased water scarcity is expected in the future in many regions due to a variety of factors such as population growth and water resource pollution. Therefore, it is really vital to improve the management of the world's limited annual freshwater supply. This responsibility is not only for water users and managers, but also for final consumers, businesses and policymakers. With agricultural and industrial production, in particular, there is a need to develop effective strategies for optimizing water use and still maintain the activities of each sector.

The concept of water footprint [4,6] and virtual water [7] accounts for all the water consumed in the production of goods and services. Through this concept it is then possible for water scarce regions to import water intensive products and thus focus only on the production of non-water intensive goods. Different methodologies have been proposed to support the planning of large-scale bioethanol production under water constraints or so called water footprint. Pinch analysis [8] for example, relies on graphical displays that provide guidelines for the optimal allocation of resources across economic regions. Related modeling techniques and mathematical programming methods such as input-output analysis (IOA) [9], life cycle assessment (LCA) [10] may also be applied to analyze biofuel production systems. In this paper, a mathematical model is developed for determining the optimal bioethanol supply chain under regional water footprint constraints. The rest of the paper is organized as follows. A generic input-output model is mentioned in Section 2 and the problem statement is discussed in Section 3. Section 4 gives the fuzzy optimization model for the bioethanol system. Case study 1 applies this model for defining optimum bioethanol supply chain in three regions independently and analyzing the sensitivity of bioethanol production subject to statutory biofuel targets under water constraint for Vietnam's case. The modified input-output model for fuzzy optimization is presented in Section 6. Case study 2 will be given in the succeeding sections to illustrate the use of the model for the multi-regional supply chain network of bioethanol production under multi-regional water constraints. Finally, conclusions and directions for future work are given.

Generic Input- Output Model

The modeling framework is based on a linear input-output model that is applied in life cycle assessment [11 - 12]. The simplest model form is given in Equation 1:

$$\mathbf{As} = \mathbf{f} \tag{1}$$

A is the technology matrix, **f** is the net output vector, and **s** is the scaling vector. Each column *j* of the technology matrix, **A**, represents a process, while each row *i* describes a product or an intermediate. Negative and positive values in each column denote inputs and outputs, respectively. The value of the scaling vector itself adjusts to satisfy the system's overall energy, material balance and final output. By manipulating Equation (1) it is then possible to determine the scaling vector using equation (2).

$$\mathbf{s} = \mathbf{A}^{-1}\mathbf{f} \tag{2}$$

The flow of environmental interactions on the other hand, is given by Equation (3).

$$\mathbf{Bs} = \mathbf{g} \tag{3}$$

Where **B** is the intervention matrix and **g** is environmental impact vector. The columns of **B** correspond to the same processes as those found in matrix **A**, whereas the rows of **B** represent environmental flows. The combination of Eqs.(2) and (3) gives Equation (4):

$$\mathbf{g} = \mathbf{B}\mathbf{A}^{-1}\mathbf{f} \tag{4}$$

In this study, the value of **g** represents the total footprint, while **B** denotes the footprint of the component processes. Eq.(4) allows the footprint, **g**, to be solved in order to satisfy the required system output, **f**, given the technological values for the processes.

Recently, Tan et al. [10] utilized an input-output model to develop a fuzzy multiple objective optimization model of life cycle systems under multiple intervention flow targets and technology alternatives within a single-region. Aviso et al. [9] extended this model in consideration of multi-region systems wherein trade effects are taken into account.

The model developed in this paper on the other hand, deals with the optimization of the bioethanol production processes in consideration of demand and environmental objectives. It is then applied to the individual-region supply chain network and the multi-region one. The objective of the model is to enhance the satisfaction of energy demand as well as technological factors and environmental flows for all participants. This model would be helpful for planning and implementing the appropriate biofuel policy to meet the consumer demands and at the same time manage resources efficiently.

Problem Statement

The production of bioethanol from agricultural crops requires the total water consumed in growing the feedstock and in the conversion of the feedstock into ethanol. Each region can be self-sufficient in ethanol product or they may import it from another region depending on energy demand and environmental constraints. In the case of trading ethanol, environmental burdens may significantly vary between different regions. The general system has N_k regions, N_i economic flows (i.e., raw materials, or products) and N_j processes or plants which consume the economic flows.

There are N_E environmental flows in the production of raw materials and bioethanol. In this paper, only water footprint is considered as environmental footprint. Furthermore, it is possible to exchange final product (bioethanol) among different regions. Bioethanol manufactured by one region may be utilized to satisfy its own demand or may be exported to other regions in the network. The production of bioethanol has associated water use, and the challenge is how to optimally allocate water use between the entities in the network in consideration of regional water resource limits. Each region has limited water resource available which can limit the production of raw material or bioethanol in that region. It is therefore important to identify the optimal supply network in constraints of such water resource to satisfy the overall final demand.

