A Multi-Objective Approach toward Optimal Design of Sustainable Integrated Biodiesel/Diesel Supply Chain Based on First- and Second-Generation Feedstock with Solid Waste Use †

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Abstract: This study proposes a multi-objective approach for the optimal design of a sustainable Integrated Biodiesel/Diesel Supply Chain (IBDSC) based on first- (sunflower and rapeseed) and second-generation (waste cooking oil and animal fat) feedstocks with solid waste use. It includes mixed-integer linear programming (MILP) models of the economic, environmental and social impact of IBDSC, and respective criteria defined in terms of costs. The purpose is to obtain the optimal number, sizes and locations of bio-refineries and solid waste plants; the areas and amounts of feedstocks needed for biodiesel production; and the transportation mode. The approach is applied on a real case study in which the territory of Bulgaria with its 27 districts is considered. Optimization problems are formulated for a 5-year period using either environmental or economic criteria and the remainder are defined as constraints. The obtained results show that in the case of the economic criterion, 14% of the agricultural land should be used for sunflower and 2% for rapeseed cultivation, while for the environmental case, 12% should be used for rapeseed and 3% for sunflower. In this case, the price of biodiesel is 14% higher, and the generated pollutants are 6.6% lower. The optimal transport for both cases is rail.

Keywords: integrated biodiesel/diesel supply chain; optimal design; 1G and 2G feedstock; life cycle analysis; GHG emissions; solid waste use; economic, environmental and social criteria

1. Introduction

The global trend for energy consumption shows a steady increase until 2030, with liquid fuels accounting for the largest share of fuel demand in the transport sector. Biodiesel is one of the most commercially available biofuels, which has many advantages, such as reducing harmful emissions of SO_x, CO, CO_2, soot and NO_x [1], a higher cetane number, improved engine performance, increased power, and reduced fuel consumption, as well as the production of glycerol as a by-product, which is applicable in medicine, cosmetics and others [2]. The biodiesel production has resulted in the adoption of Directive 2003/30/EC on the promotion of the use of biofuels for transport, which aims to gradually integrate biofuels into diesel and petrol fuels in the countries of the European Union [3]. However, the high production costs of biodiesel are one of the main drawbacks to achieving the commercial viability of biodiesel. This is due to the price of used feedstock, which accounts for 70–95% of the total production costs.

Biodiesel is classified can be classified as first-, second-, third- or fourth-generation (G) biodiesel, depending of the feedstock used for its production. For production of 1G biodiesel, cultures such as sunflower, rapeseed, soybean, coconut, palm are used. 2G

biodiesel is produced from non-food or waste sources such as waste cooking oil and animal fats. 3G biodiesel is produced from microalgae, etc. 4G biodiesel is produced from synthetic biology.

Production of biodiesel using certain cereals as feedstock can lead to some problems related to increase in crop area and the shortage of food and food products which impacts on food prices. Its advantage is the reliability and sustainability of the technologies used, leading to high productivity. Using of some feedstocks such as palm oil leads to a decrease in brake thermal efficiency and an increase in brake-specific fuel consumption, a reduction in CO and HC emissions, and an increase in NO_x emissions [4]. Biodiesel production from some non-food or waste sources is associated with high production costs due to the application of expensive technologies for pre-treatment of used feedstocks. However, the latter is offset by the low feedstock costs and their full use, which makes a valuable contribution to reducing greenhouse gas emissions. Microalgae biodiesel has high energy content, high oil content and a less polluting nature [5]. Using other feedstock as Spirulina leads to acceleration of the ignition process, reducing NO_x, PM and SO_2 emissions [6]. Waste cooking oil is also a very valuable feedstock due to its very low price and unlimited quantities [7]. Razzaq et al. (2020) [8] investigated the process of biodiesel production from waste cooking oil (WCO), where the pretreatment of WCO was performed using mineral acids to reduce the acid value. The authors applied response surface methodology (RSM) to create an interaction for different operating parameters that affect biodiesel yield. On the other hand, Yesilyurt and Cesur (2020) [9] studied the process of biodiesel production from Styrax officinalis L. oil and found the parameters that affect the biodiesel yield: catalyst concentration, molar ratio of methanol to oil, reaction time and reaction temperature. Using jatropha biodiesel, polanga biodiesel and microalgae biodiesel leads to hydrocarbon, carbon monoxide and smoke emissions reduction [10]. Biodiesel produced from synthetic biology achieves better physiochemical properties and carbon neutral economy [5]. From the abovementioned information it is clear that the choice of feedstock is essential for the quality of the biodiesel produced as well as for improving the performance of the engine [11].

Apart from the type of feedstock used, the quality and price of the biodiesel produced depends on other factors, such as transport logistics, production and storage technologies, as well as the location of the biorefineries. One of the ways to increase the economic and environmental benefits of the biodiesel production is to optimize all activities in the network, from raw materials, through the productions themselves, to the customer, or to implement strategies for sustainable management of the so-called supply chains (SC) [12]. The SC for biofuel production consists of a network of producers of raw materials, biorefineries, storage facilities, blending stations and customers [13]. Habib and co-authors [14] proposed an optimization model for design of an animal fat-based biodiesel supply chain network. The purpose was to minimize the cost of total biodiesel supply chain operations and carbon emissions during the involved operations.

The SC design begins with determining the type of feedstock and the location for its cultivation, in cases where 1G feedstocks are used. At the next stage it is necessary to solve problems such as collection and transportation to storage warehouses and subsequent processing and transportation to biorefineries, forming a special coordination system, providing the best opportunity between the different areas. The choice of location and technology is the most important stage of biofuel production. The optimal capacities of the biorefineries should also be taken into account. After selecting the technology, the type of transport and route for transporting the product to the blending facilities are selected, and their locations should be determined in advance [15].

The optimal design of a biofuel SC is related to making strategic, tactical and operational decisions to reduce the total cost and increase the profit [13]. Globalization and modern communication technologies provide a large number of opportunities to improve SC efficiency. Therefore, the integrated overall optimization of operations and activities throughout the enterprise is key to the competitiveness of a company [16]. To this end,

an approach for optimal design of integrated biodiesel/diesel supply chain using first generation feedstock was developed [17].

However, full sustainability can be achieved by taking into account the three aspects of sustainability-economic, environmental and social sustainability [18]. The main issues related to achieving environmental sustainability are reducing greenhouse gas emissions, improving the quality of water resources, reducing soil degradation and biodiversity loss [19]. The main aspects of economic sustainability are related to the price of the biofuel produced, achieving energy balance by reducing energy for production [20], and increasing budget programs to stimulate biofuel production [21]. Some of the issues involved in the concept of social sustainability are related to reduction: such as poverty [22], indirect effects on soil and plants [23], and the impact on social resources, such as water supply systems.

Many of the studies in the available literature related to the production of biodiesel from various feedstocks are related to the investigation of some of the economic and technical parameters of the process and how they affect the performance of the engine in terms of fuel consumption, ignition and reduction of CO, HC and NO_x. Some studies are related to the investigation of the process parameters that affect the yield of biodiesel. There are studies that are based on the optimization of all activities across the network or the optimal design of biodiesel supply chains using only of one feedstock, where economic environmental and/or social criteria are taken into consideration. There are no approaches for the design of integrated biodiesel/diesel supply chain using different feedstocks and while accounting for all aspects of sustainability.

This study proposes an approach for the optimal design of an IBDSC based on 1G and 2G feedstocks with solid waste use. Sunflower and rapeseed are used as 1G feedstocks, while the 2G feedstocks used are waste cooking oil, animal fats and sunflower husk. The approach is applied in the territory of Bulgaria and its corresponding 27 districts. The approach includes mathematical models of the economic, environmental and social impact of considered supply chain which are defined in terms of mixed integer linear programming (MILP). The aim is to develop a strategy, methods and software for optimal use of resources in the biodiesel production. The approach applies the principle of life cycle analysis, which considers all stages of biodiesel production. The latter includes feedstock cultivation, transport of feedstocks to the plant, production of biodiesel, and its transport to the blending centers. Three optimization criteria are defined-economic, environmental and social—in terms of costs. The economic criterion is related to the price of the produced biodiesel, the environmental criterion is related to the amount of greenhouse gas emissions generated during SC operation, and the social criterion determines the number of new jobs related to the design and operation of the considered SC. Optimization problems are formulated and solved for one criterion at a time-economic or environmental—while the others, including the social one, are defined as constraints.

2. Problem Description

The proposed approach is developed in order to plan the activities in an integrated biodiesel/diesel supply chain using as feedstocks cereals such as sunflower, rapeseed and others within a 5-year horizon, including government regulations, production, construction and a carbon tax. The supply chain includes a set of collection sites and a set of search areas, as well as potential locations for individual facilities and biorefineries as the feed materials are transported to biorefineries for further processing. Data about the costs of cultivation and harvesting energy crops are available. For each potential collection facility, the fixed and variable costs of building the facilities are defined, as well as the production costs and the capacity for each potential biorefinery. For each search area, the respective biofuel is defined, as well as its environmental impact. For each transport connection, the transport capacity, the available transport modes, the transport costs per unit distance, as well as the transport distances and emissions for each type of transport are defined.

