CHEMICAL ENGINEERING TRANSACTIONS
VOL. 45, 2015
A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216
DOI: 10.3303/CET1545060

Fuzzy Mathematical Programming Approach in the Optimal Design of an Algal Bioenergy Park

Aristotle T. Ubando*[a,b], Alvin B. Culaba[a,b], Kathleen B. Aviso[b,c],
Raymond R. Tan[b,c], Joel L. Cuello[d], Denny K.S. Ng[e], Mahmoud M. El-Halwagi[f]

[a]Mechanical Engineering Department, De La Salle University, 2401 Taft Avenue Manila, Philippines
[b]Center for Engineering and Sustainable Development Research, De La Salle University, 2401 Taft Avenue Manila Philippines 1004
[c]Chemical Engineering Department, De La Salle University, 2401 Taft Avenue Manila, Philippines
[d]Agricultural and Biosystems Engineering Department, The University of Arizona, Tucson, Arizona, USA
[e]Deaprtment fo Chemical and Environmental Engineering/ Centre of Excellence for Green Technologies, The University of Nottingham, Malaysia Campus, Semenyih, Malaysia
[f]Center for Engineering and Sustainable Development Research, De La Salle University, Manila, Philippines
aristotle.ubando@dlsu.edu.ph

Algal biofuels are considered to be the only biomass-based fuel capable of producing the global fuel demand in terms of land constraint. However, its sustainable production and commercialization have been criticized with respect to its environmental impact, energy requirement, and economic potential. Hence, a viable approach to address such a concern is through synergistic networks between multiple industries in an eco-industrial park framework. Applying the concept of industrial symbiosis (IS), it enables the collaborative exchange of by-products and energy surplus between companies leading to inter-industry benefits. An algal bioenergy park (ABP) is a special example of an eco-industrial park focusing on algal biofuel production. It consists of anchor tenants and support tenants. The former are industries which comprise the core companies of the ABP while the latter are the considered industries which may complement the core companies in the production of algal biofuels. To encourage mutual benefit between companies in the ABP, satisfaction of individual targets such as production level and profitability must be met. Thus, a fuzzy mathematical programming approach is proposed in this study for the optimal design of an ABP with multiple conflicting objectives. The results revealed that in considering the support tenants, the annual profit of the ABP increased by 220 % with a considerable amount of increase in the environmental emissions. The results of the study provide a rational basis for negotiations, signing contracts, and agreements between firms in an ABP. A hypothetical but realistic case study is presented to illustrate the developed model.

1. Introduction

Algal biofuels offer promising benefits such as high oil yield with lesser land requirement (Chisti 2007). However, its commercialization and sustainable production have encountered challenges in the aspects of economic viability, energy consumption, and environmental impact. One of the approaches to address such a concern is to consider a synergistic collaborative network between various industries under the concept of industrial symbiosis (IS) in an eco-industrial park (EIP). IS provides a platform for different companies to reuse their material and energy wastes with other companies in the EIP. Thus, increasing the profit and minimizing the wastes of a company. An algal bioenergy park (ABP) is a special example of an EIP mainly focusing on the production of algal bioenergy products such as biofuels, biochemicals and energy. An ABP consists of two types of industry players: 1) anchor tenants, and 2) support tenants. The anchor tenants are composed of industries which are considered to be the main core companies of the industrial park. These companies have previously established a working synergistic network between their organizations. The support tenants are industries who are new players and are being considered to be part

Please cite this article as: Ubando A.T., Culaba A.B., Aviso K.B., Tan R.R., Cuello J.L., Ng D.K.S., El-Halwagi M.M., 2015, Fuzzy mathematical programming approach in the optimal design of an algal bioenergy park, Chemical Engineering Transactions, 45, 355-360 DOI:10.3303/CET1545060

of the ABP. Previous studies on the design of EIP have been conducted. Lovelady and El-Halwagi (2009) proposed the use of non-linear programming for the optimum design of a water network. Ng and Ng (2013) adapted the mixed-integer linear programming model for the design of an EIP for a single owned integrated palm-oil processing complex. The analysis was later on expanded by Ng et al. (2013) to a multiple owner scenario using fuzzy multi-objective optimisation. Castaño et al. (2015) used a life cycle optimization approach for the optimal operation of a petrochemical complex. Pinzón et al. (2014) adapted the techno-economic optimization model to determine the optimal microalgae composition for the development of a topology of a biorefinery. The study was later on expanded by Frias et al. (2015) to explore potential configuration of biorefineries based on the optimal microalgae strain composition and biomass consumption. There has been minimal work on applying fuzzy mathematical programming model in designing an ABP. Fuzzy set theory has been applied recently for evaluating factors involving uncertainties in risk assessment (Djapan et al., 2015). Hence, this study focuses on application of fuzzy mathematical programming model to design an ABP with multiple objectives: satisfy product demand, maximize annual profit for each of the companies in the ABP, and minimize the environmental impact.

