Multi-objective Optimization of Biomass Supply Chain Networks

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Abstract

Food waste is a growing problem in our modern society. Approximately one third of the food produced for human consumption is disposed. Food losses and wastes occur along the entire food supply chain from harvesting to consumption. Tackling the problem of food waste will lead to a more sustainable life. Another problem facing our society is the drastic increase in energy consumption due to the continuous growth in the world population and the rise in standard of living. This increase stresses on the amount of fossil fuels being used to meet current demand, and eventually fossil fuel alone will not be able to meet the amount of energy needed by the world. This paper addresses the design of a food waste to bioethanol supply chain to tackle both problems of food wastes and energy. Three key decisions are addressed for the optimal design of the supply chain: (1) the number, sizes and location of the bio-refineries; (2) the sites and amount of food wastes collected; (3) the transportation plans of bioethanol to demand points. A multi objective (Economic, Environmental, social) model is proposed. A case study in Egypt is introduced and is proposed for future implementation.

Keywords
Biofuel; bioethanol; food waste; sustainable; biomass supply chains

1. Introduction
Energy consumption has been increasing drastically over the last 200 years and is expected to increase by 28% from 2015 to 2040 (U.S. energy information administration). The major source of energy comes from fossil fuels, with the most used today being oil, coal and natural gas (Riddle *et al.*, no date). The use of renewable resources aims at solving the problem of the limited fossil fuels. This led to an increase in research towards the production of bioenergy from biomass for a more sustainable living. Biomass refers to non-fossilized and biodegradable elements of the products, byproducts, residues and waste from agriculture, forestry and related industries which are used as the feedstock for producing biofuels and generating heat and power (Demirbas, 2009). The biomass feedstock, biofuels, can be classified into three generations. The first generation biofuel are produced directly from food crops. The biofuel is derived from the starch, sugar or vegetable oils present in the crop. Second generation biofuels are produced from non-food crops such as wood, organic wastes, food crop waste and specific biomass crops. Third generation biofuels use specially engineered crops such as algae as the energy source. The major disadvantage of first generation biofuel is that it threatens the food chain, since the feedstock used in this process can be used as food. Therefore, second and third generation biofuels have been developed to overcome the limitations of first generation biofuels (Mullan and Walker, 2009).

Food waste, which is one of the sources for second generation biofuel, is also creating serious environmental and social problems, and according to the UN food and Agriculture organization (FAO 2011) annual food losses have been estimated at about 1.3 billion tones. The food wastes produced includes rotten fruits, vegetables, vegetable peelings etc. these food wastes are mostly disposed in landfills and are known to cause hazardous effects on people, animals, and the environment. Landfills are unsustainable as they produce methane which is a common greenhouse gas and also generate large amount of harmful leachate when rainwater falls on the garbage, which can contaminate water and soil (Karmee and Lin, 2014).

One of the most important and challenging aspects of biofuel production is the design and operation of the biomass supply chain network (Kim *et al.*, 2011). In that regard, this paper aims at achieving sustainability by minimizing the amount of food wastes by utilizing food waste in the production of bioethanol. Specifically, the paper presents a mathematical model for supply chain of biofuels from potato wastes (agricultural wastes or consumption wastes) considering the maximization of the overall profit, while increasing the number of jobs created and minimizing the GHG emissions across the supply chain. The rest of the paper is organized as follows; Section 2 reviews the related work done on biomass supply chains. Section 3 highlights the potato waste supply chain structure followed by section 4 which shows the model development and finally section 5 discusses the conclusions and the future work intended for this work.

2. Literature Review

Early work related to the design of biomass supply chains focused mainly on the optimization of decision criteria (Strategic, tactical or operational) by implementing a single objective function. A multistage mixed integer linear program to minimize the total system cost throughout the entire planning horizon was developed by (Huang, Chen and Fan, 2010), the costs included harvesting of different feedstocks, fixed costs of opening a refinery, cost of ethanol production, transportation costs and finally penalty cost of not meeting ethanol demand. A scenario optimization model that minimizes the cost of biomass supply to a bio-refinery considering harvest, transportation, and storage costs was considered by (Sharma *et al.*, 2013). Similarly, (Zhang *et al.*, 2013, 2016; Bairamzadeh, Saidi-Mehrabad and Pishvaee, 2018) developed their models as a single objective function that aims to minimize the total supply chain costs. In other studies, researchers moved towards defining their objective function in order to maximize their overall profits, this can be seen in the work of (An, Wilhelm and Searcy, 2011; Awudu and Zhang, 2013; Shabani and Sowlati, 2016). While other studies incorporated the time value of money in their objective function by focusing on optimizing the net present value (NPV) of the supply chain examples of that is the work of (Rentizelas, Tatsiopoulos and Tolis, 2009a); where, they developed a decision support system, focusing at investigating and optimizing a bioenergy supply chain and conversion facility while maximizing the total NPV. Another example of optimizing NPV is a five echelon supply chain network considering multiple feed stocks studied by (Babazadeh, 2017); who designed a multi-period and MILP model that integrates the most important strategic and tactical level decisions to avoid suboptimal solutions targeting strategic and tactical decisions while minimizing the NPV of total costs.

