A mathematical pathway to achieve sustainable design and friendly management of combined biodiesel/dairy supply chain

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Abstract: *This study proposes a mathematical pathway to achieve sustainable design and resource-friendly management of a biodiesel supply chain produced from dairy waste scum. In the work, the features of a combined biodiesel/dairy supply chain are outlined and a set of design and management tools is developed, which is formulated in MILP terms. The optimization criterion is defined in terms of economic sustainability and environmental assessment data is applied as part of it. The purpose of the defined mathematical model is to obtain optimal operating conditions of the considered combined supply chain. A test example based on a case study from Bulgaria was considered. The results of the toolbox implementation can be used as a decision-making tool.*

Keywords*: MILP, OPTIMIZATION, SUSTAINABLE, SUPPLY CHAIN, BIODIESEL, DAIRY WASTE SCUM*

1. Introduction

Energy saving is pointed out as one of the world's problems to solve in the modern world. This is dictated by the gradual but sure exhaustion of natural resources and the complex economic, political and social situation in different parts of the world. Along with this, the need arises to overcome climate change, the degradation (deterioration) of lands and ecosystems. These facts provoke the scientific community to face global challenges, such as finding alternative sources of energy and developing approaches for sustainable use of energy carriers. In the last few decades, biodiesel has been introduced as an analogue of traditional energy carriers and in particular promising alternative source of energy in transport sector [1], [2]. Biodiesel is defined as ecologically clean fuel obtained from practically inexhaustible raw material (biomass).

The first document to pay significant attention to the consumption of biofuels and set the stage for the development of a policy on biofuels was the 1997 White Paper "Energy for the Future: Renewable Energy Sources" [3]. The negatives in the use of conventional fuels, such as environmental pollution, disrupted supplies around the world, energy security [4] reinforce the role of biofuels as a possible substitute for fossil energy carriers. Currently, the role of biofuels could be defined as the "Gold Rush" of industry in the 21st century. Biodiesel is classified as a monoalkyl ester obtained by the transesterification of methanol with higher fatty acids, which may be of vegetable or animal origin [5], [6] Main raw materials are soybean oil, rapeseed oil, sunflower oil, waste oil from cooking, animal fats and other edible or inedible fats [7]. The replacement of traditional diesel fuels with biodiesel leads to minimization of emissions of greenhouse gases and dust particles in the air [7]. The cost of biodiesel is higher than that of petrodiesel and it’s a major difficulty in its commercialization [8]. The cost of raw materials constitutes 75–85% of the production cost of biodiesel [9]. However, what is the real price to pay for biodiesel to be a sustainable alternative to fossil fuels? The problem comes from the fact that a large part of the planet's population is starving or undernourished. In counterpoint to this, the cultivation of oil crops used as raw material for the production of biodiesel takes up agricultural land, thereby reducing the area sown with food crops. Advanced second-, third- and fourth-generation feedstock’s such as cellular biomass, microbial oils, algae and others are attracting increasing interest because they have a shorter life cycle, do not require arable land, and can use organic waste as a carbon source [10], [11], [12]. These feedstock has opened new avenue for less expensive and competitive biodiesel production [13] The food industry and in particular milk processing and the production of dairy products (drinking milk, cheese, yogurt, milk powder, ice cream, melted butter, breading and others) also generate large amounts of waste biomass with a high fat concentration, which can to be used as a potential feedstock in biodiesel production. A large dairy that processes 500,000 liters of milk per day generates about 250-300 kg dairy waste scum per day. A significant amount, which makes it difficult to dispose of it [14]. The dairy waste scum (DWS) is a non-solid, dense, floating substance, white in texture and color because it is usually formed by a mixture of fats, proteins, lipids and others. DWS is generated during equipment cleaning, processing, storage, packaging and transportation of milk and milk products. A large proportion of dairies dispose of this waste in solid waste storage facilities or incinerate it [15]. This is economically unprofitable and could be seen as a "dissipation" of hidden energy carriers. Waste from the dairy industry causes direct and indirect obstacles to wastewater treatment, and can lead to eutrophication in water bodies. There are mainly four different methods used for production of biodiesel, viz. blending, micro emulsification, pyrolysis, and transesterification. The transesterification is the most convenient and established methods. The reaction of alcohol and triglycerides in presence or absence of catalyst to produce alkyl ester is known as transesterification. The triglyceride molecules having long and branched chains are converted to monoester, known as biodiesel. The high proportions of saturated and mono saturated fatty acids in dairy waste scum oil are considered optimal for fuel production [8].