Fuzzy Optimization Model For Bioethanol Systems

This section presents a fuzzy linear programming (FLP) model for calculating footprint and final demand in a single- region. Each region has specified fuzzy limits on the final demand of bioethanol expressed in kilogram of oil equivalent (kgoe). Agricultural and process yields are defined in the form of technological coefficients. Each region produces agricultural crops for bioethanol production to partially or completely satisfy its final bioethanol demand. Depending on the gasoline demand for motor and the policy of biofuel of each country, final bioethanol demand can be calculated. It is assumed that each region will independently set fuzzy final demand limits defined by an upper demand limit (f_k^U) which is the maximum replaceable ethanol demand, and a lower limit (f_k^L) which is the least acceptable amount of bioethanol as shown in Equation 5.

$$f_k^L \leq f_k \leq f_k^U \qquad \forall k \in K \tag{5}$$

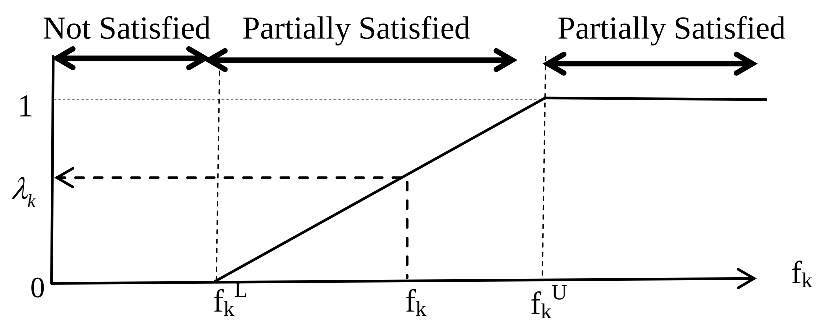

Figure 1: Function for fuzzy final demand goals

The degree of satisfaction of each region (λ_k) increases linearly from 0 to 1 as the final demand varies from minimum limit (f_k^L) to maximum bioethanol demand (f_k^U). If the capacity of ethanol production in each region is greater than its maximum final demand limit, the goal is completely satisfied and (λ_k) equals 1. In contrast, if the capacity is less than its desired minimum demand, (λ_k) is 0. If the final demand of Region k falls between the upper and lower limit, the goal becomes partially satisfied. This function of (λ_k) [9] is shown in Equation 6 and illustrated in Figure 1.

$$\lambda_k = \begin{cases} 0 & \text{if } f_k < f_k^L \\ \dfrac{f_k - f_k^L}{f_k^U - f_k^L} & \text{if } f_k^L \leq f_k \leq f_k^U \quad \forall k \in K \\ 1 & \text{if } f_k > f_k^U \end{cases} \tag{6}$$

Besides the fuzzy limit of final demand, there also exists a fuzzy limit on environmental flow for each region. The footprint flow considered in this paper is water constraint. The total *production-based water footprint* of a Region k is defined as the amount of water utilized in the local production of goods for both local and export consumption while the *consumption-based water footprint* accounts for the total amount of water needed to manufacture the goods consumed by a particular region whether manufactured locally or imported [9]. In either case, the total water footprint is the sum of blue, green and grey water [6]. It is important to differentiate between the two types of water footprint since the *production-based water footprint* will directly impact the available resources in the region. Similar to the final bioethanol demand goal, each region will also independently set fuzzy water footprint limits, with an upper value (WF_k^U) and a lower limit (WF_k^L) as shown in Equation 7. These limits are associated with the available water resource in the region.

$$WF_k^L \leq WF_k \leq WF_k^U \qquad \forall\, k \in K \tag{7}$$

The degree of water footprint satisfaction (λ_{kw}) must satisfy the water constraint objectives of individual regions which are presented by Equation (8):

$$\lambda_{kw} = \begin{cases} 0 & \text{if } \; WF_k > WF_k^U \\ \dfrac{WF_k^U - WF_k}{WF_k^U - WF_k^L} & \text{if } \; WF_k^L \leq WF_k \leq WF_k^U \quad \forall k \in K \\ 1 & \text{if } \; WF_k < WF_k^L \end{cases} \tag{8}$$

From Equation 8 it can be seen that if the *consumption-based* regional water footprint is less than the minimum limit then $\lambda_{kw} = 1$, whereas if it is at maximum, $\lambda_{kw} = 0$.

