Mathematical Modeling and Optimization of United Dairy Waste Scum-Biodiesel Supply Chain According to The Sustainability Principle: Part1: Optimal Structure and Size of Flows on The Bulgarian Scale

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Abstract

Climate change, environmental problems, limited oil reserves and complicated conjuncture of socio-economic agents in our modern times are among head prerequisites for the search of suitable sustainable energy alternatives. The production of biodiesel is considered to be one of the particularly promising ones. The biodiesel has characteristics close to those of petroleum diesel and it's considered particularly acceptable as a fuel. But the biodiesel generates some big outlay which is a substantial hardship when implementing it in the economic system. With the growing importance of biofuels and in particular biodiesel the optimal functioning is necessary not only for the individual production unit, but also for each element of the supply chain. This research introduces part of an optimization mathematical model of united dairy waste scum - biodiesel supply chain according to the principle of sustainability. The purpose is to predict the possibility for minimizing economic cost, taking into account the environmental impact. The environmental impact is part of an optimization criterion which is determined contingent upon a full capital expenditure for the biomass-based biodiesel manufacture plants, expenditure for the construction of the factories and also the functioning of the supply chain for the operating stage. The workability of the method has been verified and demonstrated by creating a software application using General Algebraic Modeling System (GAMS). In this work are shown the results in terms of optimal structure and size of flows on the Bulgarian scale.

Keywords: biofuel, energy efficiency, Mixed Integer Linear Programming (MILP), optimal design, dairy production

1. Introduction

From one point of view, due to the constant increase in the general need for fuels, and from another point of view, because of the irreversible exhaustion of basic material, biofuels can be described as one of the most reliable energy opportunities. The environmental contamination, affect supplies worldwide, energy safety (Dutta et al., 2014) strengthen the appearance of biofuels as an applicable alternative for nonrenewable energy materials. Nowadays, the exploring of the renewable-energy could be indicated as a "Gold Fever" of manufacturing in the present millennium. Biomass – based diesel defined as a monoalkyl ester extract received by the methanol transesterification with long-chain fatty acids. It is possible to produce biodiesel from different edible or inedible fats. (Dutta et al., 2014), (Zahan & Kano, 2018). When replacing petro-fuels with biodiesel, greenhouse gas emissions (GHG's) and small dry particles of earth, sand, or dirt in the air will be reduced (Meng et al., 2009), (Zahan and Kano, 2018). But the price of biodiesel is higher than that of standard diesel - the basic barrier to be this biofuel a profitable item. (Sivakumar et al., 2011). 75–85% of a biodiesel manufacturing cost are the expenses directly related to the raw materials (Demirbas, 2009). Nevertheless, why is it necessary we pay this substantial expense to be the biodiesel a genuine option to conventional diesel? The parts of the agricultural land occupied with food crops and the parts of the land occupied with oil crops (raw material for biodiesel production) are in competition. The difficult situation is getting stronger because still at the present moment still a large part of the people on earth suffers from not enough food supply. Ever more sources with a brief life cycle do not need cultivated land. Such are, for example microbial oils, upper generation cellular biomass, algae and other. (Kumar & Banerjee, 2019), (Yellapu et al., 2019). The agri-food sector produces great measure of waste biomass. Specially in dairy industry, the waste biomass has a large fat concentration. A dairy factory that rework milk (approximately 500 m^3 daily) can be produce nearly 250-300 kg. waste scum daily. (Kavitha et al., 2019). The dairy waste scum is a no rigid substance with relative density in consistency. The dairy waste biomass is borne on the liquid surface and forms a white layer. It is usually created by a combination of proteins, lipids and fats. (Kelessidis and Stasinakis, 2012). After conducting analysis, research team concludes that the dairy waste biomass can be treated as a future prospected raw material for biodiesel manufacturing. (Yatih et al., 2022).