The superstructure of IBDSC represented in Figure 1 includes the following:

1. A set of biomass production areas where different types of feedstocks are used for biorefineries.
2. A set of adopted initiatives for the implementation of plants for the production of biodiesel with different capacities.
3. A set of blending and sales areas where final products meeting certain requirements are sold.
4. A set of existing refineries for petroleum diesel fuel.
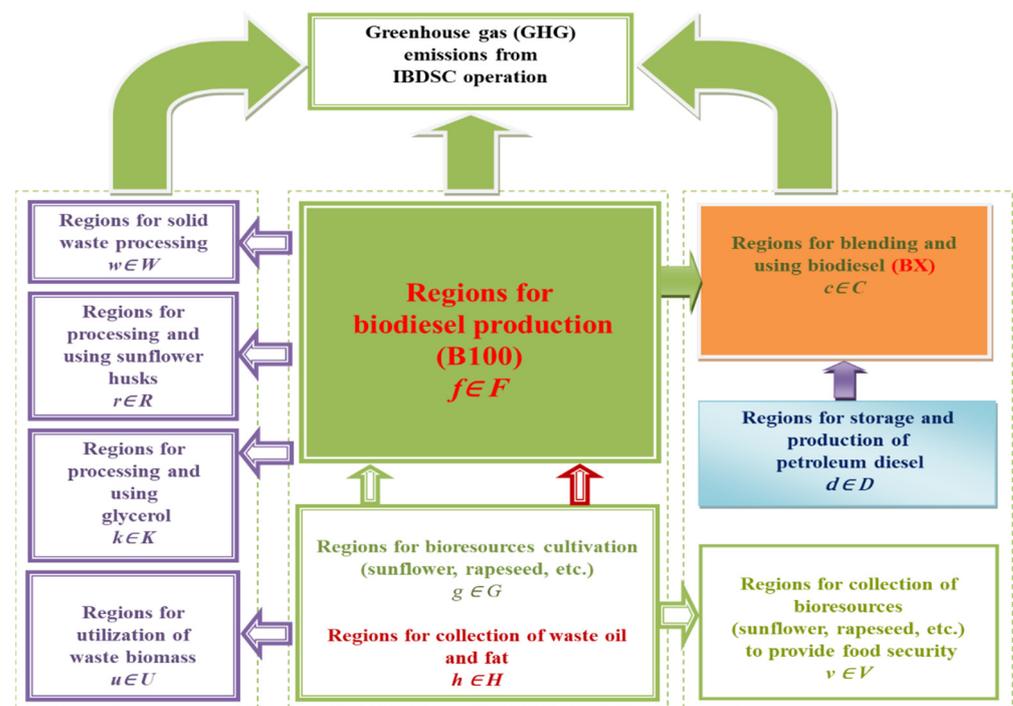
Figure 1. Superstructure of the integrated biodiesel/diesel supply chain.

The aim is to determine the number, location and the capacity of biodiesel refineries, as well as the bioresources to be transported between the different sites of designed supply chain with minimal costs while satisfying product demand constraints. It is planned that the biodiesel refineries will operate in the determined time interval with the possibility of upgrades related to increasing the production capacity.

The 5-year planning horizon H is divided into a set of discrete time intervals t. This time interval is divided into several equal time intervals $t = \{0, 1, 2, \ldots, T\}$, each of which lasts ∇t. Within the planning horizon, it is assumed that diesel consumption will change by an estimated value. At the same time, it is assumed that the annual growth of biodiesel consumption is known, in order to meet the requirements of the directives adopted by the government.

Generally, the problem for each time interval t is to determine:

1. Potential locations of the centers for realization of biofuels;
2. Diesel demand for each of the fuel search centers;
3. Relevant requirements for the percentage of biodiesel as a constituent of diesel fuel during the considered period of time;
4. Types of biomass and their geographical availability;
5. Costs for the cultivation of a unit of biomass for each type of raw material;
6. Unit cost of biodiesel according to the type of raw material;
7. Characteristics of the transport logistics (costs, modes);
8. Capital investment costs of biodiesel production facilities;
9. Specific emission factors of greenhouse gases during the life cycle stages of biodiesel production;

10. Carbon tax;
11. Government incentives for the production and the use of biodiesel.

The aim of the study is to find values of variables that optimize the economic, environmental and social performance of IBDSC in the interval t of the time horizon *H*:

1. Supply chain (SC) structure;
2. Time for biomass cultivation for each type of biomass and biodiesel production;
3. Locations of biodiesel production facilities and locations of biomass cultivation sites;
4. Biomass and biodiesel flows of each type between regions;
5. Type of transport for the supply of biomass, biodiesel and petroleum diesel;
6. GHG emissions at each stage of the life cycle of the products;
7. Amounts transported for each transport connection and transport mode;
8. Strategy for biomass supply of the production facilities;
9. Processes of distribution of biofuels and diesel fuel, delivered in the demand areas.

3. Formulation of the Optimization Problem

The optimal design of IBDSC is related to solving three key problems, namely finding: (1) the number, sizes and locations of biorefineries and solid waste plants; (2) the sites and amount of 1G feedstocks and 2G feedstocks; (3) the transportation plans of 1G and 2G feedstocks, solid waste, fossil diesel, glycerin and biodiesel.

This leads to the formulation and solution of optimization problems in terms of Mixed Integer Linear Programming (MILP). The problems involve mathematical models for description of economic, environmental and social performance of the IBDSC, economic, environmental and social optimization criteria and constraints. The social criterion is related to the equality of work, health and safety. It depends on government policies and cultural norms as well as input parameters, decision variables, sets, subsets and indices (Appendix A). At first, the set of time intervals on the planning horizon is defined $t = \{0, 1, 2, \ldots, T\}$. The index t indicates the variable or parameter corresponding to the t-th scheduling interval.

3.1. Mathematical Modeling of the Environmental Impact Performance of IBDSC

The environmental impact of IBDSC is assessed on the basis of total annual GHG emissions, such as carbon dioxide (CO_2), methane (CH_4) and nitrogen oxide (NO_2), resulting from supply chain activities. The greenhouse gases are grouped in a common indicator in terms of equivalent carbon dioxide emissions [CO_2eq./ y] using their respective global warming potentials (GWPs) based on the recommendation of the Intergovernmental Panel on Climate Change (IPCC, 2007) [23] for a 100-year time horizon as follows: 1 for CO_2, 25 for CH_4 and 298 for NO_2. The total GHG emissions are converted into carbon credits [$kg_{CO_2eq.}$] multiplied by the price of carbon on the market.

A Life Cycle Analysis (LCA) approach was applied to assess the overall impact of IBDSC, which takes into account the following stages of the life cycle of liquid fuels for transport based on biomass:

1. Stage of biomass production. This consists of different sub-stages depending on the type of bioresource and subsequent use.
2. Stage of biomass transportation. This refers to the delivery of biomass to the processing facility.
3. Stage of biomass conversion into biodiesel.
4. Stage of transportation of biodiesel (B100) and petroleum diesel fuel to blending areas for diesel fuel and customers.
5. Stage of final biofuel consumption-a stage in which the biofuel is introduced into the engine of the vehicle and is burned to provide mechanical energy for mobility.

The environmental criterion represents the total environmental impact during the operation of the IBDSC through the resulting GHG emissions at each time interval $t \in T$.

These emissions are equal to the sum of the environmental impacts of each stage of the life cycle. GHG emissions are usually determined as follows for each time interval $t \in T$:

$$TEI_t = ELS_t + ELB_t + ELD_t + ETT_t + ESW_t + ESTRAW_t + ECAR_t + EWCO_t, \; \forall t \quad (1)$$

where TEI_t overall environmental impact of IBDSC $\left[\text{kg}_{CO_2\text{eq.}} \text{d}^{-1} \right]$.

The environmental impact assessment at each stage of the life cycle includes:

1. Biomass cultivation ELS_t;
2. Biodiesel production (B100) ELB_t;
3. Petroleum diesel production ELD_t;
4. Solid waste use ESW_t;
5. Biomass transportation ETA_t;
6. Biodiesel transportation (B100) ETE_t;
7. Petroleum diesel transportation ETD_t;
8. Solid waste transportation ETW_t;
9. Straw transportation ETU_t;
10. Transportation of sunflower/rapeseed for food security ETV_t;
11. The use of biodiesel in vehicles (B100) and diesel $ECAR_t$;
12. Use of WCO, when not used for biodiesel (B100) $EWCO_t$.

- Environmental impact of biomass cultivation ELS_t, $\left[\text{kg}_{CO_2\text{eq.}} \text{d}^{-1} \right]$

GHG emissions as a result of biomass production depend on the specifics of the crops grown as well as the geographical region in which the biomass is cultivated [24]. In particular, the environmental impact is influenced by the use of fertilizers and pesticides, the type of irrigation techniques used, and soil characteristics. It has different values for different production areas. The stage of biomass cultivation can be defined as follows:

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

where ELS_t is the total environmental impact of the biomass cultivation, which represents the rate of production of bioresource $i \in I$ in region $g \in G$, $\left[\text{kg}_{CO_2\text{eq.}} \text{d}^{-1} \right]$.

- Environmental impact of biodiesel production ELB_t, $\left[\text{kg}_{CO_2\text{eq.}} \text{d}^{-1} \right]$

The environmental impact of the biodiesel (B100) production stage is related to the feedstocks and biodiesel production technology used. GHG emissions related to this stage will be assumed in proportion to the specific amount of biomass in the biodiesel production:

$$ELB_t = \sum_{p \in P} \left(\sum_{i \in I} (EFBP_{ip} \gamma_{it}) \sum_{g \in G} \sum_{f \in F} \sum_{l \in L} QIP_{igflpt} \right) + \sum_{p \in P} \left(\sum_{y \in Y} (EWCO_{yp} \gamma w_{yt}) \sum_{g \in G} \sum_{f \in F} \sum_{l \in L} QIPw_{yhfl_cpt} \right), \; \forall t \quad (3)$$

where,

$$QI_{igflt} = \sum_{p \in P} QIP_{igflpt}, \; \forall igfl, \; \forall t \in T$$

$$QIw_{yhfl_ct} = \sum_{p \in P} QIPw_{yhfl_cpt}, \; \forall yhfl_c, \; \forall t \in T$$

$$QIP_{igflpt} \le QI_{igt}^{MAX} X_{igflpt}, \; \forall igflp, \; \forall t \in T$$

$$QIPw_{yhfl_cpt} \le QIw_{yht}^{MAX} Xs_{yhfl_cpt}, \; \forall yhfl_c p, \; \forall t \in T$$

$$\sum_{p \in P} X_{igflpt} \le 1, \; \forall igfl, \; \forall t \in T$$

$$\sum_{p \in P} Xs_{yhfl_cpt} \leq 1, \ \forall yhfl_cp, \ \forall t \in T$$

where ELB_t is the overall environmental impact of biodiesel (B100) production $\left[\text{kg}_{\text{CO}_2\text{eq.}}\text{d}^{-1}\right]$.

- Environmental impact of petroleum diesel production ELD_t, $\left[\text{kg}_{\text{CO}_2\text{eq.}}\text{d}^{-1}\right]$

$$ELD_t = \sum_{d \in D} EFDP_d \sum_{c \in C}\sum_{b \in B} QD_{dcbt}, \ \forall t \tag{4}$$

where ELD_t is the environmental impact of petroleum diesel production, $\left[\text{kg}_{\text{CO}_2\text{eq.}}\text{d}^{-1}\right]$.