To be able to consider the goals of regions which relate final bioethanol demand and water footprint, fuzzy optimization using max-min aggregation [13-14] is applied. The objective is to maximize the overall level of satisfaction, and the objective function thus becomes:

$$\max \lambda \tag{9}$$

The variable λ is limited to:

$$\lambda \in [0, 1] \tag{10}$$

The overall level of satisfaction is supposed to maximize the satisfaction of the least satisfied objective in this case water footprint and ethanol demand:

$$\lambda \leq \lambda_k \tag{11}$$

$$\lambda \leq \lambda_{kw} \tag{12}$$

It can be seen that this is a linear programming (LP) model, and thus finding the global optimum for computing is not difficult, as long as such a solution exists. In the case studies that follow, the optimization software Lingo 13.1 is used to find the global optimum solution.

Case Study 1

The first case study presents the optimization of the bioethanol supply chain in consideration of the water intensity for agricultural crop and bioethanol production of three independent regions. Each region can source the bioethanol from a variety of feedstocks which are indigenous to that region. The bioethanol produced in the region is to satisfy the local demand based on targets set for biofuel substitution. The total amount of bioethanol produced by a region is limited by the available water resource. This case considers the production of bioethanol from sugarcane, corn and cassava in three countries: Vietnam, Thailand and the

Philippines. Data supplied for calculation including available water, gasoline consumption, water footprint and land use among others, were taken from journals and official websites [15-18]. The data are summarized in Table 1. Meanwhile, data for technology and intervention matrices were derived from journal articles reported by each country [19-23]. These are shown in Tables 3 to 5. The columns indicate the processes while the rows indicate the feedstock and products considered in the supply chain which may be inputs or outputs of the processes indicated in the column. A negative value in Tables 3 to 5 indicate the consumption of the product given in the row by the corresponding plant given in the column. For example, in Table 3 the ethanol production from sugarcane requires 1 kg of sugarcane to produce 0.0423 kg of oil equivalent (kgoe) and requires the total water footprint of 0.271m^3 for the production of sugarcane and 0.0682m^3 for converting sugarcane into bioethanol.

Table 1. Land Area and Available Water of Feedstock for Case 1

Feed Stock	Land Use (ha)	Average Precipitation In 2010 (mm)	Available Water (Million m^3)	Total Available Water (Million m^3)
Sugarcane	106,000	1,821	1,930	4,990
Cassava	168,000		3,059	
Sugarcane	65,000	2,348	1,526	3,804
Maize	97,000		2,278	
Cassava	1,044,090	1,622	16,935	16,935

Table 2. Fuzzy Production and Water Footprint for Case 1

Fuzzy Targets		Limiting Values (in 10^6 kgoe)			Notes
		Vietnam	Philippines	Thailand	
Gasoline consumption (in 10^6 kgoe)		4514	1933	5327	
Ethanol Production (in 10^6 kgoe)	Lower limit	226	147	266	Upper and lower limits based on 10% and 5% substitution respectively, of annual gasoline demand
	Upper limit	451	293	533	
Water Footprint (10^6 m^3)	Lower limit	0	0	0	Based on land area used for growing the feedstock and the mean annual rainfall
	Upper limit	4,990	3,804	16,935	

Each region has a different demand for ethanol which replaces a proportion of the gasoline demand of that region. The lower limit corresponds to 5% of the gasoline demand in a region representing the level of ethanol substitution. The upper limit on the other hand corresponds to a 10% bioethanol substitution. The upper and lower limits were based from the projected gasoline consumption in the year 2030 for the three countries considered [22]. The data are given in Table 2. Furthermore, each region has a water footprint limit based on the mean annual rainfall in the region and the corresponding land area allocated for the feedstocks (shown in Table 1 and Table 2).

Table 3. Technology and Intervention Matrices for Vietnam (Case 1)

	Sugarcane Farming	Cassava Farming	Ethanol Production Sugarcane	Ethanol Production Cassava
A				
Sugar cane (kg)	1	0	-1	0
Cassava (kg)	0	1	0	-1
Ethanol (kgoe)	0	0	0.0423	0.2022
B				
Water footprint(m^3)	0.271	0.604	0.0682	0.7188

Table 4. Technology and Intervention Matrices for Philippines (Case 1)

	Sugarcane Farming	Corn Farming	Ethanol Production Sugarcane	Ethanol Production Corn
A				
Sugar cane (kg)	1	0	-1	0
Corn (kg)	0	1	0	-1
Ethanol (kgoe)	0	0	0.0423	0.211
B				
Water footprint(m^3)	0.185	2.087	0.0784	0.2137