2. Problem Statement

In designing an ABP and employing the concept of IS, the challenge is to determine the optimal capacity configuration of each company while satisfying the overall objective of the ABP. There are three objectives of the study. Firstly, the product demands **y** of the ABP is satisfied. Secondly, the environmental impact **z** of the ABP is minimized. Lastly, the annual profit **AP** for each company in the ABP is maximized. The ABP is described by its technological matrix **A** with product streams **y**. The product stream **y** follows the trapezoidal linear membership function represented by the four threshold limits $\mathbf{y}^a$, $\mathbf{y}^b$, $\mathbf{y}^c$, and $\mathbf{y}^d$ to eliminate the under- and over-production of product streams. Furthermore, the four trapezoidal threshold limits are defined by clients based on historical data and demand projections. The allowable environmental footprint **z** of the ABP is defined by the lower and upper environmental footprint limits ($\boldsymbol{z}^L$ and $\boldsymbol{z}^U$). The environmental footprint **z** follows the minimum linear membership function where a value less than the minimum threshold value $\boldsymbol{z}^L$ is desired. The annual profit (**AP**) of each of the company in the ABP is defined by the company owners. **AP** follows a maximum linear membership function hence a value greater than the maximum threshold limit AP^U is desired. The problem is to solve for the optimal scaling vector **x** such that each objective for the net product output **y**, the environmental footprint ***z***, and the annual profit **AP** for each company are satisfied to at least the degree of λ.

3. Fuzzy Mathematical Programming

Fuzzy mathematical programming (FMP) was used to solve multiple objective problems for decision making purposes (Zimmermann, 1978). One practical approach in utilizing FMP in the design of complex systems is through fuzzy linear programming (FLP) model. FLP models have been applied previously for the design of bioenergy systems (Tan et al., 2009). Recently, Ubando et al. (2012) applied FLP model in designing an algal biorefinery. One advantage of FPM models over Pareto optimal curves is that it results in a unique solution. Optimisation models consist of an objective function and the constraints. In this work, the objective function is described in Eq(1) and the constraints are elaborated in Eq (2) to Eq(11):

$$\text{Maximize } \lambda \tag{1}$$

s.t.

$$\mathbf{Ax} = \mathbf{y} \tag{2}$$

$$\mathbf{Bx} = \mathbf{z} \tag{3}$$

$$\mathbf{y} = \Sigma\, y_i \qquad \forall\, i \tag{4}$$

$$y_i \geq y_i^a + \lambda(y_i^b - y_i^a) \tag{5}$$

$$y_i \leq y_i^d + \lambda(y_i^c - y_i^d) \tag{6}$$

$$\mathbf{z} \leq \mathbf{z}^U + \lambda(\mathbf{z}^L - \mathbf{z}^U) \tag{7}$$

$$\mathrm{AP} = \mathrm{AGP} - \mathrm{ACC} \tag{8}$$

$$\mathrm{AGP} = 3600T\, \Sigma\, \mathrm{c_i}\cdot \mathrm{y} \tag{9}$$

$$\mathrm{ACC} = \mathrm{AF}\, \Sigma\, \mathrm{CAPEX_i}\cdot \mathrm{x} \tag{10}$$

$$\mathrm{AP} \geq AP^L + \lambda(AP^U - AP^L) \tag{11}$$

where **A** is the technological matrix, **B** is the environmental stream matrix, **x** is the process scaling vector, **y** is the net product output vector of the ABP, and **z** is the environmental footprint vector, AP is the annual profit, AGP is the annual gross profit, ACC is the annual capitalized cost, T is the annual operating hours of the ABP, c_i is the cost for product stream i, AF is the annualizing factor, and CAPEXj is the variable cost for process unit j, AP^L is the lower limit of the annual profit for each company, and AP^U is the upper limit of the annual profit for each company.