- Environmental impact of transportation ETT_t, $\left[\text{kg}_{\text{CO}_2\text{eq.}}\text{d}^{-1}\right]$

The environmental impact of both biomass supply and fuel distribution depends on the type of the used vehicles. The resulting GHG emissions depend on both the distance and payload capacity of the used vehicles. As a result, the emission factor represents the corresponding carbon dioxide emissions:

$$ETT_t = ELA_t + ELB_t + ELD_t + ELW_t + ELU_t + ELV_t \tag{5}$$

where
ETT_t is the environmental impact of transportation of all resources, $\left[\text{kg}_{\text{CO}_2\text{eq.}}\text{d}^{-1}\right]$

$$ELA_t = \sum_{i \in I}\sum_{g \in G}\sum_{f \in F}\sum_{l \in L}\left(EFTRA_{il}ADG_{gfl}QI_{igft}\right) + \sum_{y \in I}\sum_{h \in H}\sum_{f \in F}\sum_{l_c \in LC}\left(EFTWA_{yl_c}ADG_{hf_cl}QIw_{yhfl_ct}\right), \ \forall t$$

is the environmental impact of biomass and WCO transportation

$$ELB_t = \sum_{f \in F}\sum_{c \in C}\sum_{b \in B}\left(EFTRB_b ADF_{fcb}QB_{fcbt}\right), \ \forall t$$

is the environmental impact of biodiesel (B100) transportation from areas $f \in F$ to $c \in C$;

$$ELD_t = \sum_{d \in D}\sum_{c \in C}\sum_{b \in B}(EFTBD_b ADD_{dcb}QD_{dcbt}), \ \forall t$$

is the environmental impact of petroleum diesel transportation from areas $d \in D$ to $c \in C$.

$$ELW_t = \sum_{f \in F}\sum_{w \in W}\sum_{m \in M}\left(EFTRW_m ADW_{fwm}QW_{fwmt}\right), \ \forall t$$

is the environmental impact of solid waste transportation from areas $f \in F$ to $w \in W$, $\left[\text{kg\_\{CO}_2\text{eq}\} \, \text{d}^{-1}\right]$;

$$ELU_t = \sum_{g \in G}\sum_{u \in U}\sum_{e \in E}\sum_{i \in I}(EFTRU_e ADU_{gue}QU_{iguet}), \ \forall t$$

is the environmental impact of straw transportation from areas $g \in G$ to $u \in U$, $\left[\text{kg}_{\text{CO}_2\text{eq.}}\text{d}^{-1}\right]$;

$$ELV_t = \sum_{g \in G}\sum_{v \in V}\sum_{z \in Z}\sum_{i \in I}(EFTRV_z ADV_{gvz}QV_{igvzt}), \ \forall t$$

is the environmental impact of the transportation of sunflower/rapeseed to provide food security from the areas $g \in G$ to $v \in V$, $\left[\text{kg}_{\text{CO}_2\text{eq.}}\text{d}^{-1}\right]$.

- Environmental impact of waste solids use ESW_t, $\left[\mathrm{kg}_{\mathrm{CO_2eq.}} \mathrm{d}^{-1}\right]$

$$ESW_t = \sum_{f \in F} \left(ESF1_{ft}\left(FSW_{ft} - FSWW_{ft}\right)\right) + ESWW_t, \forall t \tag{6}$$

$ESF1_{ft}$ GHG emissions released if waste solids use realizes in biodiesel plant $f \in F$, $\left[\dfrac{\mathrm{kg}_{\mathrm{CO_2eq.}}}{\mathrm{t}_{\mathrm{solid\ waste}}}\right]$

where ESW_t are the GHG emissions that should have been generated if part of the solid waste had not been treated in the areas determined for this purpose, $\left[\mathrm{kg}_{\mathrm{CO_2eq.}} \mathrm{d}^{-1}\right]$, FSW_{ft} is the amount of solid waste generated during the operation of each of the plants $f \in F$ for the time interval $t \in T$, and $FSWW_{ft}$ is the amount of solid waste generated by $f \in F$ that is processed in all plants $w \in W$.

$$FSW_{ft} = \sum_{i \in I} \sum_{p \in P} \sum_{c \in C} \sum_{b \in B} \left(SW_{ip}QBP_{ifcbpt}\right), \forall t, f$$

$$FSWW_{ft} = \sum_{m \in M} \sum_{w \in W} QW_{fwmt}, \forall t$$

$ESWW_t$ represents GHG emissions generated by solid waste use when it takes place at one of the plants $w \in W$ and it is determined as follows:

$$ESWW_t = \sum_{f \in F} \sum_{w \in W} \sum_{m \in M} \sum_{s \in S} \left(ESW1_{wst}QWS_{fwmst}\right), \forall t$$

- Environmental impact of straw use $ESTRAW_t$, $\left[\mathrm{kg}_{\mathrm{CO_2eq.}} \mathrm{d}^{-1}\right]$

$$ESTRAW_t = \sum_{i \in I} \left(ESU_i \left(\sum_{g \in G} \left(A_{igt} + A^F_{igt}\right) \beta s_{igt} - \alpha \sum_{g \in G} \sum_{u \in U} \sum_{e \in E} QU_{iguet} \right) \right), \forall t \tag{7}$$

where $ESTRAW_t$ are GHG emissions related to straw use, $\left[\mathrm{kg}_{\mathrm{CO_2eq.}} \mathrm{d}^{-1}\right]$.

- Environmental impact of the use of biodiesel (B100) and petroleum diesel during transportation $ECAR_t$, $\left[\mathrm{kg}_{\mathrm{CO_2eq.}} \mathrm{d}^{-1}\right]$

$$ECAR_t = ECB \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} QB_{fcbt} + ECG \sum_{d \in D} \sum_{c \in C} \sum_{b \in B} QD_{dcbt}, \forall t \tag{8}$$

where $ECAR_t$ are the GHG emissions from the use of biodiesel (B100) and petroleum diesel in vehicles, $\left[\mathrm{kg}_{\mathrm{CO_2eq.}} \mathrm{d}^{-1}\right]$.

- Environmental impact of WCO use if not used for biodiesel (B100) production $EWCO_t$, $\left[\mathrm{kg}_{\mathrm{CO_2eq.}} \mathrm{d}^{-1}\right]$

$$EWCO_t = \frac{1}{\alpha_t} \sum_{h \in H} \sum_{y \in Y} \left(PBIs^{MAX}_{yht}EFTWC_y \right) - \sum_{h \in H} \sum_{y \in Y} \sum_{f \in F} \sum_{l_c} \left(EFTWC_yQIw_{yhfl_ct} \right), \forall t \tag{9}$$

where $EWCO_t$ are the GHG emissions released during the WCO use in case it is not used for biodiesel (B100) production, $\left[\mathrm{kg}_{\mathrm{CO_2eq.}} \mathrm{d}^{-1}\right]$.

3.2. Mathematical Modeling of Economic Performance of IBDSC

The economic assessment of IBDSC includes all types of costs related to its operation. Annual operating costs include biomass acquisition costs, local final product costs, final

product production costs and transportation costs for the biomass and final products. The production costs take into account both the fixed annual operating costs, which are given as a percentage of the total capital investment concerned, and the net variable price, which is proportional to the amount to be processed. For transportation costs, both the fixed distances and distances with variable costs are taken into account. The economic assessments are the costs related to the plant, which include the total investment costs for biodiesel production capacity (B100) and the operation of the IBDSC. They are expressed as follows for each time interval [25] $t \in T$:

$$TDC_t = TIC_t + TIW_t + TPC_t + TPW_t + TTC_t + TTAXB_t - TL_t - TA_t + TWCO_t, \ \forall t \qquad (10)$$

where

TDC_t Total costs of IBDSC per year, $\left[\$ \, y^{-1}\right]$;

TIC_t Total investment costs for IBDSC production capacity compared to the period of operation and the purchase of the plant for a year, $\left[\$ \, y^{-1}\right]$

TIW_t Total investment costs for IBDSC solid waste treatment plants compared to the period of operation and the purchase of the plant per year, $\left[\$ \, y^{-1}\right]$];

TPC_t Production costs in biodiesel production (B100), $\left[\$ \, y^{-1}\right]$

TPW_t Production costs for solid waste disposal, $\left[\$ \, y^{-1}\right]$;

TTC_t Total transportation costs of IBDSC, $\left[\$ \, y^{-1}\right]$;

$TTAXB_t$ Carbon tax charged according to the total amount CO_2, generated during the operation of IBDSC, $\left[\$ \, y^{-1}\right]$;

TL_t Government incentives for biodiesel production and consumption (B100), $\left[\$ \, y^{-1}\right]$;

TA_t Total value of by-products (glycerol, cake), $\left[\$ \, y^{-1}\right]$;

$TWCO_t$ Price of the unused portion of WCO in the production of biodiesel (B100), which is considered to be a penalty function. (This unused portion of the WCO is considered to be a pollutant, the amount of which should be minimized).

- Investment costs for biorefineries TIC_t, $\left[\$ \, y^{-1}\right]$

The planning of the design of the facilities at IBDSC is carried out for a certain time period, ensuring that after their creation, they will work during the remaining period:

$$TIC_t = \varepsilon_t \sum_{f \in F} \sum_{p \in P} \left(Cost^F_{pft} Z_{pft} \right), \ \forall t \qquad (11)$$

where ε_t is the discount factor defined by [26], which is calculated as follows:

$$\varepsilon_t = \frac{1}{(1 + \varsigma_t)} \qquad (12)$$

where ς_t is the interest rate [%] for the time interval $t \in T$.

The refinery's capital costs consist of fixed and variable costs. Fixed capital costs vary depending on the location of the refineries. The variable capital value of plants from biomass to biodiesel (B100) is mainly influenced by the size of the plantations. Variable capital costs are scaled using a common relationship [27]:

$$\frac{CostB_{pt}}{Cost_{base}} = \left(\frac{Size_p}{Size_{base}} \right)^R, \ \forall t \in T \qquad (13)$$

where $CostB_{pt}$ is a variable capital cost and $Size_p$ is the investment costs and production capacity of new plant, $Cost_{base}$ is the known investment costs for a certain pland capacity $Size_{base}$, and R is the scaling factor varying usually between 0.6 and 0.8.

The capital costs of the biorefinery for each region are determined by the following equation:

$$Cost^F_{pft} = M^{cost}_f CostB_{pt}, \ \forall p \in P , \ \forall f \in F, \ \forall t \in T \tag{14}$$

where M^{cost}_f is the correction factor in the price of biorefineries in the region $f \in F$ according to the built biorafineries $M^{cost}_f \geq 1$.