The optimal global solution is obtained by solving Equation (9) subject to Equation (1), (3), (6-8) and (10-11). The degree of satisfaction is 0.558 for Vietnam, 0.613 for the Philippines and 0.877 for Thailand if the optimization is done independently of each other. With such lambda, the final ethanol production and water footprint levels of three countries lie within the desired bioethanol production level and the defined water footprint limits. The lambda value is highest for Thailand; it means that the potential of ethanol production to meet the local demand for energy is higher than that of the Philippines and Vietnam, while the ethanol production demand objective is least satisfied in Vietnam. Furthermore, the ethanol production in Vietnam is derived solely from cassava, in the Philippines from sugarcane, and in Thailand from cassava. These are materials which either require less water inputs per unit of ethanol equivalent or have higher efficiencies of conversion to ethanol in comparison to the other feedstocks in a given region (Table 6).

Table 5. Technology and Intervention Matrices for Thailand (Case 1)

	Cassava Farming	Ethanol Production Cassava
A		
Cassava (kg)	1	-1
Ethanol (kgoe)	0	0.2022
B		
Water use (m^3)	0.467	0.3758

Table 6. Optimal results for Case study 1

Country	Model Output	Value (10^6 kgoe)	Water footprint (10^6 m^3)
Vietnam	Ethanol production sugarcane	0	0
	Ethanol production cassava	352	2,205
Philippines	Ethanol production from sugarcane	237	1,473
	Ethanol production from maize	0	0
Thailand	Ethanol production from cassava	500	2,084

Sensitivity Analysis on Statutory Biofuel Target for Vietnam's Case

This part will analyze the sensitivity of bioethanol production subject to statutory biofuel target under water constraint particularly in Vietnam. It has been noted that the model for maximizing the degree of satisfaction will also help identify the appropriate bioethanol substitution rate. It also allows the evaluation of the suitability of government policy. However, the production of bioethanol in each country is limited by other physical constraints such as production capacity and water resource availability. In such cases, it is necessary to find the optimal substitution of ethanol which must lie within the policy requirements to minimize the importation of ethanol from other countries. The bioethanol substitution target is set between 5-10% the optimal ethanol substitution rate in Vietnam should be 7.8% (total ethanol production divided by total gasoline demand). If the production of ethanol is set in the range of 5-7% or 8-10%, the degree of satisfaction and the corresponding bioethanol substitution based on the optimization are given in Table 7.

From this table, it can be seen that by setting the bioethanol target to 8-10%, the degree of satisfaction attains 0.491. This shows that it is possible to increase the substitution rate to 9% however it reduces the attained degree of satisfaction due to the increased water footprint. While in the case of setting the bioethanol target from 5-7%, the degree of satisfaction increases by 13% (from 0.558 to 0.643) compared to setting the substitution rate between 5-10%. The gasoline replacement on the other hand, decreases by as much as 19% (from 7.8% to 6.3%). For all three scenarios, the limiting objective is that of the water footprint indicating that the biofuel policy to be implemented should strongly consider the availability of water resources in the region.

Table 7. Result of Sensitivity Analysis Subject to Bioethanol Target in Vietnam Case (Case 1)

	Bioethanol Target		
	5-7%	8-10%	5-10%
Ethanol Production (10^6 kgoe)	284	405	352
Water Footprint (10^6 m^3)	1779	2542	2205
Degree of Satisfaction	0.643	0.491	0.558
Bioethanol Contribution (%)	6.3	9	7.8

Fuzzy Optimization Model for Modified Input-Output Model

In the second case study, the variations in technology and the exchange of products between regions will be considered. Equation (1) is thus modified into Equation (13) where the index (k,l) represents the transfer of products from region k to region l:

$$\mathbf{A_k}\,\mathbf{s_{kl}} = \mathbf{f_{kl}} \quad \forall\, k,l \in K \tag{13}$$

The technology matrix for Region $\mathbf{A_k}$ has a function similar with matrix $\mathbf{A}$ in Section 2. Entries in the matrix ($[a_{ij}]_k$) express the value of economic flow i required or produced by process or plant j in Region k. Negative entries represent input value while positive entries indicate output. The vector $\mathbf{s_{kl}}$ contains scaling factors ($[s_j]_{kl}$) (Equation 14) which indicate the requirement for processes in Region k to satisfy the demand of the products of Region l. Vector **f** in this case is no longer the final demand vector but becomes an intermediate output vector of products in Region k to satisfy the demand of Region l.

$$[s_j]_{kl} \geq 0 \quad \forall\, k,l \in K;\ \forall\, j \in J \tag{14}$$

The final demand vector of product of each region $\mathbf{y_l}$ is presented in Equation (15). The entries ($[y_i]_l$) indicate the demand of product i in Region l. To meet the demand of Region l, products may be produced locally or imported from other regions.