4. Case Study

This case study involves the design of an ABP with three existing anchor tenants and two support tenants under consideration. The three anchor tenants consist of: 1) an integrated microalgae to biodiesel (IMB) plant, 2) ethanol plant (ETH), and 3) a cement factory (CMT). The two support tenants considered are: 1) combined heat and power (CHP) plant, and 2) an anaerobic digestion plant (ADP). The CHP plant consists of a gas turbine with heat recovery steam generator (GT-HRSG) and a boiler. On the other hand, the anaerobic digestion plant consists of a waste water treatment facility (WWT) and an anaerobic digester (AD). The material and energy streams between the tenants of the ABP are shown in Figure 1.

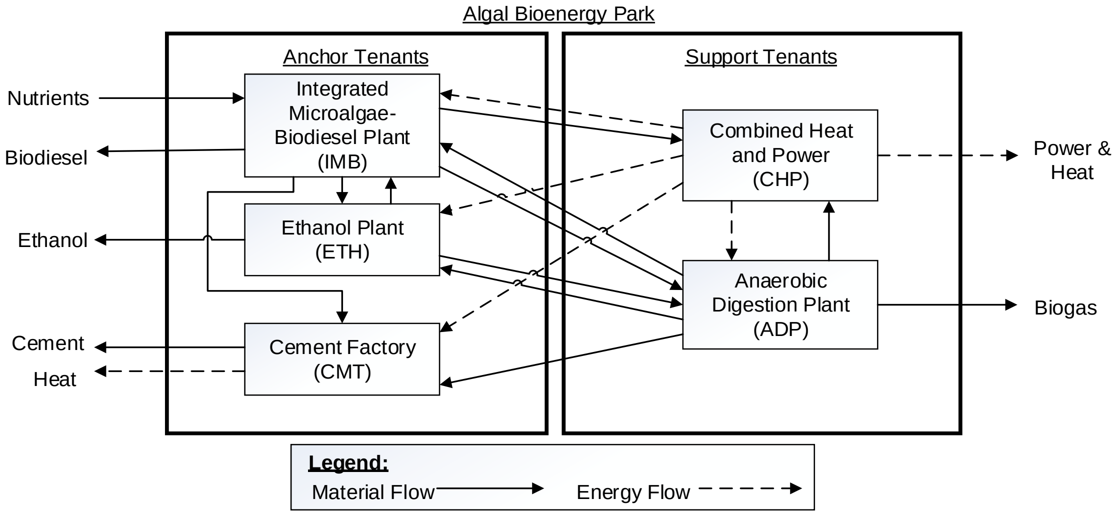

Figure 1: Algal bioenergy park schematic diagram.

The input-output process flow streams of each plant in the ABP can be summarized into the extended technological matrix as shown in Table 1. A negative value represents an input flow stream into a tenant while a positive value represents an output value from the tenant. Table 1 is configured such that each tenant represents a column vector. In addition, it also shows that there are 18 material and energy flows and 5 environmental streams considered in the design of the ABP as represented by each row. The product demand limits for the ABP, which are exogenously defined and described by a trapezoidal ($y^b \neq y^c$) or a triangular ($y^b = y^c$) fuzzy membership function as shown in Table 2. The main products considered in the ABP where y = 1 as shown in Table 2 are biogas, ethanol, biodiesel, and cement. It is assumed that all the power produced from the CHP will only be used within the ABP. All other co-products produced in excess are sold outside the ABP. The price of each product in the ABP is shown in Table 3. The footprint limits of the ABP are shown in Table 4. Five footprints are considered in the analysis. Firstly, the amount of CO_2 emitted in producing the raw materials is accounted in the analysis to keep track of its carbon footprint. Secondly, the CO_2 emissions to produce the product streams of the ABP are directly accounted. Later on in the results, the CO_2 emission from the production of the raw materials and the CO_2 emission from the product stream in the ABP shall be combined for simplification purposes. Thirdly, the water footprint of the ABP is accounted specially for the cultivation stage of the IMB where ample amount of water is required. Fourthly, the land footprints of the tenants in the ABP are considered since the land area of the ABP is mostly limited. Lastly, the nitrogen footprint represents the required nutrients of the plant in the ABP especially for the cultivation stage of the IMB. It is ideal to minimize the five environmental footprints of the ABP. The environmental footprint is governed by Eq(7) where a minimum fuzzy linear membership function is applied. The annual profit targets for each plant in the ABP are shown in Table 5. The annual profit targets are pre-defined by the owners of each plant.