Recently, research has been moving towards the development of sustainable models for the biomass supply chains by adopting a multi-objective function (Economic, Environmental and Social) to find a trade-off between conflicting criteria. The economic (mathematical cost modeling) and environmental (life cycle assessment) dimensions of sustainability were considered in the enhancement of the sustainability benefits of bioenergy industry infrastructure by applying it on a case study in the Pacific Northwest (Mirkouei *et al.*, 2017). A mixed integer non-linear programming was developed by (How, Tan and Lam, 2016) with the aim of maximizing the overall profit, at the same time ensuring minimal CO2 emissions. The optimal design of the biomass supply chain considering the three; economic, environmental, and social, dimensions of sustainability was addressed by (Cambero and Sowlati, 2016; Miret *et al.*, 2016; Osmani and Zhang, 2017; Zhang and Jiang, 2017).

Another main challenge in the design of the biomass supply chain, is incorporating the different types of uncertainties related to the biomass supply, bioethanol demand, technology and prices. Most previous works, did not consider the different types of uncertainties present in the supply chain, and thus worked with deterministic assumptions for parameters which either resulted in infeasible solutions or suboptimal solutions (Zhang *et al.*, 2013). Only recently has research moved towards developing mathematical models that include uncertainty such as supply, demand, price and even technology (Osmani and Zhang, 2017; Zhang and Jiang, 2017; Bairamzadeh, Saidi-Mehrabad and Pishvaee, 2018).

When it comes to modeling and solution approaches addressing the design of biomass supply chains, multiple tools are being adopted. Most studies are based on mathematical programming, although some researchers involve heuristics, multi-criteria decision analysis, GIS based solutions and simulation (Atashbar, Labadie and Prins, 2016). GIS is incorporated in the solution method to preselect potential biofuel facility locations or to calculate the distance between the biomass collection sites and the facilities (Rentizelas, Tatsiopoulos and Tolis, 2009; Huang, Chen and Fan, 2010; Mirkouei *et al.*, 2017), and only few researches, to the best of our knowledge, have been conducted using simulation models (Zhang, Johnson and Johnson, 2012).

Upon reviewing the recent literature, it is noticed that research is increasing towards the direction of designing the biomass supply chain under multiple objectives (a sustainable objective) considering the different uncertainties present in a supply chain to reflect the supply chain accurately and avoid infeasible or suboptimal solutions.

3. Potato Waste Supply Chain Structure

Potatoes are one of the most important agriculture crops for human consumption. Potatoes are a perishable commodity and many protocols are undertaken in order to minimize losses. These losses are usually designated for self-consumption by most poor families or farmers, as animal food or in the worst case thrown away. As an alternative for this economic and environmental problem recent research has been targeting the usage of these wastes for the generation of a value added product "bio-ethanol", due to their high starch composition. Figure 1 shows that after harvesting, the potatoes are cleaned and then manually inspected before packing and storage. Potato losses can occur at any point along the supply chain as:

A. Whole potatoes wastes due to imperfections in form, color, and size
B. Losses due to storage or transportation; and potato peel loses from processing of potatoes in industries and households.
C. Potato losses due to not being sold in markets

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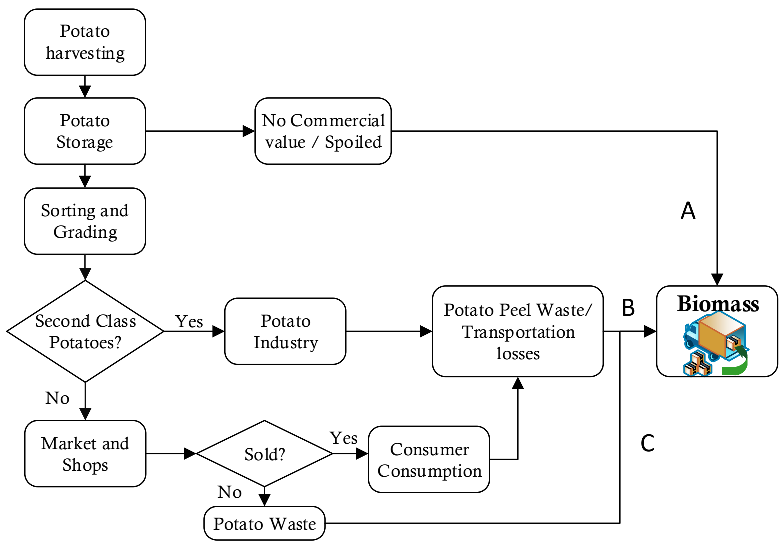

Figure 1- Potato losses

Bio-ethanol is produced from waste potatoes by undergoing a series of processes as shown in Figure 2; where, on average 0.34 liters of ethanol are produced per kilogram of dry material (approximately 24.7% of a potato is dry material) (Cardona, Orrego and Paz, 2009).

