MATHEMATICAL MODEL OF SUSTAINABLE INTEGRATED BIOETHANOL SUPPLY CHAINS

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Absract: *This paper focuses on designing mathematical model a integrated bioethanol supply chain (IBSC) that will account for economic and environmental aspects of sustainability. A mixed integer linear programming model is proposed to design an optimal IBSC. Bioethanol production from renewable biomass has experienced increased interest in order to reduce Bulgarian dependence on imported oil and reduce carbon emissions. Concerns regarding cost efficiency and environmental problems result in significant challenges that hinder the increased bioethanol production from renewable biomass. The model considers key supply chain activities including biomass harvesting/processing and transportation. The model uses the delivered feedstock cost, energy consumption, and GHG emissions as system performance criteria. The utility of the supply chain simulation model is demonstrated by considering a biomass supply chain for a biofuel facility in Bulgarian scale. The results show that the model is a useful tool for supply chain management, including selection of the optimal bioethanol facility location, logistics design, inventory management, and information exchange.*

KEYWORDS*: BIOETHANOL SUPPLY CHAIN, MATHEMATICAL MODEL, ECONOMIC AND ENVIRONMENTAL ASPECTS*

1. Introduction

Production and use of biofuels are promoted worldwide. Their use could potentially reduce emissions of greenhouse gases and the need for fossil fuels [1]. Accordingly, the European Union imposes a mandatory target of 10% biofuels by 2020 [2]. These fuels are produced from biomass. Their use for energy purposes has the potential to provide important benefits. Burning them releases such amount of CO_2 as was absorbed by the biomass in its formation [3]. Another advantage of biomass is its availability in the world due to its variety of sources. Despite the advantages of biomass with increasing quantities of biofuels to achieve the objectives of the European Union, this is accompanied by growing quantities of waste products. These wastes are related to the lifecycle of biofuels from crop cultivation, transportation, production to distribution and use. The main liquid biofuels are bioethanol and biodiesel. Depending on the raw material used, production is considered in three generations.

The first generation used as feedstock crops containing sugar and starch to produce bioethanol, and oilseed crops to produce biodiesel [4]. In the production of biodiesel, the advantage of these materials is that they can be grown on contaminated and saline soils, as the process does not affect the fuel production. The drawback is that they raise issues related to their competitiveness in the food sector. These materials also have a negative impact in terms of the quantity of water consumed. This is related to their cultivation that requires significant amounts of water resources. Excessive use of fertilizers, pesticides and chemicals to grow them also leads to accumulation of pollutants in groundwater that can penetrate into water courses and thus degrade water quality.

According to the second generation, bioethanol is produced by using as raw material waste biomass (agricultural and forest waste) [5], i.e. lignocellulose which is transformed into a valuable resource as bioethanol. Biofuel production second generation is an excellent way to deal with increasingly restrictive national and European regulations in this area and the use of organic waste for energy production and fertilizer as a byproduct. Logistics and use of these materials can be challenging due to the fact that they are usually dispersed. Another disadvantage from an environmental perspective is the need for further purification and processing.

The third generation comprises production from microalgae which occur as promising feedstock for biofuel production. The advantage of this biomass is that it is a year-round production and does not compete with the food industry.

The main technologies for production of bioethanol are fermentation, distillation and dehydration [6]. The wastes of biofuels are divided into production and performance. The technological waste is produced mainly in the creation of products that occur as waste production. The management of these wastes is related to their reduction, recovery and disposal. These guidelines are united in the idea of acquiring more sophisticated production processes. Efforts are focused on the use of new sources of raw materials, new processes, and new ways of realization of the side products. The use of by-products as raw materials for other production closes cycle in the supply chain, reducing the price of obtaining fuel. Operational waste associated with gases and emissions released during operation and the burning of biofuels.

2. Aim

The present study deals with the issue of designing optimal Integrated Bioethanol Supply Chains (IBSC) for waste management in the process of biofuel production and usage. Tools have been developed for formulation of a mathematical model for description of the parameter, the restrictions and the goal function.

3. Problem statement

The problem addressed in this work can be formally stated as follows. Given are a set of biofuel crops that can be converted to bioethanol. These include agricultural feedstock's e.g. wheat, corn, etc. A planning horizon of one year for government regulations including manufacturing, construction and carbon tax is considered. A IBSC network superstructure including a set of harvesting sites and a set of demand zones, as well as the potential locations of a number of collection facilities and bio refineries are set. Data for biofuel crops production and harvesting are also given. For each demand zone, the biofuel demand is given, and the environmental burden associated with bioethanol distribution in the local region is known. For each transportation link, the transportation capacity, available transportation modes, distance, and emissions of each transportation type are known.

3.1. General Formulation of the Problem

The overall problem can be summarized, as follows:

- Optimal locations of biofuel production centers,
- Demand for petroleum fuel for each of the demand centers,
- The minimum required ratio between petroleum fuel and biofuel for blending,
- Biomass feedstock types and their geographical availability,
- Specific Green House Gas (GHG) emission factors of the biofuel life cycle stages,
- Potential areas where systems for utilization of solid waste from production can be installed.