- Investment costs for solid waste use plants TIW_t, $\left[\$ \ y^{-1} \right]$

The total value of solid waste processing facilities is determined as follows:

$$TIW_t = \varepsilon_t \sum_{w \in W} \sum_{s \in S} \left(Cost^W_{swt} ZW_{swt} \right), \ \forall t \tag{15}$$

where

$$Cost^W_{swt} = M^W_w CostW_{st}, \ \forall s \in S, \ \forall w \in W, \ \forall t \in T \tag{16}$$

and M^W_w is the correction factor in the price of the solid waste plant in the region $w \in W$ according to the built solid waste plants $M^W_w \geq 1$.

- Total production costs of IBDSC TPC_t, $\left[\$ \ y^{-1} \right]$

Total production costs TPC_t include the costs of biomass cultivation (sunflower/rapeseed) TPA_t, costs for used WCO TPW_t, costs for biodiesel (B100) production (TPB_t, $TPBs_t$), production costs for petroleum diesel TPD_t for each time interval $t \in T$ as follows:

$$TPC_t = TPA_t + TPW_t + TPB_t + TPBw_t + TPD_t, \ \forall t \tag{17}$$

where

$$TPA_t = \sum_{i \in I} \sum_{g \in G} \left(UPC_{igt} \beta_{igt} \left(A_{igt} + A^F_{igt} \right) \right), \ \forall t \ ;$$

$$TPW_t = \sum_{y \in Y} \sum_{h \in H} \sum_{f \in F} \sum_{p \in P} \sum_{l_c \in LC} \left(\alpha_t UPW_{yht} QIPw_{yhfl_cpt} \right), \ \forall t;$$

$$TPB_t = \sum_{i \in I} \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} \sum_{p \in P} \left(\alpha_t UPB_{ipft} QBP_{ifcbpt} \right), \ \forall t;$$

$$TPBw_t = \sum_{y \in Y} \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} \sum_{p \in P} \left(\alpha_t UPBw_{ypft} QBPw_{yfcbpt} \right), \ \forall t;$$

$$TPD_t = \sum_{c \in C} \sum_{b \in B} \sum_{d \in D} \left(\alpha_t UPD_{dt} QD_{dcbt} \right), \ \forall t.$$

- Total costs of solid waste processing TPW_t, $\left[\$ \ y^{-1} \right]$

The total costs of solid waste use are calculated as follows:

$$TPW_t = \alpha_t \sum_{f \in F} \sum_{w \in W} \sum_{m \in M} \sum_{s \in S} \left(UPW_{swt} QWS_{fwmst} \right) + \sum_{f \in F} \left(QWPLANTS_{ft} UPSW_{ft} \right), \ \forall t \tag{18}$$

Only one of the sizes $s \in S$ can be selected for the region $w \in W$ (this is provided by satisfying the system of inequalities $\sum_{s \in S} ZWF_{swt} \leq 1.0 \ \forall t, \ w$), and QWS_{fwmst} is "0" for all sizes except the selected one $s \in S$. This is provided by satisfying inequalities $G^{MAX} ZWF_{swt} \geq QWS_{fwmst}, \ \forall f, m, s, t$, where G^{MAX} is a large enough number.

$QWFULL_{ft}$ is the total amount of solid waste $\left[\$\,\text{y}^{-1}\right]$, which are generated by each biorefinery $f \in F$, and $QWPLANTS_{ft}$ is the total amount of solid waste that is treated in each of the plants $f \in F$:

$$\left.\begin{array}{l} QWPLANTS_{ft} = QWFULL_{ft} - \alpha_t \sum\limits_{s \in S} \sum\limits_{w \in W} \sum\limits_{m \in M} QWS_{fwmst} \\ QWFULL_{ft} = \alpha_t \sum\limits_{i \in I} \sum\limits_{c \in C} \sum\limits_{b \in B} \sum\limits_{p \in P} \left(SW_{ipt} QBP_{ifcbpt} \right) \end{array}\right\}, \forall t, f \qquad (19)$$

- Total transportation costs TTC_t, $\left[\$\,\text{y}^{-1}\right]$

The transportation, supply of biomass to processing plants as well as the distribution and transportation of biodiesel (B100) to blending facilities are treated as an ancillary service, provided by those already working within the industrial/transport infrastructure. As a result, TTC_t is calculated as follows:

$$TTC_t = TTCA + TTCH_t + TTCB_t + TTCD_t + TTCW_t + TTCU_t + TTCV_t, \ \forall t \qquad (20)$$

where

$$TTCA_t = \sum_{i \in I} \sum_{g \in G} \sum_{f \in F} \sum_{l \in L} \left(\alpha_t UTC_{igfl} QI_{igflt} \right), \ \forall t$$

are the transportation costs of energy crops (sunflower and rapeseed) for the biodiesel (B100) production,

$$TTCH_t = \sum_{y \in Y} \sum_{h \in H} \sum_{f \in F} \sum_{l_c \in LC} \left(\alpha_t UTH_{yhfl_c} QIw_{yhfl_ct} \right), \ \forall t$$

are the transportation costs of WCO for the biodiesel (B100) production,

$$TTCB_t = \sum_{b \in B} \sum_{c \in C} \sum_{f \in F} \left(\alpha_t UTB_{fcb} QB_{fcbt} \right), \ \forall t$$

are the transportation costs of biodiesel (B100),

$$TTCD_t = \sum_{b \in B} \sum_{c \in C} \sum_{d \in D} \left(\alpha_t UTD_{dcb} QD_{dcbt} \right), \ \forall t$$

are the transportation costs of petroleum diesel,

$$TTCW_t = \sum_{m \in M} \sum_{w \in W} \sum_{f \in F} \left(\alpha_t UTW_{fwm} QW_{fwmt} \right), \ \forall t$$

are the transportation costs of solid waste,

$$TTCU_t = \sum_{e \in E} \sum_{g \in G} \sum_{u \in U} \sum_{i \in I} \left(\alpha_t UTU_{gue} QU_{guet} \right), \ \forall t$$

are the transportation costs of collected straw for processing,

$$TTCV_t = \sum_{i \in I} \sum_{z \in Z} \sum_{g \in G} \sum_{v \in V} \left(\alpha_t UTV_{igvz} QV_{igvzt} \right), \ \forall t$$

are the transportation costs of grain to provide food security.

$$
\left.\begin{aligned}
UTC_{igfl} &= IA_{il} + \left(IB_{il}\,ADG_{gft}\right)\\
UTCs_{igfe} &= OAU_e + \left(OBU_e\,ADG_{gft}\right)\\
UTB_{fcb} &= OA_b + \left(OB_b\,ADF_{fcb}\right)\\
UTD_{dcb} &= OAD_b + \left(OBD_b\,ADD_{dcb}\right)\\
UTW_{fwm} &= OAW_{em} + \left(OBW_m\,ADW_{fwm}\right)\\
UTU_{gue} &= OAU_e + \left(OBU_e\,ADU_{gue}\right)\\
UTV_{igvz} &= OAV_{iz} + \left(OBV_{iz}\,ADV_{gvz}\right)\\
UTH_{yhfl_c} &= OAH_{yh} + \left(OBH_{yh}\,AHF_{hfl_c}\right)
\end{aligned}\right\}
$$

where $(IA_{il},\ IB_{il})$ are fixed or variable costs for transportation of biomass of type $i \in I$, $\left(OAH_{yh}, OBH_{yh}\right)$ are fixed or variable costs for transportation of WCO of type $y \in Y$, (OA_b, OB_b) are fixed or variable costs for transportation of biodiesel (B100), OAD_b and OBD_b (OA_b, OB_b) are fixed or variable costs for transportation of petroleum diesel, OAW_m and OBW_m (OA_b, OB_b) are fixed or variable costs for transportation of solid waste, OAU_e and OBU_e (OA_b, OB_b) are fixed or variable costs for transportation of straw, OAV_{iz} and OBV_{iz} are fixed or variable costs for transportation of biomass of type $i \in I$.

The costs of biomass transportation UTC_{igfl} are described in [28], using tractor, truck and train as vehicles UTB_{fcb}. These include fixed costs (IA_{il}, OA_b) and variable costs (IB_{il}, OB_b). Fixed costs include loading and unloading costs. They do not depend on the transportation distance. Variable costs include fuel costs, vehicle maintenance costs, driver salary, etc. They depend on the transportation distance [27].

- Carbon tax $TTAXB_t$, $\left[\$\,\mathrm{y}^{-1}\right]$

Many countries have different mechanisms in place to reduce GHG emissions by imposing a carbon tax or government incentives to produce biofuels. Carbon taxes and carbon markets (emissions trading) are recognized as the most cost-effective mechanisms. The main idea is to set a price value for carbon emissions and to create new investment opportunities to generate a fund for the development of green technologies. There are several active markets for carbon trading [29].

The introduced carbon tax is determined as follows:

$$
TTAXB_t = \alpha_t TEI_t C_{co_2},\ \forall t \tag{21}
$$

α_t is the IBDSC operating period for one year, $[\mathrm{d/y}]$.

The total emissions are converted into carbon credits by multiplying by the carbon price C_{CO_2} on the market, where it has a value $0.149\ \$/\mathrm{kg_{CO_2eq}}$.

- Government incentives costs for biodiesel (B100) production, $\left[\$\,\mathrm{y}^{-1}\right]$

The government incentives TL_t for biodiesel (B100) production and their use determines as follows:

$$
TL_t = \alpha_t \sum_{f\in F}\sum_{c\in C}\sum_{b\in B}\left(INS_{ft}\,QB_{fcbt}\right),\ \forall t \tag{22}
$$

- Total costs of selling straw for other purposes, $\left[\$\,\mathrm{y}^{-1}\right]$

$$
TS_t = \alpha_t \sum_{i\in I}\left(PSU_{it}\sum_{g\in G}\sum_{u\in U}\sum_{e\in E} QU_{iguet}\right),\ \forall t \tag{23}
$$

- Total costs for by-products (glycerin and cake), $\left[\$\,\mathrm{y}^{-1}\right]$

By-products (glycerol and cake) are used as a substitute for related products [30]. The use of by-products can effectively reduce the environmental impact. Biomass sludge was used to replace organic fertilizers, and glycerol from biodiesel production is used in cosmetics. The price of by-products (glycerol, cake and pellets) is determined as follows:

$$TA_t = \sum_{i \in I}(PGl_{it} + PMl_{it}) + \sum_{y \in Y}(PGlW_{yt} + PMlW_{yt}), \ \forall t \tag{24}$$

where

1. Price, obtained from the sale of glycerol obtained from the *i*-th raw material (glycerol in the production of soap)

$$PGl_{it} = cost\_Gl\ Gl_i \sum_{g \in G}(A_{igt}\beta_{igt}), \ \forall i \in I, \ \forall t \in T$$

$$PGlW_{yt} = cost\_Gl\ GlW_y \alpha_t \sum_{h \in H}\sum_{f \in F}\sum_{l_c \in LC} QIw_{yhfl_ct}, \ \forall y \in Y, \ \forall t \in T$$

2. Price, obtained from the sale of cake obtained from the *i*-th raw material (animal feed cake)

$$PMl_{it} = cost\_Ml\ Ml_i \sum_{g \in G}(A_{igt}\beta_{igt}), \ \forall i \in I, \ \forall t \in T$$

$$PMlW_{yt} = cost\_Ml\ MJW_y \alpha_t \sum_{h \in H}\sum_{f \in F}\sum_{l_c \in LC} QIw_{yhfl_ct}, \ \forall y \in Y, \ \forall t \in T$$

- Price of unused WCO for biodiesel (B100) production.