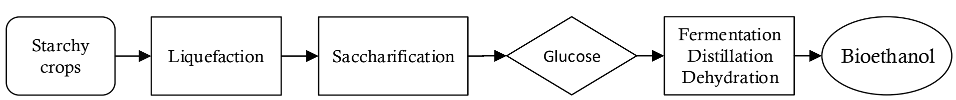

Figure 2- Stages undergone to produce bio-ethanol from potato waste

The sustainable supply chain network design addressed in this paper is a multi-period, multi-echelon network that consists of 5 layers; multiple potato waste suppliers, collection centers (c.c), bio-refineries, oil-refineries and gas stations. The ultimate objective is to determine the locations and capacities of the collection centers and bio-refineries, and make decision concerning the flow of the wastes and bio-ethanol along the network in order to maximize the economic goal, while minimizing the environmental impact and increasing the social benefit.

Figure 3 shows that potato waste is acquired from different sources, these sources differ from farm warehouses, to markets, potato industries, and even consumer households as shown in Figure 1. These wastes are collected and stored in collection centers (*cc*) of potential locations *(e)*. Later these wastes are transported to the different bio-refineries of potential locations *(i)* and capacity *(K_i)* in order to produce bio-ethanol. After the production, bio-ethanol is transferred to the oil-refineries of known locations *(r)* with predetermined capacity *(K_r)*, where they are blended at a certain percentage (from 5% to 15%) with fuel to produce a bio-ethanol fuel blend, which is then sold at gas stations of locations *(j)* where it can be used by most car engines.

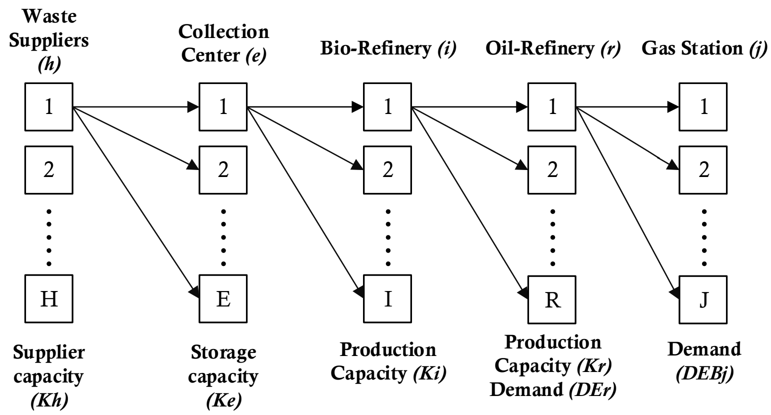

Figure 3- Structure of proposed potato waste to bio-ethanol supply chain network

4. Model Development

After presenting the food waste supply chain structure, this section aims to present a detailed description of the proposed mixed integer linear programming mathematical model for the food waste supply chain under deterministic assumptions.

4.1 Mathematical formulation

Indices

h	Waste Supply Source (h = 1, 2…H)	e	Collection Centre location (e = 1, 2…E)
i	Bio-Refinery Location (i = 1, 2…I)	r	Oil-Refinery location (r = 1, 2… R)
j	Gas Station Location (j = 1, 2… J)	t	Planning Period (t = 1, 2…T)
m	Transportation mode (m = 1, 2…M)		

Decision Variables

X_{het}	Tons of waste sent from source *(h)* to c.c. *(e)* at time *(t)*	X_{eit}	Tons of waste sent from c.c. *(e)* to bio-ref *(i)* at time *(t)*
X_{irt}	Tons of ethanol sent from bio-ref *(i)* to oil-ref *(r)* at time *(t)*	X_{rjt}	Tons of EB sent from oil-ref *(r)* to station *(j)* at time *(t)*
Y_{ht}	1 if waste source *(h)* is used at time *(t)*, 0 otherwise	Y_{ek}	1 if c.c. is opened at location *(e)* with capacity *(k)* at time *(t)*, 0 otherwise
Y_{ik}	1 if bio-refinery is opened at location *(i)* with capacity *(k)* at time *(t)*, 0 otherwise	H_{et}	Number of workers hired at collection center *(e)* at time *(t)*
H_{it}	Number of workers hired at ref*(i)* at time *(t)*	H_{rt}	No. of workers hired at oil ref *(r)* at time *(t)*
L_{et}	No. of workers laid-off from c.c. (*e*) at time *(t)*	L_{it}	No. of workers laid off from bio-ref. *(i)* at time *(t)*
L_{rt}	No. of workers laid off from oil ref. *(r)* at time *(t)*	W_{et}	Total no. of workers at c.c. *(e)* at time *(t)*
W_{it}	Total no. of workers at bio-refinery *(i)* at time *(t)*	W_{rt}	Total no. of workers at oil-refinery *(r)* at time *(t)*
HO_e	Initial no. of workers hired for the installation of c.c. *(e)*	HO_i	Initial no. of workers hired for the installation of bio-refinery *(i)*