The objectives are to minimize total cost of a IBSC by optimizing the following decision variables:

- Supply chain network structure,
- Locations and scales of bioethanol production facilities and biomass cultivation sites,
- Flows of each biomass type and bioethanol between regions,
- Modes of transport for delivery for biomass and bioethanol,
- The GHG emissions for each stage in the life cycle,
- Supply strategy for biomass to be delivered to facilities,
- Distribution processes for biofuel to be sent to demand zones.

4. Model formulation

The role of the optimization model is to identify what combination of options is the most efficient approach to supply the facility. The problem for the optimal location of bioethanol production plants and the efficient use of the available land is formulated as a MILP model with the following notation:

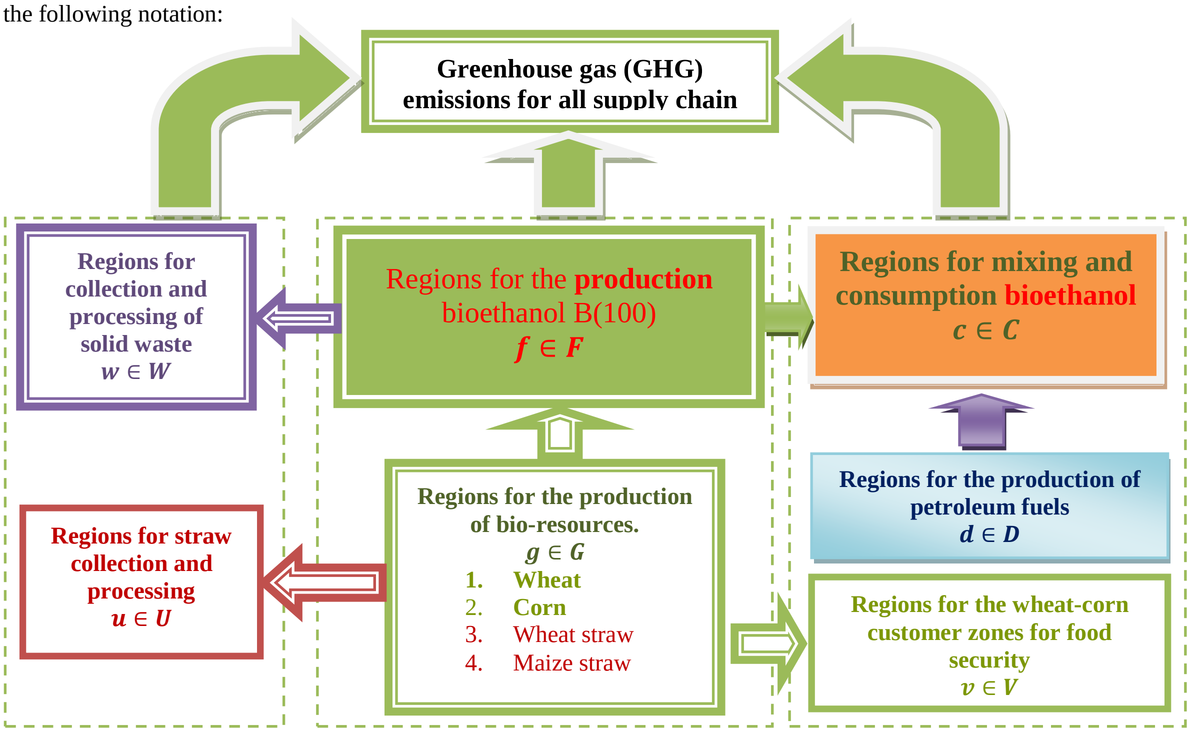

Figure 1. Superstructure integrated bioethanol supply chain (IBSC)

4.1. Mathematical model description

To start with the description of the MILP model, we first introduce the parameters, that are constant and known a priori, and the variables that are subject to optimization. Then we describe step by step the mathematical model by presenting the objective function and all the constraints. First of all, we introduce the set of time intervals of the horizon of planning $t = \{1, 2, ..., T\}$.

In this article the mathematical model that is used in the network design is described. Before describing the mathematical model, the input parameters, the decision variables, and the sets, subsets and indices are listed below.

4.1.1. Sets, subsets and indices

The following sets and subsets are introduced:

Sets/indices

I	Set of biomass types indexed by i;
LF	Set of transport modes indexed by lf;
P	Set of plant size intervals indexed by $p = \overline{1, N_p}$;
S	Set of utilization plant size intervals indexed by $s = \overline{1, N_s}$;
GF	Set of regions of the territorial division indexed by gf;
K	Set of proportion of bioethanol and gasoline indexed by k;
T	Set of time intervals, indexed by t.

Subsets/indices

B	Set of transport modes for bioethanol and gasoline is a subset of LF ($B \subset FL$) indexed by b;
L	Set of transport modes for biomass is a subset of LF ($L \subset LF$) indexed by l;
M	Set of transport modes for solid wastes is a subset of LF ($M \subset LF$) indexed by m;
E	Set of transport modes for straw is a subset of LF ($E \subset LF$) indexed by e;
Z	Set of transport modes for wheat-corn for food security is a subset of LF ($Z \subset LF$) indexed by z;
F	Set of candidate regions for bioethanol plants established, which is a subset of GF ($F \subset GF$) indexed by f;
C	Set of bioethanol mixing and customer zones, which is a subset of GF ($C \subset GF$) indexed by c;
D	Set for delivery and production gasoline, which is a subset of GF ($D \subset GF$) indexed by d;
W	Set for regions for collection and processing of solid waste, which is a subset of GF ($W \subset GF$) indexed by w;
U	Set for regions for straw collection and processing, which is a subset of GF ($U \subset GF$) indexed by u;
V	Set for regions for the wheat-corn customer zones, which is a subset of GF ($V \subset GF$) indexed by v;