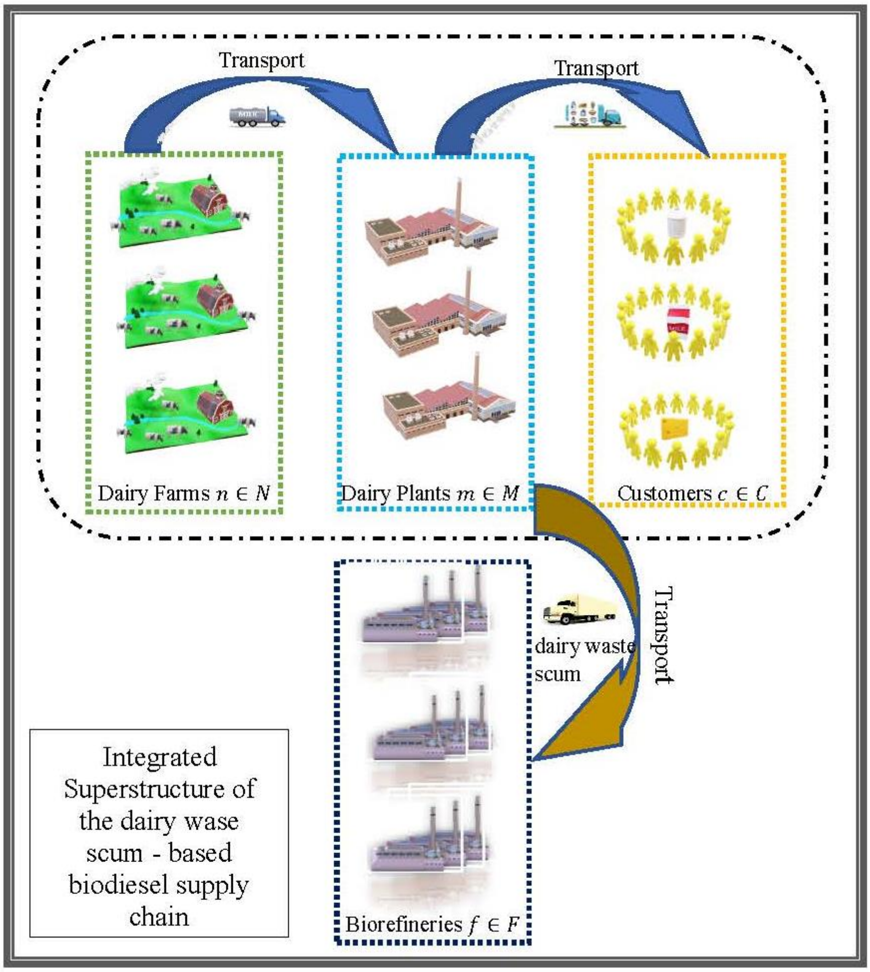
The effective design of sustainable supply chains in the production and supply of biodiesel from dairy waste involves three interrelated levels of decision-making – strategic, tactical and operational. In order to be able to achieve global optimal solutions in terms of supply chain as a whole, a combination between the decisions of the different levels of management is necessary (Babazadeh and Razmi, 2012).

The purpose of the presented study is to suggest a mathematical model and optimization of dairy waste scum-based biodiesel supply chain under the principal of sustainability. The main function of this research is to find the highest in quality solution between economic and environmental problems. The aim is minimizing of the total annual expenditure. These annual expenditures are sum of the annual operating expenditure, the total annual capital expenditure and the annual government incentive, also the emission expenditure CO_2. The criterion used for optimization is determined with economic sustainability. The environmental assessment data are inserted into it.

2. Problem definition

This study considers a dairy waste scum-based biodiesel supply chain presented in Figure 1. The focus of the researched supply chain falls on integrating the dairy supply chain into the biodiesel supply chain. The proposed supply chain includes dairy farms for production of different raw milks; dairy plants for production of different type of milk products according known technologies (recipes) as yellow and white brined cheese, yogurt 4,5 % and fresh drinking milk 3 %; customers of end dairy products and biorefineries for utilization of dairy waste scum according the known technology

Figure 1: Integrated Superstructure of the dairy waste scum-based biodiesel supply chain



A brief problem definition is clearly stated in Table 1.

Table 1: A definition of the problem

Considering that:	To be found:
the farms capacity and locations;	dairy farms portfolios;
the selling price of milk;	dairy plants portfolios;
the dairy plants capacity and locations;	capacity, size and location of biorefineries that should be built;
the manufacture technologies;	optimal performance of biorefineries;
demand of biomass - based diesel; demand of milk products;	transportation connections.
class of the conveyance;	
GHG emissions for all point of the life cycle;	
conveyance expenditure;	

In the presented study it’s formulated the optimization problem of dairy waste scum-biodiesel supply chain, and a solution is found as the best agreement between environmental and economic concerns. The optimization criterion outlines economic sustainability and environmental assessment data are inserted into it.

2.1.Mathematical model

The model of the optimization is described with regard to Mixed Integer Linear Programing (MILP) and its role is to determine the most profitable approach to minimize the total expenditure of operating the supply chain and provide the best case for decreasing of the environmental impact along the chain of delivery. A long planning view H (10 years) is discussed. All over time distance H is separated into aggregate of discrete time periods t={0,1,2,…,T}, every one of which lasts ∇t. Over the planning view, dairy consumption is allowed to change by an estimated amount. The task is solved in the conditions of the specialized computer software General Algebraic Modeling System (GAMS). Detailed description of formulated optimization problems including needed data, all mathematical models, constraints and optimization criterions is given in (Ivanov et al., 2022).

2.1.1 Environmental effect assessment model

The overall greenhouse gas emissions $(kgCO_{2eq}/d)$, which are result in the activity of the proposed supply chain, are used in the environmental impact assessment. They are transformed into carbon credits. The proposed environmental effect assessment model aims to keep down the greenhouse gas emissions produced during the activity of the cradle-to-grave supply chain,$t \in T$:

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

where,

EIJ_t – General ecological effect as result from the activity of the supply chain "from the cradle to the grave", $(kgCO_{2eq}/d)$;

EPI_t - Effect on the environment during the operation of dairy plants, $(kgCO_{2eq}/d)$;

ETF_t - Effect on the environment during the delivery of material flows, $(kgCO_{2eq}/d)$.