Parameters

d_{hem}	Distance between waste source *(h)* and c.c. *(e)* using transp. mode *(m)* (miles)	d_{eim}	Distance between c.c. *(e)* and bio-ref. *(i)* using transp. mode *(m)* (miles)
d_{irm}	Distance between bio-ref. *(i)* and oil-ref. *(r)* using transp. mode *(m)* (miles)	d_{rjm}	Distance between oil-refinery *(r)* and gas station *(j)* using transp. mode *(m)* (miles)
S_{ht}	Amount of waste potato available at supply source *(h)* during time *(t)*	K_e	The storage capacity of c.c. *(e)* (tons)

K_r	The blending capacity of oil-refinery *(r)* (tons)	K_i	The production capacity of bio-refinery *(i)* (tons)
$OCap_r$	Max inventory capacity at bio-refinery *(i)*	$BCap_i$	Max inventory capacity at oil-refinery *(r)*
C_{ht}	Cost of acquiring waste from *(h)* at time *(t)* ($/ton)	CW_{et}	Wages per worker at collection center *(e)* at time *(t)*
F_{ek}	Fixed cost of opening c.c. at location *(e)* with capacity *(k)*	O_{ekt}	Operating cost of c.c. at location *(e)* with capacity *(k)* at time *(t)*
F_{ik}	Fixed cost of opening bio-refinery at location *(i)* with capacity *(k)*	O_{ikt}	Operating cost of bio-refinery at location *(i)* with capacity *(k)* at time *(t)*
PRe	Production rate of ethanol per hour (tons /hour /worker)	$PReb$	Production rate of ethanol blend per hour (tons /hour /worker)
$Hour_{rt}$	Number of hours worked per worker at oil-refinery *(r)* at time t	$Hour_{it}$	Number of hours worked per worker at bio-refinery *(i)* at time t
DEB_{jt}	The tons of ethanol blend required by station *(j)* at time *(t)*	DE_{rt}	The tons of ethanol required by oil-refinery *(r)* at time *(t)*
CL_t	Cost of laying off a worker at time *(t)* ($/worker)	CH_t	Cost of hiring a worker at time *(t)* ($/worker)
CW_{rt}	Wages per worker at oil-refinery *(r)* at time *(t)* ($/worker)	CW_{et}	Wages per worker at c.c. *(e)* at time *(t)* ($/worker)
HC_{et}	Holding cost in c.c. *(e)* at time *(t)* ($/ton/month)	CW_{it}	Wages per worker at bio-refinery *(i)* at time *(t)* ($/worker)
HC_{it}	Holding cost in bio-ref. *(i)* at time *(t)* ($/ton/month)	HC_{rt}	Holding cost in oil-ref. *(r)* at time *(t)* ($/ton/month)
SPE_t	Selling price of ethanol at time t	$SPEB_t$	Selling price of ethanol blend at time t
PW_{it}	Cost of processing 1 ton of waste at bio-ref. *(i)* at time t	PE_{rt}	Cost of processing 1 ton of ethanol at oil-ref. *(r)* at time t
EPR_{it}	Amount of ethanol produced in bio-ref. *(i)* at time *(t)*	EBP_{rt}	Amount of ethanol blend produced in oil-refinery *(r)* at time *(t)*
ETB_m	Emission of transporting a ton of biomass per mile using transportation mode m.	ETE_m	Emission of transporting a ton of ethanol per mile using transportation mode m.
$ETEB_m$	Emission of transporting ton of ethanol blend per mile using transp. mode m.	$ESEB$	Emission of storing unit amount of ethanol blend.
ESB	Emission of storing unit amount of biomass.	ECW	Emission of converting unit amount of waste biomass
ESE	Emission of storing unit amount of ethanol.	EBE	Emission of blending unit amount of ethanol
TW_{mt}	Cost of transp. 1 ton of waste using transp. mode *(m)* at time *(t)* ($/ton/mile)	TE_{mt}	Cost of transp. 1 ton of ethanol using transp. mode *(m)* at time *(t)* ($/ton/mile)
TEB_{mt}	Cost of transp. ton of ethanol blend using transp. mode *(m)* at time *(t)* ($/ton/mile)	WIC_{et}	Ending inventory of waste in collection center *(e)* at time *(t)*
EIR_{it}	Ending inventory of bio-ethanol in bio-refinery *(i)* at time *(t)*	$EBIR_{rt}$	Ending inventory of ethanol blend in oil-refinery *(r)* at time *(t)*
SW_t	Waste shortage cost at time *(t)* ($/ton)	SE_t	Ethanol shortage cost at time *(t)* ($/ton)
SEB_t	Ethanol blend shortage cost at time *(t)* ($/ton)	BW_{et}	Backordered amount of waste in c.c. *(e)* at time *(t)* (tons)
BE_{it}	Backordered amount of ethanol in bio-refinery *(i)* at time *(t)* (tons)	BEB_{rt}	Backordered amount of ethanol blend in oil-refinery *(r)* at time *(t)* (tons)
α	Rate of converting 1 ton of waste to ethanol	β	Rate of converting 1 ton of ethanol to ethanol blend