Apart from the type of feedstock used, the quality and price of the biodiesel produced depends on transport logistics, production and storage technologies, as well as the location of the biorefineries because of which the commercialization of biodiesel is related to the design and management of efficient and sustainable supply chains [16]. The sustainable design and friendly management of supply chain is one possible way to increase the economic and environmental benefits of biodiesel production through optimize all activities across the network from feedstock’s, through the production itself, to the customer. This could be achieved through the development and implementation of special mathematical approaches to designing sustainable supply chains

The present study proposes a MILP approach for sustainable design of combined biodiesel/dairy supply chain. Dairy waste scum is considered as a potential raw material for the production of biodiesel satisfying economic and environmental criteria. In the work, the features of a combined biodiesel/dairy supply chain are outlined. Optimization problem have been formulated and solved either at in terms of economic sustainability and environmental assessment data is applied as part of it. The purpose of the defined mathematical model is to obtain optimal operating conditions of the considered combined supply chain. The proposed approach has been implemented on real case study, in which the territory of the Republic of Bulgaria has been considered with its 27 administrative regions. The results of the toolbox implementation can be used as a decision-making tool.

2. Supply chain optimization problem formulation

This study presents a combined biodiesel/dairy supply chain represented in Fig. 1. It comprises suppliers of dairy farms, dairy plants, customers of milk products and bio refinery plants.

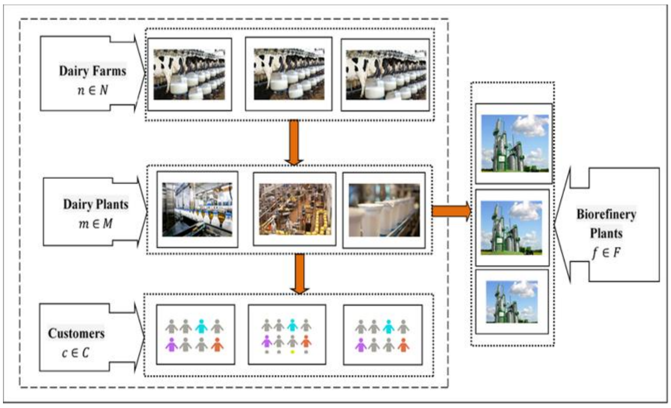

Fig. 1 A combined biodiesel/dairy supply chain

The problem considered in this paper can be formulated as follows Table 1:

Table 1: *Problem statement*

Given are:	Determine the optimal parameters of the supply chain as:
the location of farms and their production capacity;	dairy farms portfolios;
the selling price of milk;	dairy plants portfolios;
the locations of dairy plants and their capacities;	size, capacity and location of biorefineries that should be built;
the technologies for production of dairy products and the technologies for biodiesel production from dairy waste scum;	optimal performance of biorefineries;
the dairy products and biodiesel demands;	transportation connections.
type of transportation for their delivery;	
greenhouse gas emissions for each stage of the life cycle;	
transportation costs for each transport connection and transportation mode.	

MILP optimization model includes the definition of constant parameters and decision variables; the optimization criterion is defined in terms of economic sustainability and environmental assessment data are implemented as part of it. An objective function and constraints are included. To model the set of time intervals of the planning horizon $\tau = \{1,2, \dots, T\}$ is introduced. The ecological, economic constants and continuous and binary variables are taken from [17].

The optimization problem can be solved using the GAMS application software and it is possible to use it to make comprehensive smart decisions. After changing the necessary data, the proposed plan can be adapted to different territories.

2.1. *Environmental performance of the combined biodiesel/dairy supply chain [18]*

The environmental impact of the combined dairy and biodiesel supply chain is represented as the total greenhouse gas emissions generated over the whole live cycle of the production of dairy and biodiesel products. They are converted into carbon credits multiplied by the price of carbon emissions on the market.