EWS_t - Effect on the environment during the utilization of unused quantity of dairy waste scum, $(kgCO_{2eq}/d)$;

EPB_t - Effect on the environment during the production of biodiesel by utilization of dairy waste scum, $(kgCO_{2eq}/d)$;

2.1.2 Economic effect assessment model

Economic effect assessment model is defined as the sum of the investment value for biodiesel production plants, value for building the plants and the functioning of the supply chain for the period of operation. This value is calculated for each time distance l $t \in T$:

$$TDC_t = TPC_t + TIC_t + TDKN_t + TDWS_t + TPI_t +$$

$$TTC_t + TPW_t + TCO2_t - TB_t - TL_t, \forall t \quad (2)$$

where,

TDC_t – the overall value of the supply chain annually, $(\$/y)$;

TPC_t – the production value for the overall quantity of biodiesel annually, $(\$/y)$;

TIC_t – the overall investment value for the manufacturing volume of the supply chain considering the period of operation and the acquirement of the biodiesel plant annually, $(\$/y)$;

$TDKN_t$ – the value of raw milk for the manufacture of dairy products annually, $(\$/y)$;

$TDWS_t$ – the value of dairy waste biomass for the biodiesel manufacturing annually, $(\$/y)$;

TPI_t – the manufacturing value for dairy products annually, $(\$/y)$;

TTC_t – the overall transportation value of the supply chain annually, $(\$/y)$;

TPW_t – the manufacturing value for utilization of not used dairy waste biomass left from production of biomass-based diesel annually, $(\$/y)$;

$TCO2_t$ - the carbon tax levied considering to the overall quantity CO_2 generated for the time of operation the supply chain service ever year, $(\$/y)$;

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

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

2.1.3 Constraints

In the second part of currently work, the detailed description of the constraints is given in (Dzhelil et al., 2023). The ones mentioned constraints are linear functions.

2.1.4 Objective function

The method of optimization applies group of ruling variables. The variables are continuous and binary and lead to minimizing the aim function (3). The autonomous ruling variables are: the structure of the supply chain, the flows of each type of milk, dairy products, dairy waste scum; class of the conveyance for their delivery; GHG's for all point of the life cycle; expenditure and transport mode.

$$Find: X_t[Decis\ \text{variables}]\ MINIMIZE\{EXPENDITURE(T_t)\}\ s.t.:\{Constr\ s\}$$

$$EXPENDITURE = \sum_{t \in T}(LT_t TDC_t) \quad (3)$$

where LT_t - period of time intervals $t \in T$, (y).

The objective function (3), which is a linear function is to minimize the sum of logistics expenditure of the supply system, consider variable, fixed, emission expenditure.

The assignment of defining the optimal facilities position on the considered territory and their parameters is prepared in terms of MILP and is solved with the program package GAMS.

3. Case study

The optimization approach presented above is implemented to a taste study of potential biodiesel production in the Republic of Bulgaria. The production of biodiesel obtained from one main type of resource - waste biomass generated during the production of four category of dairy products (yellow and white brined cheese, yogurt 4,5 % and fresh drinking milk 3 %) is considered. Only fresh cow's milk is used for the manufacturing of these dairy products. The integrated superstructure of the dairy waste biomass-based biodiesel supply chain includes: 12 areas for dairy farms; 12 areas for dairy plants; 5 possibility areas for biorefineries and 27 clients' areas. A ten-year period divided into equal time intervals is considered.

Figure 2 presents the optimal structure of the dairy waste scum-based biodiesel supply chain by Truck_1 and Truck_3 for each time interval. The analysis of the received results of the optimization procedure in terms of logistics shows that the optimal transportation of all considered raw materials and products for all time intervals in a considered period is Truck_1 and Truck_3.