4.2 Objective function

This model serves as a multi objective function to achieve a maximum profit, while minimizing the GHG emissions and maximizing the total number of jobs created while minimizing the tons of wastes uncollected.

4.2.1 Economic objective function

The economic objective is to maximize the total net profit throughout the supply chain which is represented by subtracting the total revenue acquired from the total costs throughout the entire life of the supply chain equation (1). The total revenues acquired is presented in equation (2) which consists of the revenues gained from selling bioethanol *(X_{irt})* to the oil refineries and fuel blend *(X_{rjt})* to the gas stations. As for the total costs, it is the sum of all equations (3-12), it contains all the cost factors across the entire supply chain, which typically include costs of acquiring the wastes, cost of transportation, cost of holding wastes, bioethanol and fuel blend, fixed cost of opening collection centers at location *(e)* with capacity *(K_e)* and bio-refineries at locations *(i)* with capacity *(K_i)*, operating cost of bio-refinery and oil-refinery, cost of not meeting demand and finally workforce cost, and hiring and laying off costs.

$$Total\ profit = TR - TC \quad (1)$$

$$TR = \sum_{i,r,t} X_{irt} * SPE_t + \sum_{r,j,t} X_{rjt} * SPEB_t \quad (2)$$

$$Cost\ of\ transportation\ = \sum_{t,m,e,h} TW_{mt} * d_{hem} * X_{hemt} + \sum_{t,m,i,e} TW_{mt} * d_{eim} * X_{eimt} + \sum_{t,m,r,i} TE_{mt} * d_{irm} * X_{irmt} + \sum_{t,m,j,r} TEB_{mt} * d_{rjm} * X_{rjmt} \quad (3)$$

$$Cost\ of\ aquiring\ waste = \sum_{t,e,h} X_{het} * C_{ht} \quad (4)$$

$$Cost\ of\ holding\ inventory = \sum_{t,e} HC_{et} * WIC_{et} + \sum_{t,i} HC_{it} * EIR_{it} + \sum_{t,r} HC_{rt} * EBIR_{rt} \quad (5)$$

$$Fixed\ cost\ of\ collection\ center = \sum_{e,k} F_{ek} * Y_{ek} \quad (6)$$

$$Fixed\ cost\ \ and\ operating\ cost\ of\ bio-refinery = \sum_{i,k} F_{ik} * Y_{ik} + \sum_{t,i} X_{it} * PW_{it} \quad (7)$$

$$Operating\ cost\ of\ oil-refinery = \sum_{t,r} X_{rt} * PE_{rt} \quad (8)$$

$$Backlog\ cost = \sum_t (SW_t * \sum_e BW_{et}) + \sum_t (SE_t * \sum_i BE_{it}) + \sum_t (SEB_t * \sum_r BEB_{rt}) \quad (9)$$

$$Hiring\ cost = \sum_t [CH_t * (\sum_e H_{et} + \sum_i H_{it} + \sum_r H_{rt})] \quad (10)$$

$$Laying\ off\ cost = \sum_t [CL_t * (\sum_e L_{et} + \sum_i L_{it} + \sum_r L_{rt})] \quad (11)$$

$$Workforce\ cost = \sum_t [\sum_e W_{et} * CW_{et} + \sum_i W_{it} * CW_{it} + \sum_r W_{rt} * CW_{rt}] \quad (12)$$

4.2.2 Environmental objective function

The environmental objective is to minimize the total greenhouse gas emissions from the supply chain equation (13); where, different sources of emissions are considered. These include emissions from transportation of the wastes to collection centers and bio-refineries (ETB_m), bioethanol to oil-refineries (ETE_m) and fuel blend to gas stations$(ETEB_m)$, emissions due to storage of the waste (ESB) bio-ethanol (ESE) and fuel blend $(ESEB)$ and finally emissions due to the processing of wastes to bioethanol(ECW), and blending bioethanol with fuel (EBE).