The environmental impact criteria include the overall environmental impact of the operation of the combined dairy and biodiesel supply chain, by means of the generated greenhouse gas emissions for each time interval t∈T. The latter includes greenhouse gas emissions generated at each stage of the life cycle of the products. They are determined for each time interval t∈T:

$$EIJ_t = EPI_t + EPB_t + EWS_t + ETF_t\,, \quad \forall t \tag{1}$$

Where:

EIJ_t - Total environmental impact of the operation of the combined dairy and biodiesel/diesel supply chain for the whole life cycle, $[kgCO_{2eq}/d]$;

EPI_t - Environmental impact in the production of dairy products in dairy plants, $[kgCO_{2eq}/d]$;

$$EPI_t = \sum_{i \in I} \sum_{m \in M} \sum_{k \in K} \left(EIM_{im}\, CI_{imkt}\, PIB_{imkt}\right), \quad \forall t \tag{2}$$

EPB_t - Emissions from biodiesel production using dairy waste scum as feedstock, $[kgCO_{2eq}/d]$;

$$EPB_t = \sum_{j \in J} \sum_{f \in F} \sum_{p \in P} \left(EFB_{jfp}\, PBFP_{jfpt}\right), \quad \forall t \tag{3}$$

EWS_t - Emissions from unused dairy waste scum for biodiesel production, $[kgCO_{2eq}/d]$;

$$EWS_t = \sum_{j \in J} \left(\sum_{m \in M} \sum_{k \in K} \left(\begin{array}{l} \sum_{i \in I} \left(\beta_{ijmkt} CIJ_{ijmkt} CI_{imkt} PIB_{imkt}\right) - \\ - \sum_{l3 \in L3} \sum_{f \in F} \left(QJ_{jmfl3t}\right) \end{array} \right) \right) EDWS_j, \quad \forall t \tag{4}$$

ETF_t - Emissions released during transport of raw materials, products and dairy waste scum to the respective facilities, $[kgCO_{2eq}/d]$.

$$ETF_t = ETNM_t + ETMC_t + ETMF_t, \quad \forall t \tag{5}$$

2.2. *Economic performance of the combined biodiesel/dairy supply chain [18]*

For definition of the economic impact assessment of the supply chain operation the annual operating costs are used. The economic criterion includes the total investment costs for the biodiesel plant, costs for building the biodiesel plants and the operation of the combined dairy and biodiesel supply chain for the planned time period. They define for each time interval t∈T as:

$$\begin{aligned} TDC_t &= TIC_t + TPC_t + TDWS_t + TDKN_t + TPI_t + \\ & TPW_t + TTC_t + TCO2_t - TB_t - TL_t, \forall t \end{aligned} \tag{6}$$

TDC_t – the total costs of the combined supply chain per year, $(\$/y)$;

TIC_t – the total investment costs for the production capacity of the combined supply chain according to the operation period and the purchase of the biodiesel plant per year, $(\$/y)$;

$$TIC_t = \varepsilon_t \sum_{f \in F} \sum_{p \in P} \left(Cost_{pf}^{F} Z_{pft}\right), \quad \forall t \tag{7}$$

TPC_t – the production costs for the total quantity of biodiesel per year, $(\$/y)$;

$$TPC_t = \alpha_t \sum_{f \in F} \sum_{j \in J} \sum_{p \in P} \sum_{l3 \in L3} \sum_{m \in M} \left(UPB_{jpft} QJ_{jmfl3t}\right), \quad \forall t \tag{8}$$

$TDWS_t$ – the dairy waste scum costs for the biodiesel production per year, $(\$/y)$;

$$TDWS_t = \alpha_t \sum_{f \in F} \sum_{j \in J} \sum_{p \in P} \sum_{l3 \in L3} \sum_{m \in M} \sum_{i \in I} \sum_{k \in K} \left(PJ_{jimt} CIJ_{ijmkt} CI_{imkt} QJ_{jmfl3t}\right), \quad \forall t \tag{9}$$