4.1.2. Input parameters for the problem

Environmental parameters:

$EFBP_{ip}$ Emission factor for bioethanol production from biomass type $i \in I$ using technology $p \in P$, [$kg\ CO_2 - eq / ton\ biofuel$];

ESW Emission factor of pollution caused by one tone of solid waste if not used, [$\frac{kg\ CO_2 - eq}{ton\ solid\ waste}$]

$EFDP_d$ Emission factor for gasoline production in region $d \in D$, [$kg\ CO_2 - eq / ton$ gasoline];

$EFTRA_{il}$ Emission factor for biomass $i \in I$ supply via mode $l \in L$, [$kg\ CO_2 - eq / ton$ km];

$EFTRB_b$ Emission factor for bioethanol supply via mode $b \in B$, [$kg\ CO_2 - eq / ton$ km];

$EFTM_{il}$ Emission factor of transportation of biomass $i \in I$ for mode $l \in L$, [$kg\ CO_2 - eq / ton$ km];

$EFTB_b$ Emission factor of transportation of bioethanol and gasoline for mode $b \in B$, [$kg\ CO_2 - eq / ton$ km];

$EFTRW_m$ Emission factor for transport of solid waste with transport $m \in M$, [$kg\ CO_2 - eq / ton$ km];

$EFTRU_e$ Emission factor for transport of straw with transport $e \in E$, [$kg\ CO_2 - eq / ton$ km];

$EFTRV_z$ Emission factor for transport of wheat-corn for food security with transport $z \in Z$, [$kg\ CO_2 - eq / ton$ km];

ECB, ECG Emissions emitted during the combustion of CO_2 unit bioethanol and, gasoline, [$kg\ CO_2 - eq / ton\ bioethanol$] or; [$kg\ CO_2 - eq / ton$ gasoline$l$].

Monetary parameter:

$CosB_p$, $CosW_s$ Capital investment of bioethanol plant size $p \in P$ and capital investment of solid waste plant size $s \in S$, [\$];

C_{CO_2} Carbon tax per unit of carbon emitted from the operation of the IBSC, [$\$ / kg\ CO_2 - eq$];

PG Price of gasoline, [$\$ / ton$];

UTI_{il}, UTB_b, UTG_b, UTS_m, UTU_e, UTV_z, Unit transport cost for biomass $i \in I$, via mode $l \in L$, bioethanol via mode $b \in B$, gasoline via mode $b \in B$, solid wastes via mode $m \in M$, straw via mode $e \in E$, wheat-corn for food security via mode z, [$\$ / ton\ k$m];

Technical parameters:

PB_p^{MAX} / PB_p^{MIN} Maximum/Minimum annual plant capacity of size $p \in P$ for bioethanol production, [$ton / year$];

ENO, ENB Energy equivalent unit of gasoline&bioethanol, [GJ / ton];

ADD_{dcb}, ADG_{gfl}, ADF_{fcb}, ADU_{gue}, ADW_{fwm}, ADV_{gvz} Actual delivery distance between grids via model of transport ($b \in B$, $l \in L$, $e \in E$, $m \in M$, $z \in Z$), [km];

SW_{ip} The total amount of solid waste generated for production of bioethanol using biomass i for technology p, [$\frac{ton\ solid\ waste}{ton\ biofuel}$];

$JobB_p$, $JobO_p$ The number of jobs needed to build and operation a bio-refinery with size $p \in P$ for year;

$JobG_{ig}$ The number of jobs required to grow a unit of $i \in I$ biosource in the region $g \in G$ per year.

Environmental parameters depending on the time interval:

$EFBC_{igt}$ Emission factor for cultivation of biomass type $i \in I$ in region $g \in G$ for each time interval t, [$kg\ CO_2 - eq / ton\ biomass$];

TEI_t^{MAX} Maximum total environmental impact, [$kg\ CO_2 - eq\ d^{-1}$].

Monetary parameters depending on the time interval

ς_t Interest rate, $\%$;

ε_t Discount factor;

M_{ft}^{const} Factor to the change of the base price, depending on the region $f \in F$ where the plant is installed, [$Dimensionless$];

$Cost_{pft}^F$ Capital investment of plant size $p \in P$ for bioethanol production in each zones $f \in F$, [\$];

INS_{ft} The government incentive includes construction incentive and volumetric from region $f \in F$, [$\$ / ton$];

UPC_{igt} Unit production costs for biomass type $i \in I$ in region $g \in G$ for each time interval $t \in T$, [$\$ / ton$];

UPB_{ipft} Unit bioethanol production cost from biomass type $i \in I$ at a biorafinery of scale $p \in P$ installed in region $f \in F$, [$\$ / ton$];

UPD_{dt} Unit gasoline production cost at a rafinery d, [$\$ / ton$].