$$\sum_{t,m,e,h} (ETB_m * d_{hem}) * X_{hemt} + \sum_{t,m,i,e} (ETB_m * d_{eim}) * X_{eimt} + \sum_{t,m,r,i} (ETE_m * d_{irm}) * X_{irmt} + \sum_{t,m,j,r} (ETEB_m * d_{rjm}) * X_{rjmt} + \sum_{t,e} ESB * BIC_{et} + \sum_{t,i} ESE * EIR_{it} + \sum_{t,r} ESEB * EBIR_{rt} + \sum_{t,i,e} ECW * X_{eit} + \sum_{t,r,i} EBE * X_{irt} \quad (13)$$

4.2.3 Social objective function

In this section the two social objectives are discussed. The first is to maximize the expected number of jobs created over the entire life of the supply chain, which is the number of jobs created during the installation of collection centers and bio-refineries plus the number of jobs created due to the operation of the collection center, bio-refinery and oil-refinery equation (14). The second objective function aims at increasing the public health by minimizing the potato waste left uncollected equation (15).

$$Max\ Jobs\ created = \sum_e H_{oe} + \sum_i H_{oi} + \sum_t [\sum_e (H_{et} - L_{et}) + \sum_i (H_{it} - L_{it}) + \sum_r (H_{rt} - L_{rt})] \quad (14)$$

$$Min\ uncollected\ Potato\ waste = \sum_{t,h} (S_{ht} - \sum_e X_{het}) \quad (15)$$

4.3 Constraints

4.3.1 Supply Constraint

Equation (16) ensures that the amount sent from and waste source h, does not exceed the supply capacity of that source given that source *(h)* is used at time t. While equations (17 and 18) guarantee that the amount of units sent from bio-refinery to the oil-refinery, or from the oil-refinery to the gas stations do not exceed the amount of ethanol / ethanol blend produced during time t.

$$\sum_{e=1}^{E} X_{het} \leq S_{ht} * Y_{ht} \quad \forall_h \in H, \quad \forall_t \in T \quad (16)$$

$$\sum_{r=1}^{R} X_{irt} \leq EP_{it} \quad \forall_i \in I, \quad \forall_t \in T \quad (17)$$

$$\sum_{j=1}^{J} X_{rjt} \leq EBP_{rt} \quad \forall_r \in R, \quad \forall_t \in T \quad (18)$$

4.3.2 Mass balance constraint

Equations (19, 20 and 22) in this section ensures that the total quantities that are sent from the collection center, bio-refinery or oil-refinery; respectively, are equal to the inventory of the previous period plus the quantities that are received at period t plus the amount backordered in period t minus the amount that was backordered the previous period and finally minus the ending inventory of this period. While equations (21 and 23) explain that the amount of ethanol and ethanol blend produced in refinery *(i)* and refinery *(r)* at time t equals the total amount of waste, ethanol that was received by refinery *(i)*, refinery *(r)* times the conversion factor respectively.

$$\sum_i X_{eit} = WIC_{e\,t-1} + \sum_h X_{het} - BW_{e\,t-1} + BW_{et} - WIC_{et} \quad \forall_e \in E, \quad \forall_t \in T \tag{19}$$
$$\sum_r X_{irt} = EIR_{i\,t-1} + EP_{it} - BE_{i\,t-1} + BE_{it} - EIR_{it} \quad \forall_i \in I, \quad \forall_t \in T \tag{20}$$
$$EP_{it} = \sum_{t,i,e} X_{eit} * \alpha \tag{21}$$
$$\sum_j X_{rjt} = EBIR_{r\,t-1} + EBP_{rt} - BEB_{r\,t-1} + BEB_{rt} - EBIR_{rt} \quad \forall_r \in R, \quad \forall_t \in T \tag{22}$$
$$EBP_{rt} = \sum_{t,r,i} X_{irt} * \beta \tag{23}$$

4.3.3 Capacity constraints

Equation (24) ensures that the quantities of waste that are received by collection center *(e)* do not exceed its storage capacity during time *(t)*. While equations (25 and 26) ensures that the quantities of waste and ethanol used in bio-refinery *(e)* and oil-refinery *(i)* do not exceed the maximum production capacity at time *(t)*.

$$\sum_h X_{het} + WIC_{et} \leq K_e * Y_{ek} \quad \forall_e \in E, \quad \forall_t \in T \tag{24}$$
$$\sum_e X_{eit} \leq K_i * Y_{ik} \quad \forall_i \in I, \quad \forall_t \in T \tag{25}$$
$$\sum_i X_{irt} \leq K_r \quad \forall_r \in R, \quad \forall_t \in T \tag{26}$$

4.3.4 Work force constraint

Equations (27 and 28) ensure that the tons of ethanol/ethanol blend do not exceed the workforce production rate at time t. while equations (29 and 30) show that the workforce level at time t equals the workforce level of the period before plus the number of workers hired minus the workers fired during period *(t)*.