Figure 2: Optimal structure of the dairy waste scum-based biodiesel supply chain

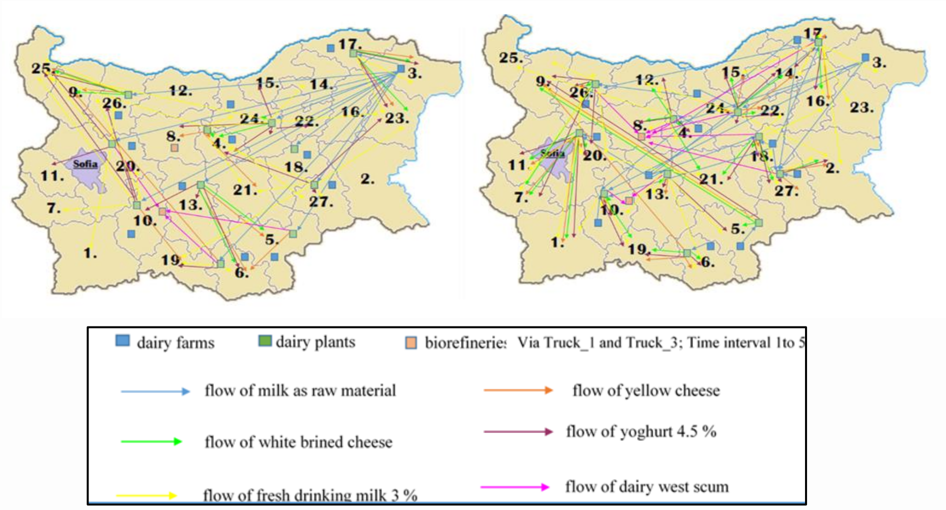
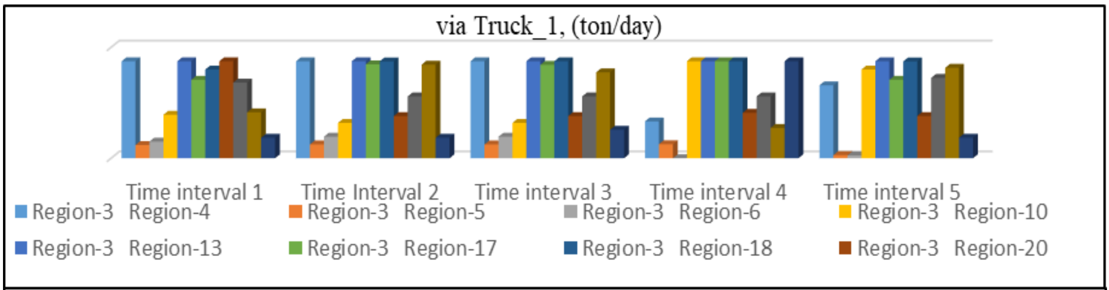
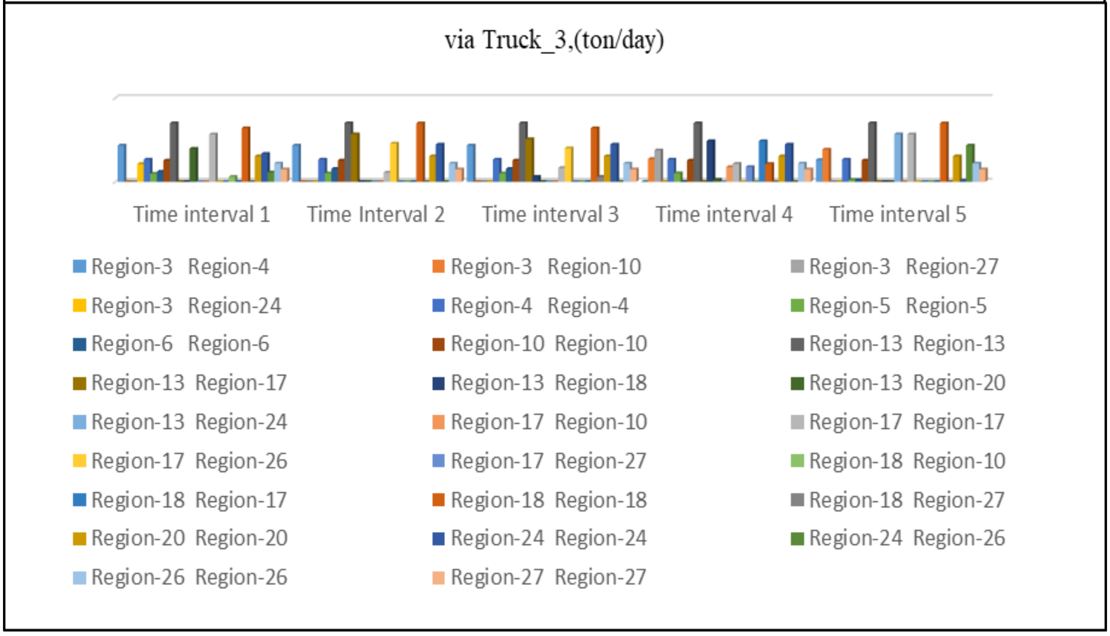


Figure 3: Optimal flows of the raw milk delivered via Truck_1 and Truck_3 to dairy plants