Technical parameters depending on the time interval

K_{ct}^{mix} Proportion of bioethanol and gasoline subject of mixing for each of the customer zones, [$Dimensionless$];

A_{gt}^S Set-aside area available in region $g \in G$ for biomass production for each time interval $t \in T$, [ha];

A_{gt}^{Food} Set-aside area available in region $g \in G$ for food, [ha];

β_{igt} Production rate of biomass i in region $g \in G$, [ton / ha];

LT_t Duration of time intervals $t \in T$, [$year$];

α_t Operating period for IBSC in a year, [$d / year$];

γ_{ipt} Biomass to bioethanol conversion factor specific for biomass i using technology p, [$ton\_bioethanol / ton\_biomass$];

YO_{ct} Gasoline demand in customer zones $c \in C$, [$ton / year$];

$PBI_{igt}^{MIN} / PBI_{igt}^{MAX}$ Minimum/ Maximum biomass of type $i \in I$ which can be produced in the region, $g \in G$ per year, [$ton / year$];

QI_{igt}^{MAX} Maximum flow rate of biomass i from region g, [ton / d];

QB_{ft}^{MAX} Maximum flow rate of bioethanol from region f, [ton / d];

QD_{dt}^{MAX} Maximum flow rate of gasoline from region d, [ton / d];

QW_{ft}^{MAX} Maximum flow rate of solid wastes from f, [ton / d];

QU_{gt}^{MAX} Maximum flow rate of srtaw from region $g \in G$, [ton / d];

QV_{gt}^{MAX} Maximum flow rate of wheat-corn from $g \in G$, [ton / d];

4.1.3. Decision variables for the problem X_t

To find the optimal configuration of the IBSC, the following decision variables are required:

A/ Positive continuous variables

PBB_{igt} Biomass i demand in region $g \in G$ at time interval $t \in T$;

QI_{igflt} Flow rate of biomass $i \in I$ via mode $l \in L$ from region $g \in G$ to $f \in F$, for each $t \in T$, [ton / d];

QB_{fcbt} Flow rate of bioethanol produced from all biomass $i \in I$ via mode $b \in B$ from region $f \in F$ to $c \in C$ for each $t \in T$, [ton / d];

QBP_{ifcbpt} Flow rate of bioethanol produced from biomass i via mode b from f to c using technology p for each $t \in T$, [ton / d];

QD_{dcbt} Flow rate of gasoline via mode $b \in B$ from region $d \in D$ to $c \in C$, for each time interval $t \in T$, [ton / d];

QW_{fwmt} Flow rate of solid waste via mode $m \in M$ from region $f \in F$ to $w \in W$, for each $t \in T$, [ton / d];

QU_{guet} Flow rate of straw collection and processing via mode e from region g to u, for each $t \in T$, [ton / d];

QV_{gvzt} Flow rate of wheat-corn for food security via mode $z \in Z$ from region $g \in G$ to $v \in V$, for each $t \in T$, [ton / d];

QED_{ct} Quantity of gasoline to be supplied to meet the energy needs of the region $c \in C$, for each $t \in T$, [$ton / year$];

QEB_{ct} Quantity of bioethanol produced from biomass to be supplied to meet the energy needs of the region $c \in C$, [$ton / year$];

A_{igt} Land occupied by crop $i \in I$ in region $g \in G$, [ha];

A_{igt}^F Land by crops $i \in I$ needed for food security of the population in the region $g \in G$, for each $t \in T$, [ha];

B/ Binary variables

X_{igflt} 0-1 variable, equal to 1 if a biomass type i is transported from region g to f using transport l, and 0 otherwise at $t \in T$;

Y_{fcbt} 0-1 variable, equal to 1 if a bioethanol is transported from region f to c using transport b, l, and 0 otherwise at $t \in T$;

WS_{fwmt} 0-1 variable, equal to 1 if a solid waste is transported from region f to w using transport m and 0 otherwise for each $t \in T$;

WU_{guet} 0-1 variable, equal to 1 if a straw is transported from region g to $u \in U$ using transport $e \in E$ and 0 otherwise for each $t \in T$;

WV_{gvzt} 0-1 variable, equal to 1 if a wheat-corn is transported from region g to v using transport z and 0 otherwise for each $t \in T$;

ZW_{swt} 0-1 variable, equal to 1 if a solid waste utilization plant size s is installed in region w and 0 otherwise at time interval $t \in T$;

ZWF_{swt} 0-1 variable, equal to 1 if a solid waste utilization plant size s is to be working in region w and 0 otherwise at $t \in T$, which includes the plants installed in the previous time and the new ones built during this time which is calculate with equation $ZWF_{swt} = ZWF_{sw(t-1)} + ZW_{swt}$ for first year ($t = 1$) configuration is set by initializing $ZWF_{sw'1'} = ZW_{sw'1'}$;

Z_{pft} 0-1 variable, equal to 1 if a bioethanol production plant size p is to be established in region f and 0 otherwise for each $t \in T$;

ZF_{pft} 0-1 variable, equal to 1 if a bioethanol production plant size $p \in P$ is to be working in region $f \in F$ and 0 otherwise at time interval $t \in T$, which includes the plants installed in the previous time interval and the new ones built during this time interval which is calculate with equation $ZF_{pft} = ZF_{pf(t-1)} + Z_{pft}$ for first year ($t = 1$) configuration is set by initializing $ZF_{sw'1'} = Z_{sw'1'}$;

PD_{dt} 0-1 variable, equal to 1 if a gasoline is manufactured by the region $d \in D$ and 0 otherwise at time interval $t \in T$;

DT_{dcbt} 0-1 variable, equal to 1 if a gasoline is transported from region d to c using transport b and 0 otherwise for each $t \in T$.