$$EP_{it} \leq PRe * W_{it} * Hour_{it} \quad \forall_i \in I, \quad \forall_t \in T \tag{27}$$
$$EBP_{rt} \leq PReb * W_{rt} * Hour_{rt} \quad \forall_r \in R, \quad \forall_t \in T \tag{28}$$
$$W_{it} = W_{i\,t-1} + H_{it} - L_{it} \quad \forall_i \in I, \quad \forall_t \in T \tag{29}$$
$$W_{rt} = W_{r\,t-1} + H_{rt} - L_{rt} \quad \forall_r \in R, \quad \forall_t \in T \tag{30}$$

4.3.5 Ethanol production constraint

Equation (31) ensures that all the waste biomass transported to the bio-refinery in period *t* should be transformed to ethanol in period *(t)* (since there is no inventory of waste at the bio-refinery).

$$\alpha * \sum_{t,i,e} X_{eit} = EIR_{it} + \sum_{t,r,i} X_{irt} \tag{31}$$

4.3.6 Ethanol blend constraint

Equation (32) ensures that all the ethanol transported to the oil-refinery in period *t* should be transformed to ethanol blend in period *t* (as there is no inventory of ethanol at the oil-refinery).

$$\beta * \sum_{t,r,i} X_{irt} = EBIR_{rt} + \sum_{t,j,r} X_{rjt} \tag{32}$$

4.3.7 Demand Constraint

Equations (33 and 34) ensures that the quantities of ethanol and ethanol blend sent does not exceed the demand required by the oil-refinery and gas stations respectively.

$$\sum_i X_{irt} = DE_{rt} \quad \forall_r \in R, \quad \forall_t \in T \tag{33}$$
$$\sum_r X_{rjt} = DEB_{jt} \quad \forall_j \in J, \quad \forall_t \in T \tag{34}$$

4.3.8 General constraints

The non-negativity, integer and binary constraints are expressed in equations (35, 36 and 37) respectively.

$$X_{het}, X_{irt}, X_{eit}, X_{rjt}, S_{ht} \geq 0 \tag{35}$$
$$H_{oe}, H_{oi}, H_{et}, H_{it},, H_{rt}, L_{et}, L_{it}, L_{rt}, W_{et}, W_{it}, W_{rt} \quad integer \tag{36}$$
$$Y_{ht}, Y_{ikt}, Y_{ekt} \in \{0,1\} \tag{37}$$

5. Case Study

This paper takes General Company for Agricultural Agencies (GECO), Egypt as a case study to verify the proposed methodology. GECO is the sole Agent for Agro-plant Holland Company which produces the finest quality of potato seeds. GECO imports these potato seeds, a portion of them is distributed to potato industries where those seeds are sent to the factories farms for planting. While the remaining potato seeds are planted in GECO farms. The harvested potatoes are then distributed to local markets around Cairo and Alexandria. GECO currently owns two farms; 170 acres farm located in Kilo 122 Alex-Cairo Desert Road & a 1000 acres farm located in Al-Minya Governorate, and is preparing the opening of their third farm in 2018 located in El-Dabaa as shown in Figure 4.

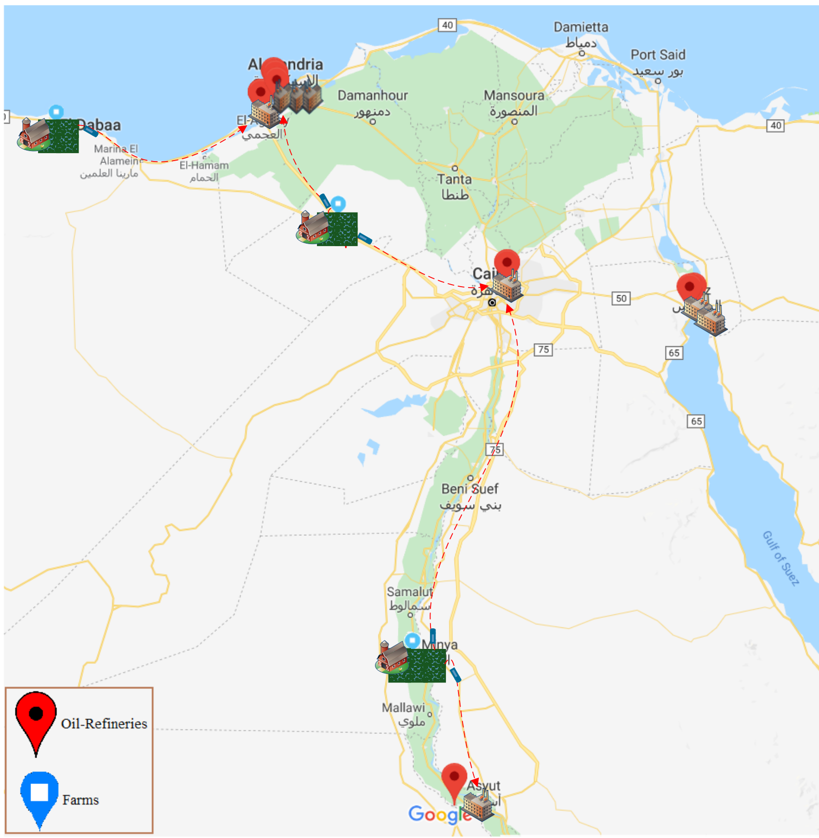

Figure 4- The locations of the oil-refineries (Red locator) with the farm locations (Blue)