Table 1: Extended process matrix of the algal bioenergy park.

	Anchor Tenants			Support Player 1		Support Player 2	
Extended Process Matrix	IMB Plant	Ethanol Plant	Cements Factory	Combined Heat and Power Plant		Anaerobic Digestion Plant	
				GT-HRSG	Boiler	WWT	AD
Nutrients (kg/s)	-3.45	0	0	0	0	0	0
Carbon Dioxide (kg/s)	-36.67	0	0	0	0	0	1.23
Treated Water (kg/s)	-206.71	-1.96	-0.01	-2.74	-0.59	1	-10.49
Power (MW)	-168.55	-0.77	-0.17	1	-0.02	-0.01	-0.01
Heat (MW)	-239.06	-0.03	2.67	1.49	1	0	-0.52
Algal Biomass (kg/s)	1.47	-4.85	0	0	-1.26	0	-0.81
Bio-solid wastes (kg/s)	0.35	0	-4.4	0	0	0	-4.03
Wet Biomass (kg/s)	8.15	0	0	0	0	1.5	-4.85
Biogas (kg/s)	0	0	0	0	0	0	1
Natural Gas (kg/s)	0	0	0	-0.06	0	0	0
Waste water (kg/s)	0	0.2	0	0	0	-2.5	10.83
Microalgal Culture (kg/s)	-0.03	0	0	0	0	0	0
Ethanol (kg/s)	-0.11	1	0	0	0	0	0
Bio-oil (kg/s)	0.74	0	0	0	0	0	0
Biodiesel (kg/s)	1	0	0	0	0	0	0
Glycerol (kg/s)	0.11	0	0	0	0	0	0
Limestone (kg/s)	0	0	-0.41	0	0	0	0
Cement (kg/s)	0	0	1	0	0	0	0
Carbon Dioxide of raw materials (kg/s)	0.22	14.65	0.79	2.8	14.65	0	25.38
Carbon Dioxide of plant (kg/s)	14.65	0.89	0.24	0.02	0.016	0	0.001
Water of plant (kg/s)	44.66	1.95	0.005	2.73	0.58	1	0.34
Land (1×10^3 m^2)	44.65	11.16	8.04	8.93	5.358	10.95	15.63
Nitrogen of plants (1×10^{-3} kg/s)	11.04	0	2.2	0.001	0.002	0	0.09

Table 2: Exogenously defined product demand limits.

Products	y^a	y^b	y^c	y^d
Biogas (kg/s)	0.6	0.8	0.8	1
Ethanol (kg/s)	0.83	0.87	0.87	0.91
Biodiesel (kg/s)	4	4.25	4.5	5.1
Cement (kg/s)	32.08	35.64	37.51	41.67

Table 3: Price of each product in the algal bioenergy park.

Product Price	Price	Reference
Nutrients (US$/kg)	0.008	Adapted from FF (2014)
Carbon Dioxide (US$/kg)	0.003	Adapted from Davis et al. (2011)
Treated Water (US$/kg)	0.0013	Adapted from SD (2014)
Electricity (US$/MJ)	0.028	Adapted from USEIA (2014)
Heat (US$/MJ)	0.021	Adapted from USEIA (2014)
Algal Biomass (US$/kg)	0.47	Christiansen (2011)
Bio-solid Waste (US$/kg)	0.047	Assumed 10% of the price of algal biomass
Wet Biomass (US$/kg)	0.033	Adapted from Christiansen (2011)
Biogas (US$/kg)	0.23	USEIA (2014)
Natural gas (US$/kg)	0.23	USEIA (2014)
Waste water (US$/kg)	0.002	Adapted from NYC (2014)
Microalgal Culture (US$/kg)	0.588	Adapted from Grima et al. (2003)
Bioethanol (US$/kg)	6.5	Adapted from Davis et al. (2011)
Bio-oil (US$/kg)	5.32	Adapted from Davis et al. (2011)
Biodiesel (US$/kg)	6.24	Adapted from Davis et al. (2011)
Glycerol (US$/kg)	0.775	Adapted from Quispe et al. (2013)
Limestone (US$/kg)	0.01	EFCC (2014)
Cement (US$/kg)	0.45	ENR (2014)

Table 4: *Footprint limits of the algal bioenergy park.*

Footprints	z^L	z^U	Reference
Carbon Dioxide of raw materials (kg/s)	0	4,700	Adapted from Tan et al. 2009
Carbon Dioxide of plant (kg/s)	0	200	Adapted from Tan et al. 2009
Water of plant (kg/s)	0	5,000	Adapted from Tan et al. 2009
Land (1×10^3 m^2)	0	18,000	Adapted from Tan et al. 2009
Nitrogen of plants (1×10^{-3} kg/s)	0	200	Adapted from ADB and CAI-Asia 2006

Table 5: Annual profit targets for each plant in the algal bioenergy park.