4.1. Basic Relationships

As noted above, the assessment of IBSC production and distribution of bioethanol will be made by environmental and economic criteria.

4.1.1. Model of total environmental impact of IBSC

The environmental impact of the IBSC is measured in terms of total GHG emissions ($kg\,CO_2 - eq$) stemming from supply chain activities and the total emissions are converted to carbon credits by multiplying them with the carbon price in the market.

The environmental objective is to minimize the total annual GHG emission resulting from the operations of the IBSC. The formulation of this objective is based on the field-to wheel life cycle analysis, which takes into account the following life cycle stages of biomass-based liquid transportation fuels:

- biomass cultivation, growth and acquisition,
- biomass transportation from source locations to facilities,
- transportation of bioethanol facilities to the demand zones,
- local distribution of liquid transportation fuels in demand zones,
- emissions from bioethanol and gasoline usage.

Ecological assessment criteria will represent the total environmental impact at work on IBSC through the resulting GHG emissions for each time interval t. These emissions are equal to the sum of the impact that each of the stages of life cycle has on the environment. The GHG emission rate is defined as follows for each $t \in T$:

$$TEI_t = ELS_t + ELB_t + ELD_t + ETT_t + ESW_t + ECAR_t, \forall t \qquad (1)$$

where

TEI_t Total GHG impact at work on IBSC [$kg\,CO_2 - eq\,d^{-1}$];

$\{ELS_t, ELB_t, ELD_t, ETT_t\}$ GHG impact of life cycle stages;

$ECAR_t$ Emissions from bioethanol and gasoline usage in vehicle operations [$kg\,CO_2 - eq\,d^{-1}$];

ESW_t Emissions from utilization solid waste for each $t \in T$.

Evaluation of environmental impact at every stage of life cycle is:

A. *Growing biomass* ELS_t*;*
B. *Production of bioethanol* ELB_t*;*
C. *Production of petroleum* gasoline ELD_t*;*
D. *Utilization of solid wastes* ESW_t
E. *Transportation biomass* ETA_t*;*
F. *Transportation bioethanol* ETE_t*;*
G. *Transportation gasoline* ETD_t*;*
H. *Transportation of solid waste* ETW_t*;*
I. *Transportation of straw* ETU_t*;*
J. *Transportation of wheat-corn for food security* ETV_t*;*
K. *Usage bioethanol and gasoline* $ECAR_t$.

1/ Greenhouse gases to grow biomass ELS_t**,** [$kg\,CO_2 - eq\,d^{-1}$]

GHG emissions resulting from the production of biomass depend on the cultivation practice adopted as well as on the geographical region in which the biomass crop has been established [7]. In particular, the actual environmental performance is affected by fertilisers and pesticides usage, irrigation techniques and soil characteristics. The factor may differ strongly from one production region to another. Accordingly, the biomass production stage is defined as follows:

$$ELS_t = \sum_{i \in I} \sum_{g \in G} \left(EFBC_{igt} \frac{\beta_{igt} A_{igt}}{\alpha_t} \right), \ \forall t, \qquad (2)$$

2/ Total GHG emissions from bioethanol production ELB_t

The environmental impact of the bioethanol production stage is related to raw materials and the technology employed for the production of bioethanol.

$$ELB_t = \sum_{i \in I} \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} \sum_{p \in P} \left(EFBP_{ip} QBP_{ifcbpt} \right), \ \forall t \qquad (3)$$

Since only one of the technologies $p \in P$ can be selected for a region $f \in F$ (which is guaranteed by the condition $\sum_{p \in P} ZF_{pft} \le 1.0 \ \ \forall t, f$), it QBP_{ifcbpt} is equal to "0" for all except $p \in P$ for the selected technology. This is ensured by implementing the inequality $G^{MAX} ZF_{pft} \ge QBP_{ifcbpt}, \ \forall i, f, c, b, p, t$ where G^{MAX} there is a large enough number.

3/ Total GHG emissions from gasoline production ELD_t

$$ELD_t = \sum_{d \in D} \sum_{c \in C} \sum_{b \in B} EDP_{dt} QD_{dcbt}, \ \forall t \qquad (4)$$

4/ The environmental impact of transportation ETT_t

The global warming impact related to both biomass supply and fuel distribution depends on the use of different transport means fuelled with fossil energy, typically either conventional oil-based fuels. The resulting GHG emissions of each transport option depend on both the distance run by the specific means and the freight load delivered. As a consequence, the emission factor represents the total carbon dioxide emissions equivalent accordingly:

$$ETT_t = ETA_t + ETB_t + ETD_t + ETW_t + ETU_t + ETV_t \qquad (5)$$

where,

$ETA_t = \sum_{i \in I} \sum_{g \in G} \sum_{f \in F} \sum_{l \in L} \left(EFTM_{il} ADG_{gfl} QI_{igftl} \right), \ \forall t$ is environmental impact of transportation biomass **[** $kg\,CO_2 - eq\,d^{-1}$ **];**