The price of unused WCO for (B100) production, which is a penalty function determined as follows:

$$TWCO_t = \sum_{y \in Y}\sum_{h \in H} UPWCO_{yht} \sum_{f \in F}\sum_{l_c \in LC}\sum_{p \in P}\left(PBIs_{yht}^{MAX} - \alpha_t QIPw_{yhfl_cpt}\right) \tag{25}$$

3.3. Mathematical Modeling of Social Performance of IBDSC, Job_t, [Number of Jobs/y]

The social assessment model for the IBDSC operation determines the expected total number of jobs created (J_t) as a result of the action of all elements of the network during its operation:

$$Job_t = NJ1_t + LT_t NJ2_t + LT_t NJ3_t, \ \forall t \tag{26}$$

where the terms of Equation (26) are determined according to the ratios at each time interval $t \in T$, [Number of Jobs/y]:

$NJ1_t$-the number of jobs created during the building biodiesel (B100) and solid waste plants;
$NJ2_t$-the number of jobs created during the operation of the biodiesel (B100) and solid waste plants;
$NJ3_t$-the number of jobs created during the bioresources cultivation for the biodiesel (B100) production. They determine as follows:

$$\left. \begin{array}{c} NJ1_t = \sum\limits_{p \in P}\sum\limits_{f \in F}\left(M_{ft}^{JobP}JobB_pZ_{pft}\right) + \sum\limits_{s \in S}\sum\limits_{w \in W}\left(M_{wt}^{JobW}JobW_sZW_{swt}\right) \\ NJ2_t = \sum\limits_{p \in P}\sum\limits_{f \in F}\left(M_{ft}^{JobP}JobO_pZF_{pft}\right) + \sum\limits_{s \in S}\sum\limits_{w \in W}\left(M_{wt}^{JobW}JobOW_sZWF_{swt}\right) \\ NJ3_t = \sum\limits_{i \in I}\sum\limits_{g \in G}\left(JobG_{ig}PBB_{igt}\right) \end{array} \right\}, \ \forall t \tag{27}$$

Equations (26) and (27) represent a simplified model of the social criterion [31].

3.4. Constraints

The optimization problem includes constraints in terms of: balance of all products, plant capacity, demand satisfaction.

3.4.1. Plants Capacity Constraints

The capacities of the plants are limited by lower and upper boundaries. These boundaries for each region are determined by implementing the system of inequalities:

$$\sum_{p \in P} \left(PB_p^{MIN} ZF_{pft} \right) \le \alpha_t \sum_{c \in C} \sum_{b \in B} QB_{fcbt} \le \sum_{p \in P} \left(PB_p^{MAX} ZF_{pft} \right), \; \forall f, t \tag{28}$$

$$\left(PBS_{ip}^{MIN} ZF_{pft} \right) \le \left(\alpha_t \sum_{c \in C} \sum_{b \in B} QBP_{ifcbpt} \right) \le \left(PBS_{ip}^{MAX} ZF_{pft} \right), \; \forall i, f, p, t \tag{29}$$

$$\left(PBSs_{yp}^{MIN} ZF_{pft} \right) \le \left(\alpha_t \sum_{c \in C} \sum_{b \in B} QBPs_{yfcbpt} \right) \le \left(PBSs_{yp}^{MAX} ZF_{pft} \right), \; \forall y, f, p, t \tag{30}$$

where

$$QB_{fcbt} = \sum_{i \in I} \sum_{p \in P} \left(QBP_{ifcbpt} \right) + \sum_{i \in I} \sum_{p \in P} \left(QBPs_{yfcbpt} \right), \; \forall t, f, c, b.$$

3.4.2. Balance of Biodiesel (B100) to Be Produced from Biomass Available in the Regions

The equations below represent the material flows of 1st and 2nd generation raw materials that will be transported by vehicles from the regions for each time interval, as well as the biodiesel (B100) material flows that are produced from the two types of raw materials that will be transported by vehicles from the regions for each time interval.

$$\sum_{i \in I} \sum_{g \in G} \sum_{l \in L} \sum_{p \in P} \left(\gamma_{ipt} QIP_{igflpt} \right) = \sum_{i \in I} \sum_{c \in C} \sum_{b \in B} \sum_{p \in P} \left(QBP_{ifcbpt} \right), \; \forall f \in F, \forall t \in T \tag{31}$$

$$\sum_{y \in Y} \sum_{h \in H} \sum_{l_c \in LC} \sum_{p \in P} \left(\gamma w_{ypt} QIPw_{yhfl_cpt} \right) = \sum_{y \in Y} \sum_{c \in C} \sum_{b \in B} \sum_{p \in P} \left(QBPw_{yfcbpt} \right), \; \forall f \in F, \forall t \in T \tag{32}$$

$$\sum_{f \in F} \sum_{l \in L} \sum_{p \in P} \left(QIP_{igflpt} \right) \le QI_{igt}^{MAX}, \; \forall i \in I, \forall g \in G, \; \forall t \in T \tag{33}$$

$$\sum_{f \in F} \sum_{l_c \in LC} \sum_{p \in P} \left(QIPw_{yhfl_cpt} \right) \le QIs_{yht}^{MAX}, \; \forall y \in Y, \forall h \in H, \; \forall t \in T \tag{34}$$

$$\sum_{i \in I} \sum_{c \in C} \sum_{b \in B} \sum_{p \in P} \left(QBP_{ifcbpt} \right) + \sum_{y \in Y} \sum_{c \in C} \sum_{b \in B} \sum_{p \in P} \left(QBPw_{yfcbpt} \right) \le QB_{ft}^{MAX} \sum_{p \in P} ZF_{pft}, \; \forall f \in F, \forall t \in T \tag{35}$$

3.4.3. Admissibility of Flows during Operation of IBDSC

Equation (36) provides the permissible values of grain and straw flows from each of the regions for their production:

$$\left. \begin{array}{l} \sum\limits_{l \in L} \sum\limits_{f \in F} QI_{igflt} + \sum\limits_{z \in Z} \sum\limits_{v \in V} QV_{igvzt} \le QI_{igt}^{MAX} \\ \sum\limits_{e \in E} \sum\limits_{u \in U} QU_{iguet} \le QIs_{igt}^{MAX} \end{array} \right\}, \; \forall t, g, i \tag{36}$$

Equation (37) provides the admissibility of solid waste flows to the places where they are generated:

$$\sum_{m \in M} \sum_{w \in W} QW_{fwmt} \le QW_{ft}^{MAX}, \; \forall m, f \tag{37}$$

Equation (38) provides keeping the admissible rates of biodiesel (B100) flows from each region for their production:

$$\left.\begin{array}{c} \sum\limits_{i\in I}\sum\limits_{c\in C}\sum\limits_{b\in B}\left(QBP_{ifcbpt}\right) \leq QB^{MAX}_{ft}ZF_{pft} \\ \sum\limits_{b\in B}\sum\limits_{c\in C}\left(QB_{fcbt}\right) \leq QB^{MAX}_{ft}ZF_{pft} \end{array}\right\}, \ \forall t, f, p \tag{38}$$

Constraint on the balance of biodiesel (B100) produced from available biomass in the regions:

$$G^{MAX}ZF_{pft} \geq QBP_{ifcbpt}, \ \forall i, \ f, \ c, \ b, \ p, \ t \tag{39}$$

$$QB_{fcbt} = \sum_{i\in I}\sum_{p\in P} QBP_{ifcbpt}, \ \forall t, \ f, \ c, b \tag{40}$$

Equation (41) provides the permissible values of petroleum diesel flows from each of the regions for their production:

$$\sum_{b\in B}\sum_{c\in C}(QD_{dcbt}) \leq QD^{MAX}_{dt}, \ \forall t, \ d \tag{41}$$

$$\frac{\left(A_{igt} + A^{F}_{igt}\right)}{\beta_{igt}\alpha_t} \geq \left(\sum_{l\in L}\sum_{f\in F} QI_{igflt} + \sum_{z\in Z}\sum_{v\in V} QV_{igvzt}\right), \ \forall t, \ g, \ i \tag{42}$$

3.4.4. Constraints Providing the Supply of Straw to the Regions for Technical Needs

Waste biomass obtained after collection of the raw materials have different technical applications in the regions. Equation (43) ensures that it will be distributed according to the needs of each region.

$$PSTRAW^{MIN}_{iut} \leq \alpha_t \sum_{e\in E}\sum_{g\in G} QU_{iguet} \leq PSTRAW^{MAX}_{iut}, \ \forall t, i, \ u \tag{43}$$

3.4.5. Constraints Providing the Supply of Grain to Regions to Provide Food Security

Sunflower and rapeseed, which are the main raw materials for biodiesel production, have also been used to ensure food security. Equation (44) ensures that there will be no competition between the 1st generation raw materials used to produce biodiesel and these to meet nutritional needs of the population in the different regions.

$$\alpha_t \sum_{z\in Z}\sum_{g\in G} QV_{igvzt} = PGRAIN_{ivt}, \ \forall t, \ i, \ v \tag{44}$$

3.4.6. Constraints on the Facilities for Use of Solid Waste

The condition ensuring that the total amount of solid waste generated by all biorefineries can be processed in plants built for this purpose is satisfied by implementing the system of inequalities:

$$\left.\begin{array}{c} \sum\limits_{w\in W}\sum\limits_{m\in M} QW_{fwmt} \leq \sum\limits_{p\in P}\sum\limits_{i\in I}\sum\limits_{c\in C}\sum\limits_{b\in B}\left(SW_{ipt}QBP_{ifcbpt}\right) \\ \sum\limits_{w\in W}\sum\limits_{m\in M}\sum\limits_{s\in S} QWS_{fwmst} \leq \sum\limits_{i\in I}\sum\limits_{c\in C}\sum\limits_{b\in B}\sum\limits_{p\in P}\left(SW_{ipt}QBP_{ifcbpt}\right) \end{array}\right\}, \ \forall t, \ f \tag{45}$$

$$\left.\begin{array}{c} \sum\limits_{s\in S}\left(P^{MIN}_s ZWF_{swt}\right) \leq \alpha_t \sum\limits_{f\in F}\sum\limits_{m\in M} QW_{fwmt} \\ \alpha_t \sum\limits_{f\in F}\sum\limits_{m\in M} QW_{fwmt} \leq \sum\limits_{s\in S}\left(P^{MAX}_s ZWF_{swt}\right) \end{array}\right\}, \ \forall t, \ w \tag{46}$$

$$QW_{fwmt} \leq \sum_{s\in S}\left(P^{MAX}_s ZWF_{swt}\right), \ \forall t, \ w, f, m \tag{47}$$

3.4.7. Logical Constraints

- Constriants providing that in a given region $g \in G$ a plant can be built $p \in P$ for biodiesel (B100) production.