Annual Profit Targets (million US$/y)	AV^L	AV^U
IMB Plant	47	67
Ethanol Plant	136	217
Cements Factory	210	358
CHP Plant	546	941
Anaerobic Digestion Plant	42	47

Table 6: Balanced process table for the optimal algal bioenergy park configuration with support tenants.

Extended Process Matrix	Anchor Tenants			Support Player 1		Support Player 2		Algal Bioenergy Park
	IMB Plant	Ethanol Plant	Cements Factory	Combined Heat and Power Plant		Anaerobic Digestion Plant		
				GT-HRSG	Boiler	WWT	AD	Net Outputs
Nutrients (kg/s)	-17.38	0.00	0.00	0.00	0.00	0.00	0.00	-17.38
Carbon Dioxide (kg/s)	-184.69	0.00	0.00	0.00	0.00	0.00	0.76	-183.93
Treated Water (kg/s)	-1,041.08	-2.79	-0.32	-2,345.16	0.00	39.70	-6.49	-3,356.14
Power (MW)	-848.89	-1.10	-5.51	855.91	0.00	-0.40	-0.01	0.00
Heat (MW)	-1,204.01	-0.04	86.53	1,275.29	0.00	0.00	-0.32	157.45
Algal Biomass (kg/s)	7.40	-6.90	0.00	0.00	0.00	0.00	-0.50	0.00
Bio-solid wastes (kg/s)	1.76	0.00	-142.59	0.00	0.00	0.00	-2.49	-143.32
Wet Biomass (kg/s)	41.05	0.00	0.00	0.00	0.00	59.55	-3.00	97.60
Biogas (kg/s)	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.62
Natural Gas (kg/s)	0.00	0.00	0.00	-51.35	0.00	0.00	0.00	-51.35
Waste water (kg/s)	0.00	0.28	0.00	0.00	0.00	-99.25	6.70	-92.27
Microalgal Culture (kg/s)	-0.15	0.00	0.00	0.00	0.00	0.00	0.00	-0.15
Ethanol (kg/s)	-0.55	1.42	0.00	0.00	0.00	0.00	0.00	0.87
Bio-oil (kg/s)	3.73	0.00	0.00	0.00	0.00	0.00	0.00	3.73
Biodiesel (kg/s)	5.04	0.00	0.00	0.00	0.00	0.00	0.00	5.04
Glycerol (kg/s)	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.55
Limestone (kg/s)	0.00	0.00	-13.29	0.00	0.00	0.00	0.00	-13.29
Cement (kg/s)	0.00	0.00	32.41	0.00	0.00	0.00	0.00	32.41

In solving the objective function in Eq(1) and the constraints from Eq(2) to Eq(11) the overall λ-value is 0.092. The result of this case study yielded an optimal ABP configuration for the latter scenario shown in Table 6. Comparing the scenario where the anchor tenants were only considered versus the scenario where the support tenants were included with the anchor tenants, the overall ABP profit increased by 220 % for the latter scenario with an amount of US$ 1,572 M/y. However, the environmental impact favoured the former scenario since it has lesser impact compared to the latter scenario as shown in Table 7.

5. Conclusion

A fuzzy mathematical programming model has been developed for designing an algal bioenergy park satisfying its product demand, maximize annual profit for each company, and minimize its environmental impact. The results showed a trade-off between the profit and environmental impact of the ABP in considering the support tenants. The methodology developed may be used to draft negotiation agreements between the owners of the companies and defining the optimal algal bioenergy park configuration. Future work involves scenarios with varying demand load and with changing price of raw materials and energy.

Table 7: Graphical footprint analysis of the algal bioenergy park.