$ETE_t = \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} \left(EFTB_b ADF_{fcb} QB_{fcbt} \right), \ \forall t$ is environmental impact of transportation bioethanol from zones $f \in F$ to $c \in C$ where $QB_{fcbt} = \sum_{i \in I} \sum_{p \in P} QBP_{ifcbpt}$ **[** $kg\,CO_2 - eq\,d^{-1}$ **];**

$ETD_t = \sum_{d \in D} \sum_{c \in C} \sum_{b \in B} \left(EFTB_b ADD_{dcb} QD_{dcbt} \right), \ \forall t$ is environmental impact of transportation gasoline from zones $d \in D$ to $c \in C$;

$ETW_t = \sum_{f \in F} \sum_{w \in W} \sum_{m \in M} \left(EFTRW_m ADW_{fwm} QW_{fwmt} \right), \ \forall t$ is environmental impact of transportation solid wastes from zones $f \in F$ to $w \in W$;

$ETU_t = \sum_{g \in G} \sum_{u \in U} \sum_{e \in E} \left(EFTRU_e ADU_{gue} QU_{guet} \right), \ \forall t$ is environmental impact of transportation straw from zones $g \in G$ to $u \in U$;

$ETV_t = \sum_{g \in G} \sum_{v \in V} \sum_{z \in Z} \left(EFTRV_z ADV_{gvz} QV_{gvzt} \right), \ \forall t$ is environmental impact of transportation wheat-corn from zones $g \in G$ to $v \in V$;

5/ Total GHG emissions from utilization solid wastes ESW_t

$$ESW_t = \begin{pmatrix} \sum_{i \in I} \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} \sum_{p \in P} SW_{ip} QBP_{ifcbpt} - \\ \sum_{f \in F} \sum_{w \in W} \sum_{m \in M} QW_{fwmt} \end{pmatrix} ESW, \quad \forall t, \qquad (6)$$

6/ GHG emissions from bioethanol and gasoline usage in vehicle operations $ECAR_t$

$$ECAR_t = ECB\sum_{f\in F}\sum_{c\in C}\sum_{b\in B} QB_{fcbt} + ECG\sum_{d\in D}\sum_{c\in C}\sum_{b\in B} QD_{dcbt}, \ \forall t, \qquad (7)$$

4.1.2. Model of total cost of a IBSC

The annual operational cost includes the biomass feedstock acquisition cost, the local distribution cost of final fuel product, the production costs of final products, and the transportation costs of biomass, and final products. In the production cost, we consider both the fixed annual operating cost, which is given as a percentage of the corresponding total capital investment, and the net variable cost, which is proportional to the processing amount. In the transportation cost, both distance-fixed cost and distance-variable cost are considered. The economic criterion will be the cost of living expenses to include total investment cost of bioethanol production facilities and operation of the IBDS. This price is expressed through the dependence [8] for each time interval $t \in T$ **:**

$$TDC_t = TIC_t + TPC_t + TTC_t + TTAXB_t - TL_t, \ \forall t \qquad (8)$$

where

TDC_t	Total cost of a IBSC for year [$\$\, year^{-1}$];
TIC_t	Total investment costs of production capacity of IBSC relative to the operational period per year [$\$\, year^{-1}$];
TPC_t	Production cost for biorefineries [$\$\, year^{-1}$];
TTC_t	Total transportation cost of a IBSC [$\$\, year^{-1}$];
$TTAXB_t$	A carbon tax levied according to the total amount of CO_2 generated in the work of IBSC [$\$\, year^{-1}$];
TL_t	Government incentives for bioethanol production and use;

1/ Model investment costs for biorefineries by year TIC_t

A rational IBSC planning over the time is based upon the assumption that once a production facility has been built, it will be operating for the remaining time frame.

$$TIC_t = \varepsilon_t \sum_{f\in F}\sum_{p\in P}\left(Cost_{pf}^{F} Z_{pft}\right), \ \forall t \qquad (9)$$

where ε_t is calculate by equation (10):

$$\varepsilon_t = \frac{1}{\left(1+\varsigma_t\right)} \qquad (10)$$

Capital cost of biorefinery for each region is determined by the equation:

$$Cost_{pf}^{F} = M_f^{\cos t} Cost_p, \forall p \in P, \forall f \in F, \qquad (11)$$

2/ Total production cost model of IBSC TPC_t **[** $\$\, year^{-1}$ **]**

Total production cost term, TPC_t consists of biomass cultivation TPA_t, bioethanol production costs TPB_t and production cost for gasoline TPD_t as follows for each time interval t :

$$TPC_t = TPA_t + TPB_t + TPD_t, \forall t, \qquad (12)$$

where the components of (12) are defined according to the relations:

$$\left.\begin{aligned} TPA_t &= \sum_{i\in I}\sum_{g\in G}\left(UPC_{igt} A_{igt} \beta_{igt}\right) \\ TPB_t &= \sum_{i\in I}\sum_{f\in F}\sum_{c\in C}\sum_{b\in B}\sum_{p\in P}\left(\alpha_t UPB_{ipft} QBP_{ifcbpt}\right) \\ TPD_t &= \sum_{c\in C}\sum_{b\in B}\sum_{d\in D}\left(\alpha_t UPD_{dt} QD_{dcbt}\right) \end{aligned}\right\}, \ \forall t$$