$TDKN_t$ – the raw materials (milk) costs for the production of dairy products per year, $(\$/y)$;

$$TDKN_t = \alpha_t \sum_{n \in N} \sum_{m \in M} \sum_{k \in K} \sum_{l1 \in L1} \left(UNMK_{nmkt} CK_{knt} QKNM_{knml1t}\right), \quad \forall t \tag{10}$$

TPI_t – the production costs for dairy products per year, ($\$/y$);

$$TPI_t = \alpha_t \sum_{i\in I} \sum_{m\in M} \sum_{k\in K} \left(UIMK_{imkt} PIB_{imkt} \right), \quad \forall t \tag{11}$$

TPW_t – the production costs for utilization of the unused dairy waste scum remaining from biodiesel production per year, ($\$/y$);

$$TPW_t = \alpha_t \sum_{j\in J} \left(\sum_{m\in M} \sum_{k\in K} \left(\sum_{i\in I} \left(\beta_{ijmkt} CIJ_{ijmkt} CI_{imkt} PIB_{imkt} \right) - \sum_{l3\in L3} \sum_{f\in F} \left(QJ_{jmfl3t} \right) \right) \right) UPW_{jt}, \quad \forall t \tag{12}$$

TTC_t – the total transportation costs for the combined supply chain per year, ($\$/y$);

$$TTC_t = TNM_t + TMC_t + TMF_t, \quad \forall t \tag{13}$$

TTC_t are the total transportation costs for transportation of raw materials (milk), dairy products and dairy waste scum per year ($\$/y$);

TNM_t are the total transportation costs for transportation of raw materials (milk) per year ($\$/y$);

TMC_t are the total transportation costs for transportation of dairy products per year ($\$/y$);

TMF_t are the total transportation costs for transportation of dairy waste scum per year ($\$/y$).

$TCO2_t$ - the carbon tax charged according to the total amount CO_2 released during the operation of the combined supply chain per year, ($\$/y$);

$$TCO2_t = \alpha_t EIJ_t CCO2_t, \quad \forall t \tag{14}$$

TB_t – the revenue from the sale of biodiesel produced per year, ($\$/y$);

$$TB_t = \alpha_t PB_t \sum_{j\in J} \sum_{p\in P} \sum_{f\in F} \left(PBFP_{jfpt} \right), \quad \forall t \tag{15}$$

TL_t – the government incentives for biodiesel production and building per year, ($\$/y$).

$$TL_t = \alpha_t \sum_{j\in J} \sum_{p\in P} \sum_{f\in F} \left(INS_{ft} PBFP_{jfpt} \right), \quad \forall t \tag{16}$$

2.3. Constraints

The constraints are linear functions with respect to:

- ✓ the production capacity of biorefineries;
- ✓ providing admissibility of flows;
- ✓ providing that the needs of all regions of dairy products will be met;
- ✓ providing the necessary amounts of milk for the production of dairy products;
- ✓ logical and transportation constraints;
- ✓ providing that produced dairy waste scum from dairy plants will be used for the biodiesel production;
- ✓ providing satisfaction of the material balance of combined supply chain;
- ✓ providing satisfaction of the annual demand of the dairy plants;
- ✓ providing maximum annual production capacity of farm n ∈ N for the production of milk of type k ∈ K;
- ✓ providing admissibility of flows.

2.4. Objective function

The optimization problem for determining the optimal location of the plants in the regions and their parameters is formulated as:

$Find: X_t [Decision\ variables]$

$MINIMIZE\{COST(T_t)\}\ s.t.: \{Constraint\ s\}$

$$COST = \sum_{t\in T} (LT_t TDC_t) \quad (\ \ )$$

where

LTt - duration of time intervals t∈T, (y). The objective function and all constraints are linear functions of all decision variables.

3. Results and discussion

The formulated above optimization problem have been solved in terms of economic sustainability, and environmental assessment data are implemented as part of it. For that purpose, GAMS® optimization software-CPLEX solver has been used. The prepositional mathematical model is implemented on an example study from Republic of Bulgaria. The obtained results are demonstrated in Fig. 2 and Fig 3.