Environmental Footprint	Anchor Tenants Only	Anchor Tenants with Support Tenants
Carbon Dioxide of raw materials (kg/s)	47	2,460
Carbon Dioxide of plant (kg/s)	78	100
Water of plant (kg/s)	213	2,604
Land (1×10^3 m^2)	486	8,589
Nitrogen of plants (1×10^{-3} kg/s)	123	128

References

Asian Development Bank and Clean Air Initiative Asia (ADB and CAI-ASIA), 2006. Country Synthesis Report on Urban Air Quality Management Philippines. <www.cleanairinitiative.org/portal/system/files/documents/philippines.pdf> accessed 08.04.2015.

Castaño A.G., Bandoni J.A., Diaz M.S., 2015, Life Cycle Optimization for Sustainable Operations in a Petrochemical Complex, Chem. Eng. Trans., 43, 1441–1446.

Chisti Y., 2007, Biodiesel from microalgae, Biotechnol. Adv., 25, 294–306.

Christiansen K.L., 2011, Cost structures and life cycle impacts of algal biomass and biofuel production. Iowa State University Graduate Theses and Dissertations. Ames, Iowa, USA.

Davis R., Aden A., Pienkos P.T., 2011, Techno-economic analysis of autotrophic microalgae for fuel production, Appl. Energ., 88, 3524–3531.

Djapan M., Macuzic I., Tadic D., Jeremic B., 2015, Influence of HOT Factors on Risk Assessment Level Based on Fuzzy Set Theory, Chem. Eng. Trans., 43, 1231–1236.

East Fairfield Coal Co. (EFCC), 2014, Limestone Division 2014 Price List. North Lima, Ohio, USA. <www.eastfairfieldcoal.com/limestone-project-calculator-price-list.html> accessed on 22.03.2014.

Enr.com (ENR), 2014, Construction Economics, <enr.construction.com/economics> accessed 22.03. 2014.

Farm Futures (FF), 2014, Farmgate Fertilizer Prices Edge higher. <www.farmfutures.com/mdfm/Faress1/author/252/2014/3/WFertR031814.pdf> accessed 21.03.2014.

Frias A.P., González-Delgado Á.D., Kafarov V., 2014, Microalgae Biorefinery Trought Optimization of Strain Composition and Biomass Consumption, Chem. Eng. Trans., 43, 589 – 594.

Grima E.M., Belarbi E.H., Fernandez F.G.A., Medina A.R., Chisti Y., 2003. Recovery of microalgal biomass and metabolites: process options and economics, Biotechnol. Adv., 20, 491 – 515.

Lovelady E.M., El-Halwagi M.M., 2009, Design and integration of eco-industrial parks for managing water resources, Environ. Prog. Sustain., 28, 265−272.

New York City (NYC), 2014, New York City FY2014 Water and Wastewater Rate Report, New York, USA.

Ng R.T.L., Ng D.K.S., 2013, Systematic Approach for Synthesis of Integrated Palm Oil Processing Complex, Part 1: Single Owner, Ind. Eng. Chem. Res., 52, 10206-10220.

Ng R.T.L., Ng D.K.S., Tan R.R., 2013, Systematic Approach for Synthesis of Integrated Palm Oil Processing Complex, Part 2: Multiple Owners, Ind. Eng. Chem. Res., 52, 10221-10235.

Pinzón A.Y., González-Delgado Á.D., Kafarov V., 2014, Optimization of Microalgae Composition for Development of a Topology of Biorefinery based on Profitability Analysis, Chem. Eng. Trans., 37, 457–462.

Quispe C.A.G., Coronado C.J.R., Carvalho J.A.J., 2013, Glycerol: Production, consumption, prices, characterization and new trends in combustion, Renew. Sust. Energ. Rev., 27, 475-493.

Tan R.R., Ballacillo J.A.B., Aviso K.B., Culaba A.B., 2009, A fuzzy multiple-objective approach to the optimization of bioenergy system footprints, Chem. Eng. Res. Des., 87, 1162-1170.

The City of San Diego (SD), 2014. Water Rates. United States Energy Information Administration (USEIA), 2013, Short-term energy and summer fuels outlook, Washington DC, USA.

Ubando A.T., Culaba A.B., Tan R.R., Ng D.K.S., 2012, A Systematic Approach for Optimisation of an Algal Biorefinery Using Fuzzy Linear Programming, Comp. Aid. Chem. Eng., 31, 805-809.

Zimmermann H.J., 1978, Fuzzy programming and Linear programming with several objective functions, Fuzzy Sets Syst, 1, 45–55