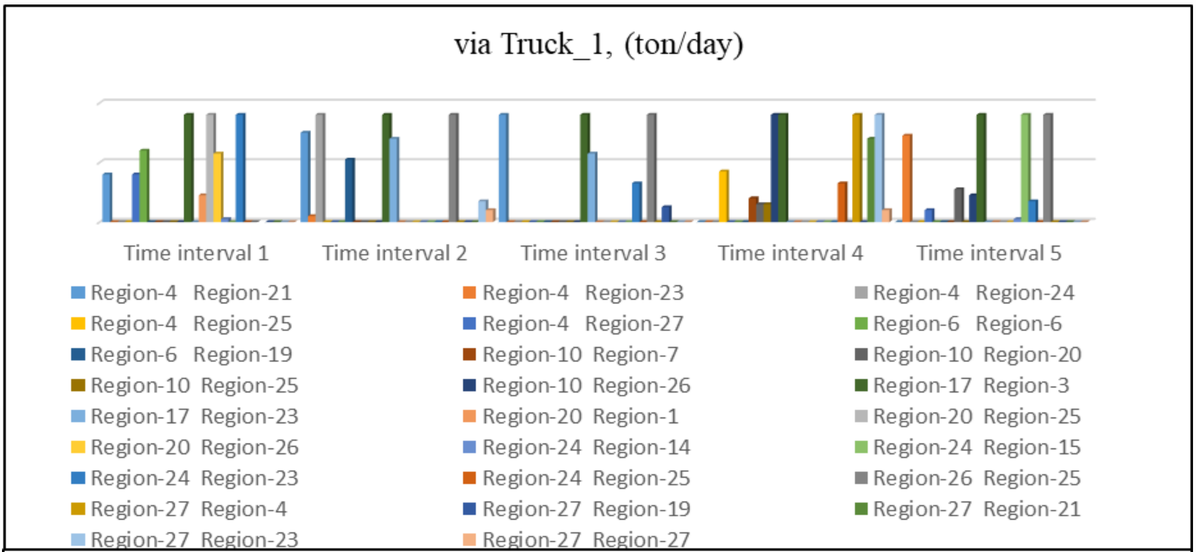


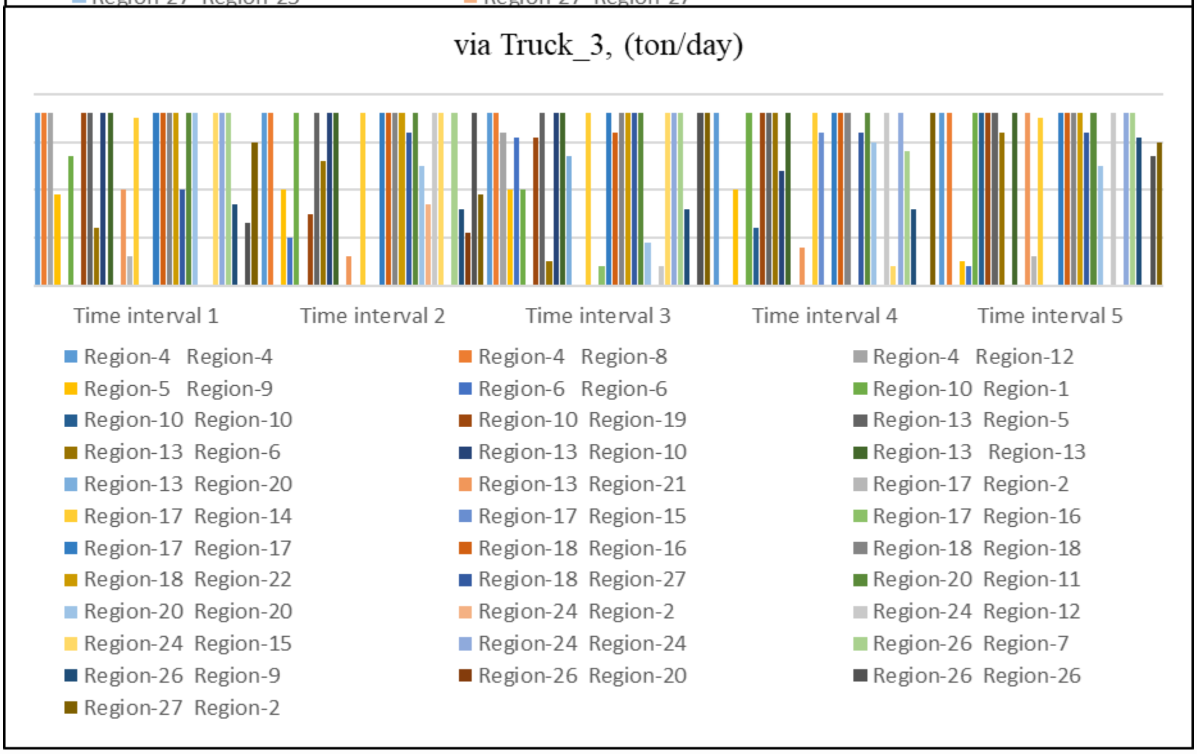


The optimal flows of the raw milk (delivered via Truck_1 and Truck_3 to dairy plants) are presented in a Figure 3. The analysis of a Figure 3 shows that the largest flows of raw milk (at time interval 1) are delivered via Truck _1 from region 3 to regions 4, 13, 20. At time interval 2 and time interval 3 via Truck_1, the largest flows of raw milk are from region 3 to regions 4, 13, 17 and 18. At time interval 4, the largest flows of raw milk are from region 3 to regions 10, 13, 17 and 18. Respectively, at time interval 5 – from region 3 to regions 13 and 18, i.e. via Truck_1 for all time intervals there is a delivery of raw fresh milk only from region 3.

Via Truck_3 during the different time intervals there is a delivery of raw fresh milk from different regions, producers of raw milk to different regions, producers of dairy products. And for each of the time intervals the largest flow is from region 13 to region 13 and from region 18 to region 18.