3/ Total transportation cost model TTC_t **[** $\$\, year^{-1}$ **]**

With regard to transports, both the biomass delivery to conversion plants and the fuel distribution and transport of diesel to blending terminals are treated as an additional service provided by existing actors already operating within the industrial/transport infrastructure. As a consequence, TTC_t is evaluated as follows:

$$TTC_t = TTCA + TTCB_t + TTCD_t +, \forall t \qquad (13)$$

where, $TTCA_t = \sum_{l\in L}\sum_{i\in I}\sum_{f\in F}\sum_{g\in G}\left(\alpha_t UTC_{igfl} QI_{igflt}\right), \ \forall t$ is transportation cost for energy crops, $TTCB_t = \sum_{b\in B}\sum_{c\in C}\sum_{f\in F}\left(\alpha_t UTB_{fcb} QB_{fcbt}\right), \ \forall t$, for bioethanol, $TTCD_t = \sum_{b\in B}\sum_{c\in C}\sum_{d\in D}\left(\alpha_t UTD_{dcb} QD_{dcbt}\right), \ \forall t$ and for gasoline, where,

$$\left.\begin{aligned} UTC_{igfl} &= IA_{il} + \left(IB_{il} ADG_{gfl}\right) \\ UTB_{fcb} &= OA_b + \left(OB_b ADF_{fcb}\right) \\ UTD_{dcb} &= OAD_b + \left(OBD_b ADD_{dcb}\right) \end{aligned}\right\},$$

IA_{il} and IB_{il} is fixed and variable cost for transportation biomass type $i \in I$ and (OA_b, OB_b) is fixed and variable cost for transportation bioethanol.

The biomass transportation cost UTC_{igfl} is described by *Börjesson and Gustavsson* **[9]**, for transportation by tractor, truck and train UTB_{fcb}. They are composed of a fixed cost (IA_{il}, OA_b) and a variable cost (IB_{il}, OB_b). Fixed costs include loading and unloading costs. They do not depend on the distance of transport. Variable costs include fuel cost, driver cost, maintenance cost etc.

4/ Government incentives for bioethanol production cost model TL_t **, [** $\$\, year^{-1}$ **]**

$$TL_t = \sum_{f\in F}\sum_{c\in C}\sum_{b\in B}\left(INS_{ft} \alpha_t QB_{fcbt}\right), \ \forall t \qquad (14)$$

5/ A carbon tax levied cost model $TTAXB_t$ **, [** $\$\, year^{-1}$ **]**

Many countries are implementing various mechanisms to reduce GHG emissions including incentives or mandatory targets to reduce carbon footprint. Carbon taxes and carbon markets (emissions trading) are recognized as the most cost-effective mechanisms. The basic idea is to put a price tag on carbon emissions and create new investment opportunities to generate a fund for green technology development. There are already a number of active carbon markets for GHG emissions **[10]**.

$$TTAXB_t = \left(\alpha_t TEI_t\right) C_{CO_2}, \ \forall t \qquad (15)$$

4.2. Restrictions

Plants capacity limited by upper and lower constrains

Plants capacity is limited by upper and lower bounds, where the minimal production level in each region is obtained by:

$$\sum_{p\in P}\left(PB_p^{MIN} ZF_{pft}\right) \le \alpha_t \sum_{c\in C}\sum_{b\in B} QB_{fcbt} \le \sum_{p\in P}\left(PB_p^{MAX} ZF_{pft}\right), \forall f, t \qquad (16)$$

$$\left.\begin{aligned} &\sum_{m\in M}\sum_{w\in W} QW_{fwmt} \le QW_{ft}^{MAX}, \forall f \\ &\sum_{e\in E}\sum_{u\in U} QU_{guet} \le QU_{gt}^{MAX}, \ \forall g \\ &\sum_{z\in Z}\sum_{v\in V} QV_{gvzt} \le QV_{gt}^{MAX}, \ \forall g \end{aligned}\right\}, \ \forall t \qquad (17)$$

Constraints balance of bioethanol to be produced from biomass available in the regions

$$\alpha_t \sum_{i\in I}\sum_{f\in F}\sum_{c\in C}\sum_{b\in B}\sum_{p\in P}\left(\frac{QBP_{ifcbpt}}{\beta_{igt}\gamma_{ipt}}\right) = \sum_{i\in I}\sum_{g\in G}\left(A_{igt}\right), \ \forall t \qquad (18)$$

A condition that ensures that the total amount of solid waste generated by all bio-refineries can be processed in the plants built for this purpose

$$\sum_{w\in W}\sum_{m\in M} QW_{fwmt} \le \sum_{p\in P}\sum_{i\in I}\sum_{c\in C}\sum_{b\in B}\left(SW_{ip} QBP_{ifcbpt}\right), \forall f, t \qquad (19)$$

A restriction that ensures that the amount of solid waste processed at the plant is within its production capacity

$$\left.\begin{aligned} &\sum_{s\in S} P_s^{MIN} ZWF_{swt} \le \alpha_t \sum_{f\in F}\sum_{m\in M} QW_{fwmt} \\ &\alpha_t \sum_{f\in F}\sum_{m\in M} QW_{fwmt} \le \sum_{s\in S} P_s^{MAX} ZWF_{swt} \end{aligned}\right\}, \ \forall t, w \qquad (20)$$

Logical Constrains

- Restriction guarantees that a given region $f \in F$ installed power plant with $p \in P$ for bioethanol production.