  Equation (48) providing the ability to select only one size $p \in P$ for each facility:

  $$\left. \begin{array}{l} \sum\limits_{p \in P} Z_{pft} \leq 1 \\ \sum\limits_{p \in P} ZF_{pft} \leq 1 \end{array} \right\}, \ \forall t, f \tag{48}$$

- Constraints providing that in a given region $w \in W$ only one plant will be built with size $s \in S$ for solid waste use:

  $$\left. \begin{array}{l} \sum\limits_{s \in S} ZW_{swt} \leq 1 \\ \sum\limits_{s \in S} ZWF_{swt} \leq 1 \end{array} \right\}, \forall t, w \tag{49}$$

  The Equation (48) provide that only one size can be selected $s \in S$ for each solid waste use plant.

- Constraints providing a possible connection between regions producing raw materials only in a certain region:

  $$X_{igftl} \leq \sum_{p \in P} Z_{pft}, \ \forall f \in F, \ \forall g \in G, \ \forall l \in L, \ \forall i \in I, \ t \in T \tag{50}$$

- Constraints providing that petroleum diesel produced in region $d \in D$ is transported from region $d \in D$ to $c \in C$ using transport $b \in B$ for the given interval $t \in T$ when petroleum diesel is currently being produced in the region $d \in D$ during the same time interval:

  $$DT_{dcbt} \leq PD_{dt}, \ \forall d \in D, \ \forall c \in C, \ \forall b \in B, \ \forall t \in T \tag{51}$$

- Constraints providing that each region producing bioreasource $i \in I$ will be connected to at least one biodiesel (B100) plant:

  $$\sum_{f \in F} \sum_{l \in L} X_{igflt} \geq 1, \ \forall t, i, g \tag{52}$$

- Constraints providing that each plant $f \in F$ for biodiesel (B100) production will be connected to at least one area $c \in C$ for blending and consumption:

  $$\sum_{b \in B} \sum_{c \in C} Y_{fcbt} \geq 1, \ \forall t, f \tag{53}$$

- Constraints providing that each plant $w \in W$ for solid waste processing will be connected to at least one plant $f \in F$ for biodiesel (B100) production:

  $$\sum_{w \in W} \sum_{m \in M} WS_{fwmt} \geq 1, \ \forall t, f \tag{54}$$

- Constraints providing that solid waste produced from a given biorefinary will be processed in only one of the plants for use:

  $$\sum_{m \in M} \sum_{w \in W} WS_{fwmt} = \sum_{p \in P} ZF_{pft}, \ \forall t, f \tag{55}$$

3.4.8. Constraints on Transportation

- The amount transported between different regions is limited by upper and lower boundaries, as follows:

$$\frac{PBI_{igt}^{MIN}}{\alpha_t} \leq \sum_{f \in F} \sum_{l \in L} QI_{igftl} \leq \frac{\left(A_{gt}^{S} - A_{gt}^{Food} \right) \beta_{igt}}{2\alpha_t}, \ \forall i \in I, \ \forall g \in G, \ \forall t \in T \quad (56)$$

- Constraints that provide flowrate eligibility for biomass and biofuel:
    - Constraint for biomass flowrate

$$QI_{igt}^{MAX} X_{igflt} \geq QI_{igflt} \geq QT_{ilt}^{MIN} X_{igflt}, \ \forall i \in I, \ \forall g \in G, \ \forall f \in F, \forall l \in L, \ \forall t \in T \quad (57)$$

    - Constraint for biomass flowrate

$$QB_{ft}^{MAX} Y_{fcbt} \geq QB_{fcbt} \geq QTB_{bt}^{MIN} Y_{fcbt}, \ \forall f \in F, \forall c \in C, \forall b \in B, \ \forall t \in T \quad (58)$$

3.4.9. Constraints for Design of IBDSC

These constraints represent material balances between the various echelons in the SC. Biomass productivity regional constraint:

$$\alpha_t \sum_{l \in L} \sum_{f \in F} QI_{igflt} \leq \beta_{igt} A_{igt}, \ \forall g \in G, \ \forall i \in I, \ \forall t \in T \quad (59)$$

3.4.10. Constraints on the Overall Environmental Impact of All Regions

Equation (60) ensures that the total greenhouse gas impact for each time interval of the SC for biodiesel (B100) and the SC for fossil fuels in the regions should not exceed a certain maximum value:

$$TEIF_t \leq TEIF_t^{MAX}, \ \forall t \in T \quad (60)$$

$$TEI_t \leq TEIF_t^{MAX}, \ \forall t \in T \quad (61)$$

where $TEIF_t^{MAX}$ are the maximum values of the total environmental impact of the SC for biodiesel (B100) and the SC for fossil fuels in the regions $\left[\text{kg}_{CO_2\text{eq.}} \text{d}^{-1} \right]$.

3.4.11. Constraints on Arable Land

- Constraints on cereal yields for food security

This type of constraint is intended to comply with the requirements regarding the amounts of cereals produced to ensure food security. The idea is to avoid competition with other sectors and to maintain sustainable land use. The model introduces a constraint to prevent competition between "used biomass for food" and "used biomass for fuel":

$$\left. \begin{array}{c} \sum\limits_{g \in G} \left(\beta_{igt} A_{igt} \right) \geq \sum\limits_{g \in G} \left(\alpha_t \sum\limits_{f \in F} \sum\limits_{l \in L} QI_{igflt} \right) \\ \sum\limits_{g \in G} \left(\beta_{igt} A_{igt}^{F} \right) \geq QB_{it}^{Food} \end{array} \right\}, \ \forall i \in I, \ \forall t \in T \quad (62)$$

Arable land used for cultivation of bioresources for food security and biofuel production should not exceed the available arable land for each region:

$$\sum_{i \in I} \left(A_{igt} + A_{igt}^{F} \right) \leq \left(A_{gt}^{S} - A_{gt}^{Food} \right), \ \forall g \in G, \ \forall t \in T \quad (63)$$

3.4.12. Constraints on Crop Rotation

Crop selection makes it possible to control pests, improve soil fertility, maintain long-term soil productivity and increase yields and profitability on rotation [32]. The planning of crop rotation with energy crops depends on the environmental and economic conditions in the different regions. In addition, the application of rotation in crop production is a common practice that is applied for environmental benefits and helps to reduce dependence on additional resources. The crop rotation in a given region is carried out according to a certain scheme of replacement of the crops $g \in G$ cultivation on areas A_{ig} and A_{ig}^F.

$$\left(A_{igt} + A_{igt}^F \right) 2.0 \leq \left(A_{gt}^S - A_{gt}^{Food} \right), \ \forall i \in I, \forall g \in G, \ \forall t \in T \tag{64}$$

3.4.13. Constraints on Energy Balances

- Constraints providing the overall energy balance in the region.

  Constraint on the applicability of the energy balance:

$$EGD_t + EB_t \geq EO_t, \ \forall t \in T \tag{65}$$

The energy equivalent diesel fuel needed to meet the energy needs of all customer areas where biodiesel (B100) is not used is determined as follows:

$$EO_t = ENO \sum_{c \in C} YO_{tc}, \ \forall t \in T$$

where EO_t is the annual consumption of energy (petroleum diesel) from all regions $\left[\text{GJ y}^{-1} \right]$.

The energy equivalent of petroleum diesel, which should be added to balance the energy required for all customer areas, is determined as follows:

$$EGD_t = ENO \sum_{c \in C} QEO_{tc}, \ \forall t \in T$$

where EGD_t is the annual energy added to petroleum diesel to balance the energy required for all regions $\left[\text{GJ y}^{-1} \right]$.

The energy equivalent of biodiesel (B100) obtained per year is determined as follows:

$$EB_t = ENB \sum_{c \in C} QEB_{tc}, \ \forall t \in T$$

where EB_t is the annual energy derived from biodiesel (B100) supply chain for the whole consumer area $\left[\text{GJ y}^{-1} \right]$.

The total value of fuel used by the regions [$/y] is:

$$TBG_t = TDC_t + PO \sum_{c \in C} QEO_{tc}, \ \forall t \in T$$

- Constraints providing the overall energy balance in each consumer area

  Constraint on the applicability of the energy balance for each region:

$$ENO \ QEO_{tc} + ENB \ QEB_{tc} \geq ENO \ YO_{tc}, \ \forall c \in C, \ \forall t \in T \tag{66}$$

- Constraints providing the required amount of fuel is provided for each region

$$ENB \sum_{f \in F} \sum_{c \in C} \sum_{b \in B} \left(\alpha f_{tf} QB_{tfcb} \right) \geq K_{tc}^{mix} ENO \sum_{c \in C} YO_{tc}, \ \forall t \in T \tag{67}$$

$$ENB \sum_{f \in F} \sum_{b \in B} \left(\alpha f_{tf} QB_{tfcb} \right) \geq K_{tc}^{mix} ENOYO_{tc}, \ \forall c \in C, \ \forall t \in T \tag{68}$$

3.4.14. Constraints on Total Costs of IBDSC

Equation (69) ensures that the total costs of considered IBDSC should not exceed actual costs:

$$TDC_t^{MAX} \geq TDC_t, \ \forall t \in T \tag{69}$$

where TDC_t^{MAX} is maximal value of the total costs of considered IBDSC [\$].