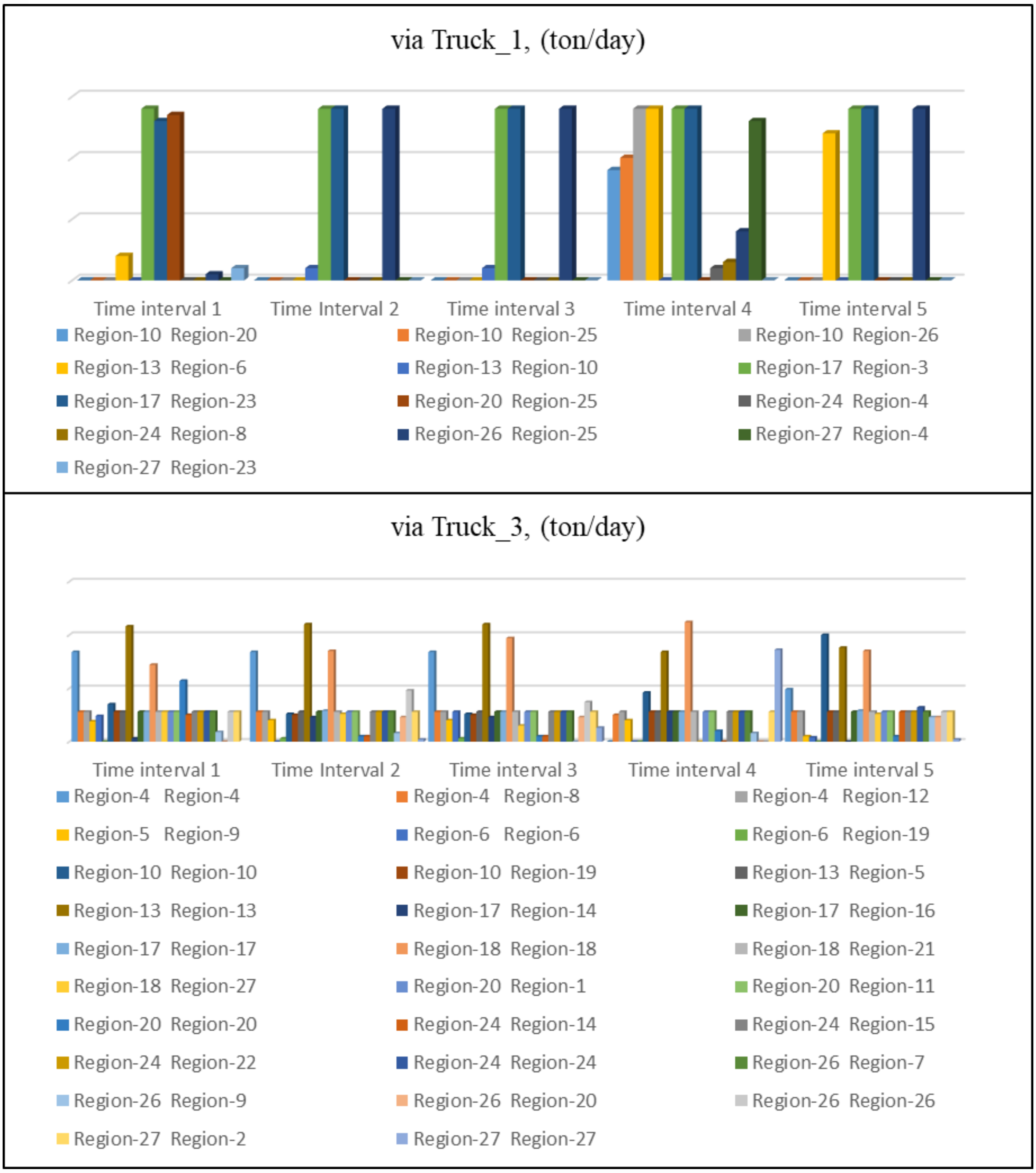
Figure 4: Optimal flows of fresh drinking milk 3% delivered via Truck_1 and Truck_3 to consumers





The optimal flows of fresh drinking milk 3% (delivered via Truck_1 and Truck_3 to consumers) are presented in a Figure 4 and it shows that the preferred transport for delivery of fresh drinking milk 3% from dairy plants to customers for each time interval is Truck 3.

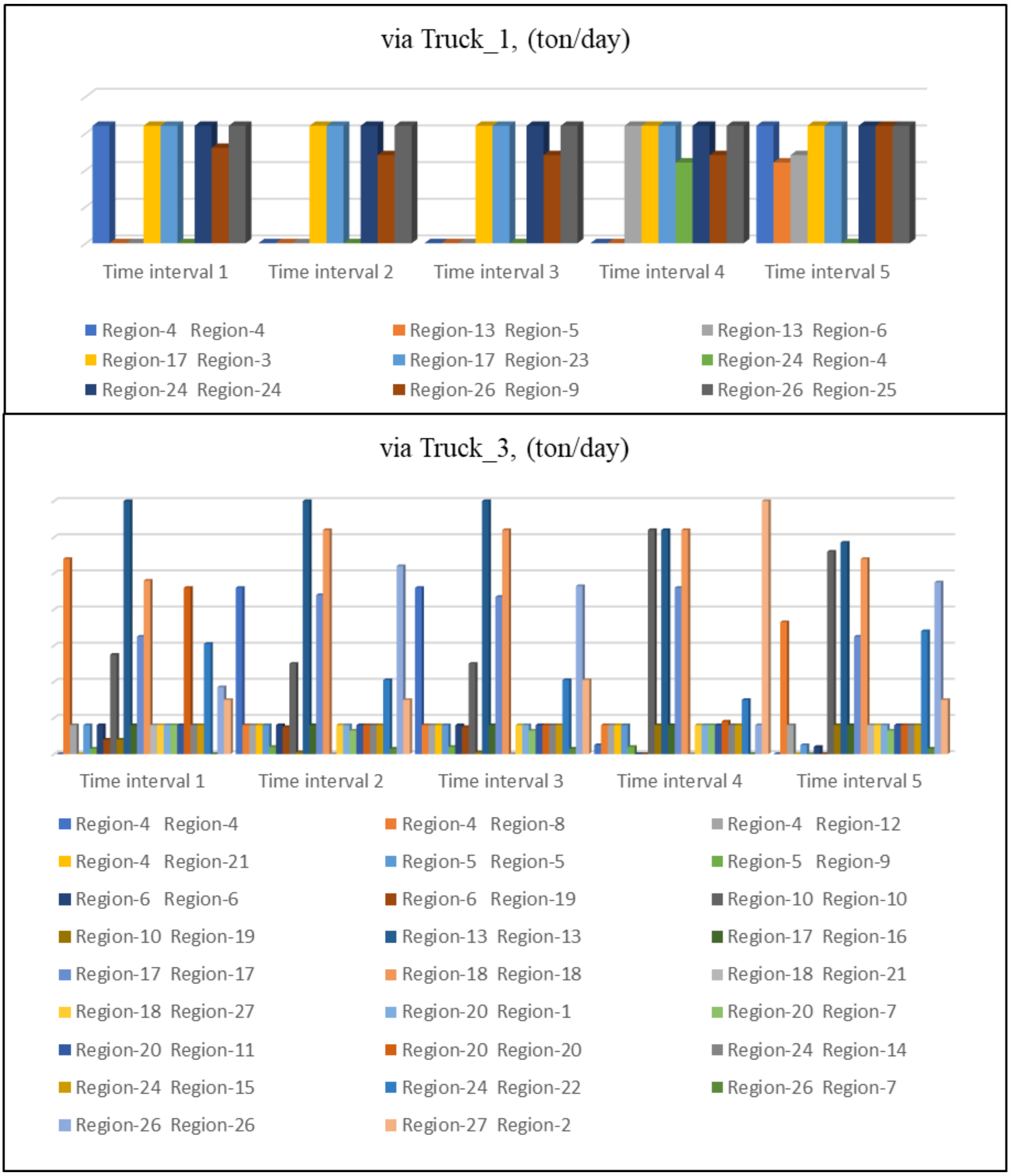
Figure 5: Optimal flows of yogurt 4,5 % delivered via Truck_1 and Truck_3 to consumers