$$\mathbf{y_l} = \sum_{k} f_{kl} \quad \forall\ k,l \in K \tag{15}$$

$$[y_i]_l \geq 0 \quad \forall\ l \in K;\ \forall\ i \in I \tag{16}$$

Moreover, the production-based water footprint of each region will comprise overall water used for all activities from region k to satisfy demand of products for itself and for other regions if it exports products. The modified matrix of environmental flows $\mathbf{B_k}$ is similar with matrix $\mathbf{B}$.

$$\mathbf{B_k\ s_{kl} = g_{kl}} \quad \forall\ k,l \in K \tag{17}$$

$$\mathbf{z_k} = \sum_{l} g_{kl} \quad \forall\ k,l \in K \tag{18}$$

Equation (17) computes the water footprint utilizing resources in Region k to supply for the demand of products of Region l. Meanwhile, vector $\mathbf{g_{kl}}$ becomes the water footprint vector in Region k which contains the production based water footprint of Region k. From Equation (18), the total of water footprint in Region k is computed.

Case Study 2

The second case study is focused on the production of bioethanol under multi-region water constraints. Unlike Case study 1 which considers only single- region, this case will consider the combination of three countries Vietnam, the Philippines and Thailand in the supply chain network. Each region may also produce raw materials i for bioethanol production. It may become an exporter or an importer, depending on the locally specified footprint constraints. The problem is to define the optimal production and trade levels to satisfy the fuzzy ethanol demand and fuzzy water footprint constraints of each region. The objective is to maximize the overall level of satisfaction as shown in Equation 9 subject to Equations 6, 8 and 10-18. The data used for this case will be similar to that of Case study 1. Solving all above equations, the results are summarized in Tables 7 and 8.

It can be seen that Philippines is an importer of bioethanol from Thailand, with only about 49% of the ethanol demand being supplied from internal production and about 51% from Thailand. Vietnam meets 40% of its requirement from local production; the rest is imported from Thailand. In contrast, Thailand is a net exporter of ethanol with 56% of its production allocated for local use, 16% exported to the Philippines and 27% to Vietnam. The results indicate the imbalance of energy demand and water resource limitation among three regions. The overall degree of satisfaction for this case study is $\lambda = 0.79$, while average value of lambda in the Case 1 equals 0.683 (it equals the average λ of three regions). This indicates that the mathematical model of multi-region supply chain network increases the degree of satisfaction for meeting the ethanol demand and minimizing water use in the multi-regional supply network rather than that in single- regions supply network. In Case study 1, Thailand achieved the highest level of satisfaction because it had the highest amount of available resources. In Case study 2, by implementing the multi-regional network, the water resources of Thailand were utilized to produce ethanol to satisfy the demands of Vietnam and the Philippines thus resulting in an increase in the levels of satisfaction of Vietnam and the Philippines.

Table 7. Allocation of Ethanol to satisfy demand of each region for Case study 2

			Demand			
		Feedstock	**Vietnam**	**Philippines**	**Thailand**	**Total Ethanol Produced**
Source	Vietnam	Sugarcane	0	0	0	0
		Cassava	160.37	0		160.37
	Philippines	Sugarcane	0	128.444	0	128.444
		Corn	0	0	0	0
	Thailand	Cassava	243.585	134.027	476.707	854.319
Total ethanol			403.956	262.47	476.707	

*Figure in million kgoe per year

Table 8. Allocation of Water Footprint between Regions for Case Study 2

		Demand			
		Vietnam	**Philippines**	**Thailand**	**Production-based Water Footprint**
Source	Vietnam	1049.15	0	0	1049.15
	Philippines	0	799.81	0	799.81
	Thailand	1015.40	558.90	1986.99	3561.29
Consumption-based Water Footprint.		2064.55	1358.71	1986.99	

*Figure in million m^3 per year

Conclusion

A fuzzy input-output model has been developed to optimize ethanol production under water resource constraints. The model utilizes the scale-invariant technological coefficients and max-min aggregation. The global solution can be easily determined to obtain the maximum value of the overall degree of satisfaction, λ, as well as optimal bioethanol substitution rates. Two case studies have been presented to illustrate how the model determines optimal production levels of ethanol in each region. Furthermore, the model also indicates that the degree of satisfaction, λ, in the case of trade between regions is higher than in the case of individual regional production. Future work on extending the model should be developed to account for environmental footprints other than water (i.e., carbon footprint, land footprint) and for other fuels and other feedstocks (i.e., biodiesel).

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