3.5. Optimization Criteria Formulation
3.5.1. Economic Objective Function

The economic objective function represents the annual costs related to cultivation and collection of biomass, its transportation to the collection facilities, storage and conversion, storage of biodiesel and its transportation to the blending facilities. It also includes the investment costs for the building of biorefineries and facilities for use of solid waste. The economic criterion is an object of minimization and is defined as follows:

$$COST = \sum_{t \in T} (LT_t TDC_t) \tag{70}$$

In addition, as the objective function, the price of the used fuel (petroleum diesel and biodiesel) can also be used. This applies to the whole time interval, provided that the needs of the regions for this energy carrier are met.

$$COST_{TBG} = \sum_{t \in T} (LT_t TBG_t) \tag{71}$$

3.5.2. Environmental Objective Function

As an environmental optimization criterion, Eco-**Indicator 99** is used [33]. It is an object of minimization. Eco-**Indicator 99** is a standard method for assessing the global impact of a process, product and/or activity. This method can be applied either as a standalone tool or in combination with an optimization model. The proposed environmental impact model uses the Eco-**Indicator 99**, which assesses the environmental impact of all activities in the network expressed in terms of the amount of carbon dioxide equivalent generated throughout the life cycle of the products.

$$ENV = \sum_{t \in T} (LT_t TEI_t) \tag{72}$$

These environmental assessments are presented as environmental costs with monetary value. The global warming coefficient was used to determine the monetary equivalent of the environmental impact C_{CO_2}, as follows:

$$Cost_{ENV} = C_{CO_2} ENV \tag{73}$$

where $Cost_{ENV}$, $\left[\$ \, \text{y}^{-1} \right]$ are the environmental costs that should be paid to prevent the environmental impact of the amount equivalent to carbon dioxide, and C_{CO_2} is the coefficient of global warming [\$/kg$_{CO_2eq.}$] (the most commonly used value is 0.135 \$/kg$_{CO_2eq.}$ [30]).

3.5.3. Social Objective Function

Regarding the use of a social indicator: jobs creation, it is first necessary to define the boundaries of variation of this indicator and then the total number of jobs is calculated. It includes: (i) Direct jobs (jobs related to the plant's activities), (ii) Indirect jobs (new employees in subcontractors), and (iii) Induced jobs (new employees in the local economy).

The latter are obtained on the basis of the previous two categories, due to their (and their families) consumption in the local economy.

To assess the social impact of the supply chain, the adjusted coefficients $JobB_p$, $JobO_p$, $JobOW_s$, $JobW_s$, which represent indirect jobs in the social economy are used. Then the social impact in terms of jobs creation is determined according to dependence (74) [Number of Jobs]:

$$JOB = \sum_{t \in T}(LT_t Job_t) \tag{74}$$

3.6. Formulation of the Optimization Problem

The purpose of optimization is to find the solution of the problem—the values of the decision (binary and continuous) variables—in which the optimization criterion has a minimum value. They are the following:

1. Structure of the SC network, which includes number, size and location of the biorefineries;
2. Localization of the areas for biomass cultivation and biodiesel (B100) production;
3. Mass flows of biomass and biodiesel between different areas;
4. Type of transport for delivery of biomass and biodiesel;
5. Amounts of GHG emissions generated at each stage of the life cycle of the biodiesel production;
6. Amounts of transport for each transport connection and mode of transportation;
7. Distribution of the biodiesel in blending areas.

The optimization problem includes the following criteria:

Economic sustainability ($COST$ or $COST_{TBG}$) (70, 71): Minimization of the total logistics costs of the supply chain, taking into account fixed and variable costs [$].

Environmental sustainability (ENV or $Cost_{ENV}$) (72, 73): Minimization of the total amount of GHG emissions, calculated in units [kg or $] of equivalent carbon dioxide emissions [$kg_{CO_2eq.}$].

Social sustainability (JOB) (74): Determining the required number of jobs to ensure sustainable implementation of the activities of the IBDSC [Number of Jobs].

The optimization problem for optimal design of IBDSC is defined as a single-objective one in terms of MILP, at one optimization criterion-environmental or economic—as the rest are considered as constraints. The strategic design of the supply chain combines two levels of decision making: decisions related to the creation of a superstructure of the supply chain, and those related to distribution of the material flows of biomass and biodiesel between different units.

- Minimization of GHG emissions, [$kg_{CO_2eq.}/d$]

When the optimization problems include an environmental criterion, then the aim is to minimize the total annual equivalent GHG emissions resulting from the IBDSC operation. Formulation of this objective function is based on total GHG emissions in SC and other fuels, which are assessed on the basis of the LCA approach, where emissions are added to each life cycle stage.

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

$$\left\{ \begin{array}{c} Find: \ X_t[Decision \ variables]^T \\ MINIMISE\{ENV\} \rightarrow (Equation \ 72) \\ s.t.: \{Equation \ 28 - Equation \ 69\} \end{array} \right\} \tag{75}$$

The objective Equation (72) and the Equations (28)–(69) are linear functions with respect to all decision variables.

- Minimization of total annual costs, [$/y]

When the optimization problems include an economic criterion, then the aim is to minimize the total annual costs. The latter include: the total annual capital costs, the annual operating costs, the annual government incentives and the emission costs of CO_2.

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

$$\left\{ \begin{array}{c} Find:\ X_t[Decision\ variables]^T \\ MINIMISE\{COST\} \rightarrow (Equation\ 70) \\ s.t.:\{Equation\ 28 - Equation\ 69\} \end{array} \right\} \tag{76}$$

The objective Equation (70) and the Equations (28)–(69) are linear functions with respect to all decision variables.

4. Case Study

The optimization problem is formulated and solved either with an economic criterion-the total annual costs for design of the IBDSC—or using environmental ones, such as the total GHG emissions related to its operation and an integrated economic and environmental criterion. The other criteria are defined as constraints. The purpose is to determine the optimal locations of biodiesel facilities in the regions and their parameters.

Two types of feedstocks, first generation-sunflower and rapeseed—and second generation-waste cooking oil (WCO) and animal fats—were used for biodiesel production.

4.1. Input Data

The proposed optimization approach is applied on a real case study from Bulgaria. For this purpose, the territory of the Republic of Bulgaria with its 27 districts is considered. The problem of optimal design of IBDSC is defined for the 5-year planning horizon (2016-2020). To calculate the amount of biodiesel needed for these regions, real data on the amounts of fossil diesel fuels taken from the National Statistical Institute of Bulgaria were used. For the considered period 2016-2020, these are: 2016 → 2,050,000 t, 2017 → 2,219,000 t, 2018 → 2,401,000 t, 2019 → 2,583,000 t, 2020 → 2,775,500 t. As a result of implementation of the proposed approach, the obtained solutions propose building solid waste use facilities in four districts of Bulgaria, as well as use of glycerin obtained as a by-product in another four districts of Bulgaria. The search areas are equipped with the necessary diesel from three refineries or combined warehouses.

The total GHG emissions for the whole life cycle of the growing energy crops vary significantly depending on the soil, meteorological conditions, the technology for growing the crops, as well as the fertilization to increase the yields for the different regions of Bulgaria. Table 1 presents the GHG in the agronomic phase of rapeseed and sunflower and the cultivation of the harvest for the different regions of Bulgaria.

Table 1. Greenhouse gas emissions in the agronomic phase and potential rapeseed yields and sunflower in the regions of Bulgaria [34].

№	Region	Greenhouse Gas Emissions during the Agronomic Phase, [$kg_{CO_2eq.}/t_{biomass}$]		Yield for Different Regions, [t/ha]	
	Energy Crops	Sunflower	Rapeseed	Sunflower	Rapeseed
1	Region-1	1700	1350	1.5	1.8
2	Region-2	1425	1120	2.8	2.8
3	Region-3	600	430	3.4	3.5
4	Region-4	1425	1120	1.8	2.2
5	Region-5	1425	1120	1.8	2.2
6	Region-6	1700	1350	1.5	1.8
7	Region-7	1700	1350	1.5	1.8

Table 1. *Cont.*

№	Region	Greenhouse Gas Emissions during the Agronomic Phase, $[kg_{CO_2eq.}/t_{biomass}]$		Yield for Different Regions, [t/ha]	
	Energy Crops	Sunflower	Rapeseed	Sunflower	Rapeseed
8	Region-8	1425	1120	1.8	3.2
9	Region-9	1150	890	2.2	2.6
10	Region-10	1700	1350	2.2	3.2
11	Region-11	1425	1120	1.8	2.2
12	Region-12	600	430	2.8	3.5
13	Region-13	1425	1120	1.8	2.2
14	Region-14	875	660	2.8	3.0
15	Region-15	600	430	3.3	3.5
16	Region-16	875	660	2.8	3.0
17	Region-17	875	660	2.8	3.0
18	Region-18	1150	890	2.4	2.6
19	Region-19	1700	1350	1.5	1.8
20	Region-20	1700	1350	1.5	1.8
21	Region-21	875	660	2.8	3.0
22	Region-22	1150	890	2.2	2.6
23	Region-23	875	660	2.8	3.0
24	Region-24	875	660	2.4	3.0
25	Region-25	1425	1120	2.8	2.2
26	Region-26	875	660	1.8	2.0
27	Region-27	1150	890	2.0	2.6

The costs for growing biomass and the maximum amount of biomass that can be produced in the regions of Bulgaria are listed in Table 2.

Table 2. Costs for growing biomass and maximum amount of biomass that can be produced in the regions of Bulgaria [35].