The optimal flows of yogurt 4,5 % (delivered via Truck_1 and Truck_3 to consumers) are presented in a Figure 5 and it shows that the flow of yogurt 4,5 % delivered via Truck_1 during each time intervals is greatest from region 17 to regions 3 and 23, but that the preferred transport is Truck_3.

The optimal flows of white brined cheese (delivered via Truck_1 and Truck_3 to consumers) are presented in a Figure 6.

Figure 6: Optimal flows of white brined cheese delivered via Truck_1 and Truck_3 to consumers

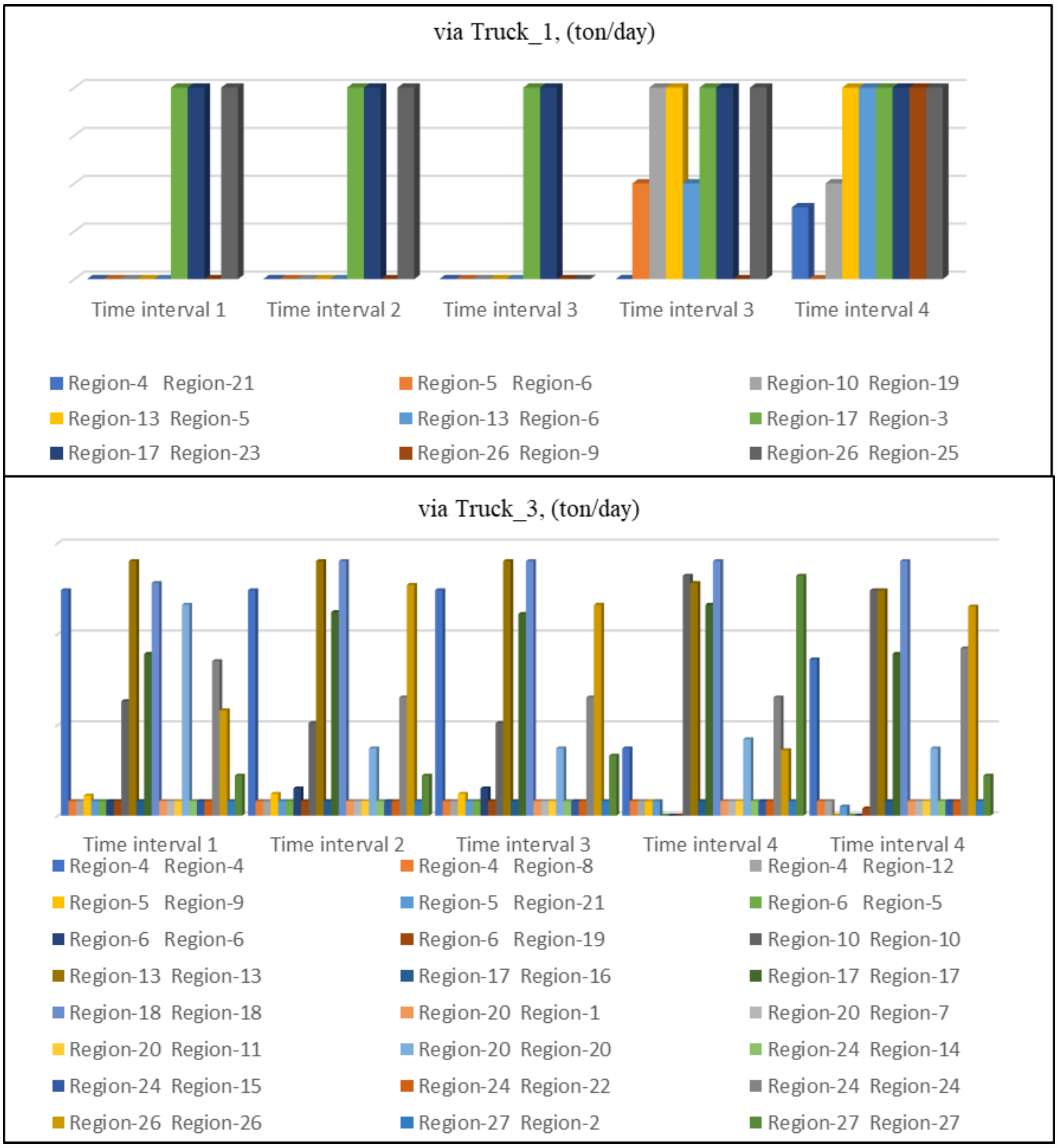


The analysis of the figure shows that most cheese producing regions prefer delivery to end customers via Truck_3.

The optimal flows of yellow cheese (delivered via Truck_1 and Truck_3 to consumers) are presented in a Figure 7. The greatest flows of yellow cheese delivered via Truck_1 during time intervals 1, 2 and are from region 17 to regions 3, 23 and from region 26 to regions 25;

during time interval 3 – from region 17 to regions 3 and 23; during time interval 4 and 5 more producing regions prefer delivery such via Truck _1, but the most regions prefer Truck_3.

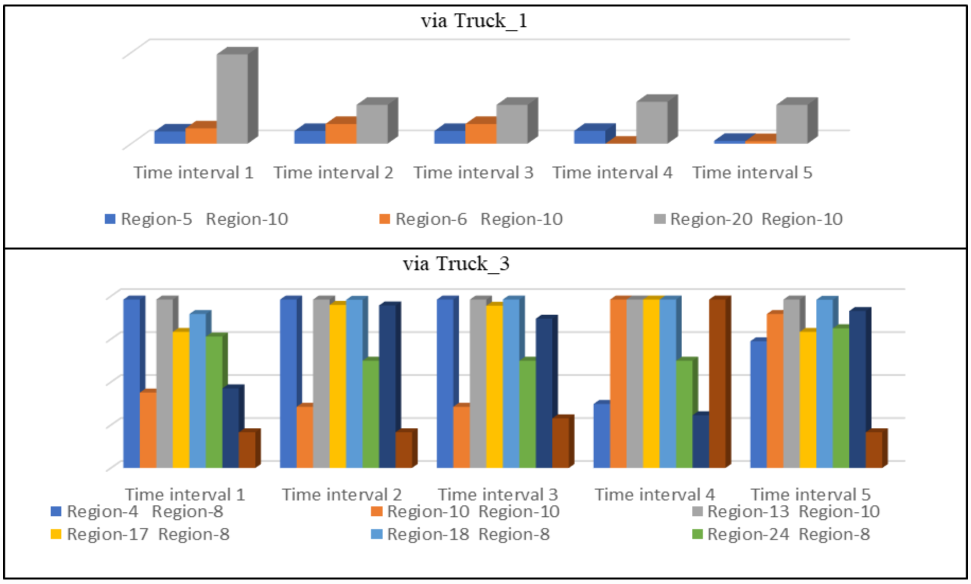
Figure 7: Optimal flows of yellow cheese delivered via Truck_1 and Truck_3 to consumers



The optimal flows of the dairy waste scum (delivered via Truck_1 and Truck_3 to biorefineries) are presented in a Figure 8. Some regions producers of dairy waste scum, as regions 5,6 and 20, choose delivery to biorefineries via Truck_1 during each time intervals. But more of them prefer delivery via Truck_3.

The analysis of the displayed results shows that the deliveries of all material flows are carried out via Truck_1 and Truck_3 but in many cases preferred transport is Truck_3.

Figure 8: Optimal flows of the dairy waste scum delivered via Truck_1 and Truck_3 to biorefineries



4. Conclusion