$$\left.\begin{aligned}\sum_{p\in P} Z_{pft} \le 1\\ \sum_{p\in P} ZF_{pft} \le 1\end{aligned}\right\},\quad \forall f,t \tag{21}$$

and for a utilization systems of solid wastes (21):

$$\left.\begin{aligned}\sum_{s\in S} ZW_{swt} \le 1\\ \sum_{s\in S} ZWF_{swt} \le 1\end{aligned}\right\},\quad \forall w,t \tag{22}$$

- Limitation ensure the availability of at least one connection to a region of bioresources and region for biofuel

$$\sum_{g\in G}\sum_{l\in L} X_{igflt} \ge \sum_{c\in C}\sum_{b\in B} Y_{fcbt} \ge \sum_{p\in P} ZF_{pft},\quad \forall i,f,t \tag{23}$$

- Limit which guarantees that each region will provide only one plant with a biomass type $i \in I$

$$\sum_{f\in F}\sum_{l\in L} X_{igflt} \le 1,\quad \forall i,g,t \tag{24}$$

- Limitation of assurance that at least one region $f \in F$ producing bioethanol is connected to a costumer zones $c \in C$

$$\sum_{b\in B}\sum_{f\in F} Y_{fcbt} \le 1,\quad \forall c,t \tag{25}$$

- Limitation of assurance that at least one region f is connected to a solid waste utilization plant located in region $w \in W$

$$\sum_{w\in W}\sum_{m\in M} WS_{fwmt} \le 1,\quad \forall f,t \tag{26}$$

- Condition ensuring that the solid waste produced from a given bio-refinery will be processed in only one of the plants for use

$$\sum_{m\in M}\sum_{w\in W} WS_{fwmt} = \sum_{p\in P} ZF_{pft},\ \forall f,t \tag{27}$$

- Condition ensuring that a plant used in a given region will be connected to at least one plant in which solid waste is generated

$$\sum_{m\in M}\sum_{f\in F} WS_{fwmt} \ge \sum_{s\in S} ZWF_{swt},\quad \forall w,t \tag{28}$$

Transport Links

Restrictions on transportation of biomass are

$$PBI_{ig}^{MIN}\sum_{l\in L} X_{igflt} \le \alpha_t \sum_{l\in L} QI_{igflt} \le PBI_{ig}^{MAX}\sum_{l\in L} X_{igflt},\ \forall i,g,f,t \tag{29}$$

Mass balances between bioethanol plants and biomass regions

The connections between bioethanol plants and biomass regions:

$$\sum_{l\in L}\sum_{g\in G}\sum_{i\in I}\left(QI_{igflt}\right) \le \sum_{p\in P}\left(\frac{PB_p^{MAX} ZF_{pft}}{\gamma_{ipt}}\right),\ \forall f,t \tag{30}$$

Mass balances between bioethanol plants and customer zones

$$\sum_{b\in B}\sum_{f\in F}\left(\alpha_t QB_{fcbt}\right) = QEB_{ct},\ \forall c,t \tag{31}$$

Energy Restriction

- limitation ensuring that the overall energy balance in the region is provided

$$ENO\sum_{c\in C} QEO_{ct} + ENB\sum_{c\in C} QEB_{ct} = ENO\sum_{c\in C} YO_{ct},\ \forall t \tag{32}$$

- limitation ensuring that each region will be provided in the desired proportions with fuels

$$ENB\ QEB_{ct} = K_{ct}^{mix} ENO\ YO_{ct},\ \forall c,t \tag{33}$$

4.3. Economic objective function

Objective function associated with the minimization of the economic costs includes all the operating costs of the supply chain, from the purchase of biomass feedstock to transportation of the final product, as well as the investment cost of biorefineries [11]. The costs of the supply chain are: the cost of raw material, the transport of raw material to the facilities, the cost of transport to the biorefineries, the cost of transformation into bioethanol and the cost of final transport to the blending facilities. The economic objective is to minimize the total annual costs. The terms of the cost objective corresponding to the annual operation costs of the IBSC are described in the following equation:

$$COST = \sum_{t\in T}\left(LT_t TDC_t\right) \tag{34}$$

5. Optimization problem formulation

The problem for the optimal design of a IBSC is formulated as a MILP model for the objective function of Minimizing cost.

The task of determining the optimal location of facilities in the regions and their parameters is formulated as follows:

$$\left\{\begin{array}{l} Find : X_t\left[\text{Decision variables}\right]^T \\ MINIMIZE\ \{COST\} \rightarrow (Eq.34) \\ s.t.: \{Eq.16 - Eq.33\} \end{array}\right\} \tag{35}$$

The problem is an ordinary MILP and can thus be solved using MILP techniques. The present model was developed in the commercial software GAMS [12]. The model chooses the less costly pathways from one set of biomass supply points to a specific plant and further to a set of biofuel demand points. The final result of the optimisation problem would then be a set of plants together with their corresponding biomass and biofuel demand points.

6. Discussion and conclusion

This paper studies the interactions among biofuel supply chain design, agricultural land use and local food market equilibrium. The study has been focused on the eco comparable behavior of the stakeholders in the biofuel supply chain incorporating them into the supply chain design model. The model includes the problem of crop rotation and solid waste utilization. The model is believed to be important for practical application and can be used for design and management of similar supply chains.

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