Fig.2 presents the distribution of GHG emissions generated at each stage of the supply chain operation and shows that the largest amount of GHG emissions are generated during the production of milk products in dairy plants, as well as during disposal of unused waste biomass for biodiesel production.

Fig. 3 presents the cost structure of the supply chain and shows that the largest cost is the carbon tax, calculated according to the total amount of CO2 generated during the operation of the supply chain and the production costs of the utilization of the unused waste biomass to produce biodiesel

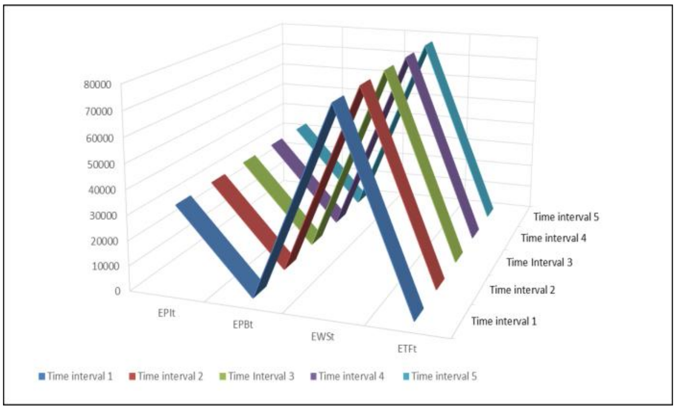

Fig. 2 *Greenhouse gas emissions generated at each stage of operation of the combined supply chain*

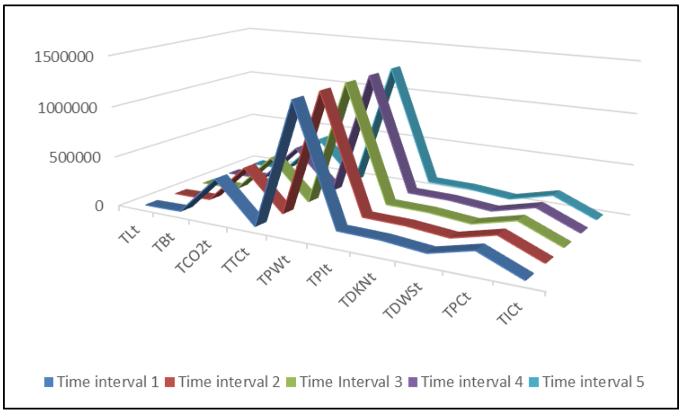

Fig. 3 *The costs for operation of combined dairy and biodiesel supply chain.*

4. Conclusion

The study proposes a MILP model for sustainable design and friendly management of combined biodiesel/dairy supply chain. The proposed approach has been based on example case study, in which the territory of the Republic of Bulgaria with its 27 administrative regions is considered. The optimization criterion is defined in terms of economic sustainability and environmental assessment data is applied as part of it. The proposed task is solved using the application software GAMS and it can be used as a decision-making tool.

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Appendix A

Sets, subsets and indices

K Set of types of milk used as a raw material in dairy plants, k

I Set of produced dairy products in dairy plants generating dairy waste scum, i

J Set of generated types of dairy waste scum in dairy plants, j

P Sets of the capacities of used biorefineries for biodiesel production, p=(1,N_p)̅

GF Sets of the administrative regions into which the territory of Republic of Bulgaria is divided, gf

L Set of vehicles used for transportation of raw materials and products, l

T Sets of time intervals, t

Subsets/indices

F Sets of regions for biodiesel production. It is a subset of GF ($F \subset GF$), f

M Set of regions where dairy plants are built. It is subset of GF ($M \subset GF$), m

N Set of dairy farms which produce milk used as a raw material in dairy plants. It is subset of GF ($N \subset GF$), n

C Set of regions where dairy products are used. It is subset of GF ($C \subset GF$), c

L1 Set of vehicles used for transportation of raw materials (milk), l1. It is subset of L ($L1 \subset L$)

L2 Set of vehicles used for transportation of dairy products, l2 . It is subset of L ($L2 \subset L$)

L3 Set of vehicles used for transportation of the types of dairy waste scum, l3; It is subset of L ($L3 \subset L$)