The production of biodiesel from waste biomass generated in dairies is attracting increased interest as a way to reduce dependence on conventional diesel and to reduce carbon emissions sought in it. The presented study examines the key activities of the supply chain, including production of milk as a raw material, processing of milk into various dairy products, its delivery to client territories and utilization of resulting waste biomass over manufacturing of biodiesel. Adding up to (Ivanov et al., 2021; Ivanov et al., 2022) this research is the first of its type to provide a detailed analysis of the implementation of united dairy waste scum-biodiesel supply chain management, focusing on the economic and environmental impacts. A mathematical model that uses overall expenditure and greenhouse gas emissions as a criterion for system efficiency was proposed. The optimization procedure in terms of Mixed Integer Linear Programming (MILP) was formulated and the specialized software General Algebraic Modeling System (GAMS) to solve it was used. The developed model can be used as a helpful instrument for the supply chain management, in this meaning optimal bio refinery site choice and logistics design. This optimization model enables decisions on infrastructure for production of biofuel, volumes and transport logistics from biomass to biorefineries and from biorefineries to blending and consumption sites under paradigm of sustainability. The proposed flexible optimization model has been applied on a test example that examines the territory of the Republic of Bulgaria. In this work, data on optimal structure and size of flows on the Bulgarian scale was reported.

Acknowledgment

The authors acknowledge financial support from National Science Fund, Ministry of Education and Science of the Republic of Bulgaria, Contract № КП-06-Н37/5/06.12.19

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