Potatoes have three seasons; early-season potatoes take approximately 60–70 days to mature and harvest; mid-season, approximately 80; and late-season, more than 90. After harvesting, potatoes are taken to the farm warehouse where they are sorted and manually inspected for any size or color defects, and then stored for delivery. Potatoes are stored in a cool well vented area, usually at a temperature of 50°F. After storage potatoes are distributed to markets around Alexandria and Cairo using trucks, since there is no area for the use of railway or air as a mean of transportation.

5.1 Suppliers

After potato harvesting and storing the potatoes are sorted and sent to different potato markets located in Alexandria and Cairo. These markets sell the potatoes to consumers for its use in households. Potato losses occur throughout these stages as mentioned in section 3. 25% of the potatoes harvested, 17% of the potatoes reaching the markets and 24% of the potatoes used in households are labelled as "losses" (Willersinn *et al.*, 2017). Therefore in this research the potato waste suppliers are the farms, markets and consumer households.

5.2 Collection Centers and Bio-Refineries

Data on the candidate locations of the collection centers and bio-refineries are still being gathered, but it is known that their locations will be mainly set around the suppliers and oil-refineries. Exact candidate locations and their associated costs are still under investigation.

5.3 Oil Refineries

Egypt is the biggest oil refiner in Africa with a total of ten refining companies operating 12 refineries. These include:

1. Middle east oil refinery (MIDOR) - is located in the Ameryia specialized free zone in Alexandria with a maximum refining capacity of 215,000 barrels/ day
2. Cairo oil refining company (CORC) - CORC has two refineries. One is in Mostorod with a maximum production capacity of 142,000 barrels a day. The other is in Tanta whose production capacity is 35,000 barrels a day
3. Egyptian refining company (ERC) - is located in Mostorod and its current maximum refining capacity is around 28 million tons a year.
4. Alexandria Petroleum company (APC) - The refinery's main facility is El Mex Refinery whose maximum refining capacity is around 117,000 barrels per day.
5. Alexandria minerals and oil company (AMOC) – Is located in El Mex
6. Alexandria National Refining and Petrochemicals Company (ANRPC) -
7. Nasr Petroleum Company (NPC)- Capacity 146,000 barrels /day
8. Amreya Petroleum Refining Company (ARPC) - Its current maximum production capacity is 81,000 barrels a day
9. Suez Oil Processing Company (SOPC) - SOPC has a maximum capacity of 70,000 barrels a day as of 2016
10. Assuit Oil Refining Company (AORC) - Its current maximum production capacity is five million tons.

The location of these oil refineries are shown in Figure 4 along with the locations of GECO's farms. As mentioned earlier, candidate location of bio refineries is still under investigation; once known, all the distances between the suppliers, collection centers, bio-refineries, oil-refineries and gas stations will be calculated by using the aid of Google Maps. The recommended tool that is considered for solving the MILP (once the remaining data are available) is LINGO as it can handle of problem with such complexity in terms of the number of variables and constraints.

6. Conclusion and Future Work

To conclude this work, a mixed integer linear programming mathematical model was constructed to help in the design of a potato waste biomass supply chain. To the best of our knowledge this paper is the first to address the design of a potato waste to ethanol supply chain. Also in this paper, the standard aggregate planning problem (which determines the production levels, inventory levels along the supply chain, hiring and laying off employees, backorders and demand satisfaction levels; while, maximizing the profit) is extended to include the environmental and social benefits with the purpose of incorporating sustainability.

The future work intended is to apply this model to the case study mentioned in the previous section to determine the optimal design of the potato waste supply chain under deterministic assumptions. Then the model will be extended to address the uncertainties present in the supply chain, such as, supply, demand, and price of potato waste and ethanol, by incorporating different scenarios to the deterministic model, in order to mimic real life and reach the optimum sustainable objective. An economic objective that maximizes the total profit earned throughout the network. An environmental objective that aims at minimizing the total greenhouse gas emitted from the transportation of wastes, bioethanol and fuel blend, and from the production process. And finally two social objectives; one that maximizes the total number of jobs created, from the installation of the collection centers and bio-refineries, and their operation, and the other aims at minimizing the total amount of potato wastes uncollected from the supply sources in order to help improve the public health.

Acknowledgment

We would like to thank the General Company for Agricultural Agencies, Alexandria Egypt, for their contributions to the case study presented in this paper.

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