	Region	Costs for Cultivation per Unit of Biomass, $[\$/t_{biomass}]$		Maximum Biomass Productivity, [t/y]	
	Energy Crops	Sunflower	Rapeseed	Sunflower	Rapeseed
1	Region-1	227	239	10,768	9230
2	Region-2	213	236	93,225	79,907
3	Region-3	192	227	173,150	148,414
4	Region-4	213	233	11,291	9678
5	Region-5	213	236	61,245	52,496
6	Region-6	227	239	6694	5738
7	Region-7	227	239	9732	8342
8	Region-8	213	236	35,087	30,075
9	Region-9	198	233	68,378	58,609
10	Region-10	227	239	30,279	25,954
11	Region-11	213	236	17,839	15,291
12	Region-12	192	227	151,911	130,210
13	Region-13	213	236	94,193	80,737
14	Region-14	195	230	73,613	63,097
15	Region-15	192	227	89,287	76,532
16	Region-16	195	230	73,932	63,370
17	Region-17	195	230	76,866	65,885
18	Region-18	198	233	44,636	38,259
19	Region-19	227	239	2675	2293
20	Region-20	227	239	35,806	30,690

Table 2. *Cont.*

	Region	Costs for Cultivation per Unit of Biomass, [$/t_{biomass}$]		Maximum Biomass Productivity, [t/y]	
	Energy Crops	Sunflower	Rapeseed	Sunflower	Rapeseed
21	Region-21	195	230	91,069	78,059
22	Region-22	198	233	51,469	44,117
23	Region-23	195	230	84,412	72,353
24	Region-24	195	230	88,301	75,687
25	Region-25	213	236	47,698	40,884
26	Region-26	195	230	92,152	78,987
27	Region-27	198	233	78,585	67,358

The most suitable possible locations for biorefineries in the regions were selected on the basis of accessibility to transport infrastructure, urban planning and zoning. All 27 regions were selected as potential sites for biorefineries that are scattered throughout Bulgaria. The refineries for oil diesel production are located in the regions of Burgas, Ruse and Sofia.

The classical esterification technology for production of biodiesel (B100) from raw sunflower and rapeseed is taken into consideration [36].

The average price of glycerin is 1.088 $/kg [37]. Another by-product is the sludge from processed oilseeds, which are rich in protein and used for animal feed. According to [36], per ton of biodiesel (B100), approximately 1.575 t oil cake is generated. The average price of sunflower seeds is 115 $/t [38].

The efficiency of biodiesel (B100) conversion from rapeseed and sunflower varies from 389 L/t to 454 L/t. For the purpose of modeling, we used 422 L/t, which represents the average of the lowest and highest conversion efficiencies found in the literature [39].

Table 3 shows the values of the conversion factor for sunflower and rapeseed, applicable to the conditions in Bulgaria by the most popular technology for extraction of biodiesel (B100). In this study, the value of the conversion factor used is 371 kg/t of biomass for sunflower and 303 kg/t of plant biomass, applicable to the conditions in Bulgaria by the most popular technology of biodiesel production (B100).

Table 3. Conversion factor for biomass to biodiesel (B100).

	Energy Crops	Conversion Factor, [$t_{biofuel}/t_{biomas}$]	Energy Equivalent of Biomass, [GJ/t]
1	Sunflower	0.37	14.023
2	Rapeseed	0.30	11.453
3	Waste animal fats	0.87	
4	Waste cooking oil	0.91	

When determining the optimal number of biorefineries to be built on the territory of the Republic of Bulgaria, it should be borne in mind that they are four types that have different maximum capacities. The capital costs, minimum and maximum capacities of biodiesel (B100) plants are given in Table 4.

It is assumed that the consumption of vegetable oil in a given region should be proportional to its population, and the amount of generated WCO is 30% of this.

Production costs per unit of biodiesel (B100) in a biorefinery built in a given region depend on the total costs for: chemicals and catalysts, gas, electricity, water supply, wastewater treatment, administrative and operational costs and labor. The average costs are, respectively, 125 $/t for each region in which biodiesel is produced (B100) (excluding raw material costs) [35].

Table 4. Total specific investment costs for biodiesel (B100) plants as a function of the plants' capacities [40,41].

Biodiesel Plant Size (B100)	Capital Costs of a Biodiesel Plant (B100) $Cost_p$, [M\$]	Minimum Capacity of the Biodiesel Plant (B100) PB_p^{MIN}, [t/y]	Maximum Capacity of the Biodiesel Plant (B100) (B100) PB_p^{MAX}, [t/y]
Size-1	3.800	1000	8500
Size-2	4.800	6000	19,000
Size-3	7.380	8000	48,000
Size-4	8.930	10,000	74,000

The emission factors of petroleum diesel and biodiesel and their corresponding energy equivalents are presented in Table 5.

Table 5. Fuel emission factor and energy equivalent.

Type of Fuel	Emission Factor, [kg$_{CO_2eq.}$/t], [42]	Energy Equivalent, [GJ/t]	Energy Equivalent, [MWh/t] [43]	Medium Density, [t/m^3] [43]	Price of Biofuel, [\$/t] [44]
Petroleum diesel	3623	42.80	11.880	0.840	1192.70
Biodiesel (B100)	1204	37.80	7.720	0.880	

The transportation costs for biomass (sunflower and rapeseed) and biodiesel (B100) related with the used vehicles—tractor, truck and train and loading and unloading costs are listed in Tables 6 and 7.

Table 6. Transport costs for different modes of transport for biomass [16].

Energy Crops		Fixed Price, [\$/(t km)] [26]			Variable Price, [\$/(t km)] [26]		
	Type of Vehicles	Tractor	Truck	Train	Tractor	Truck	Train
1	Sunflower	2.49	9.28	19.63	0.14	0.21	0.03
2	Rapeseed	2.49	9.28	19.63	0.14	0.21	0.03
3	Waste animal fats	2.49	9.28	19.63	0.14	0.21	0.03
4	Waste cooking oil	2.49	9.28	19.63	0.14	0.21	0.03

Table 7. Transport costs for the different vehicles for biodiesel (B100) and petroleum diesel [16].

Type of Vehicles		Fixed Price OA_b, OAD_b [\$/(t km)] [26]		Variable Price OB_b, OBD_b [\$/(t km)] [26]	
		Truck	Train	Truck	Train
1	Biodiesel (B100)	24.11	7.86	0.436	0.173
2	Petroleum diesel	24.11	7.86	0.436	0.173

The GHG emissions from road and rail transport assess based on the carbon content of the respective fuel, the fuel consumption per km and the amount of biomass and biodiesel transported. The respective assessments are listed in Table 8.

Table 8. Transport emission factor for different types of vehicles.

	Type of Vehicles	Emission Factor for Biomass Transport, [$kg_{CO_2eq.}$/(t km)]	Emission Factor for Biofuel Transport, [$kg_{CO_2eq.}$/(t km)]
1	Tractor	0.591	0.591
2	Truck (average)	0.228	0.228
3	Van < 3.5 t	1.118	1.118
4	Truck, 16 t	0.304	0.304
5	Truck, 32 t	0.153	0.153
6	Freight train	0.038	0.038

The rest data related with the population, cultivated and free cultivated areas used for crops production are taken from [45].

4.2. Computational Results and Analysis

The proposed MILP optimization model is coded and run in the GAMS optimization software, GAMS Release: 22.8 [46] using CPLEX 11.1 solver with WEX-WEI x86 64bit/MS Windows on Intel Core 2 Duo P8600 2.4 GHz CPU with 4GB RAM on a 32-bit platform. The optimization problem was calculated in 3:8:25:297 h. The MILP model includes 222,790 binary variables, 1,029,580 positive continuous variables and 1,512,846 constraints. The latter represent the investment possible decisions and required management.

The solution obtained in the case of optimal design of IBDSC using the optimization criteria (A) Minimum total GHG emissions and (B) Minimum annual costs shows that the GHG emissions are 6.6% lower for criterion (A) than for criterion (B), while the price of biodiesel is 14% higher for criterion (A). This is due to the increased capital and operating costs in the case of criterion (A). In the case of IBDSC design using the minimum GHG emissions optimization criterion, the best parameters are obtained if the used feedstocks for the Bulgarian conditions are sunflower, rapeseed, animal fats and waste oils.

In Figures 2–4 the structure of the obtained optimal IBDSC with corresponding logistics in terms of biodiesel, petroleum diesel and solid waste (Figure 2), as well as the raw materials used (Figures 3 and 4) is shown.

(**A**)   (**B**)
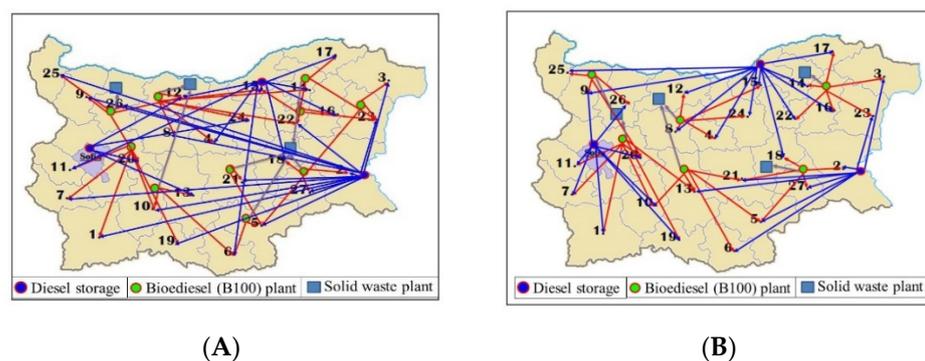
Figure 2. (**A**) Minimum total GHG emissions. (**B**) Minimum total annual costs. Optimal structure of IBDSC and logistics in terms of delivery to customers of biodiesel and petroleum diesel, as well as solid waste logistics to plants for their use for 2020.

(A)

(B)
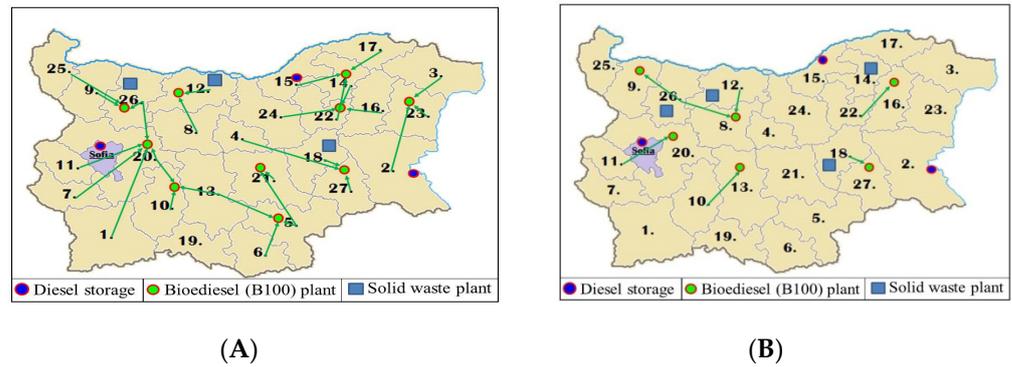
Figure 3. (**A**) Minimum total GHG emissions. (**B**) Minimum total annual costs. Optimal structure of IBDSC and logistics for delivery of sunflower and rapeseed as feedstock for 2020.

(A)

(B)
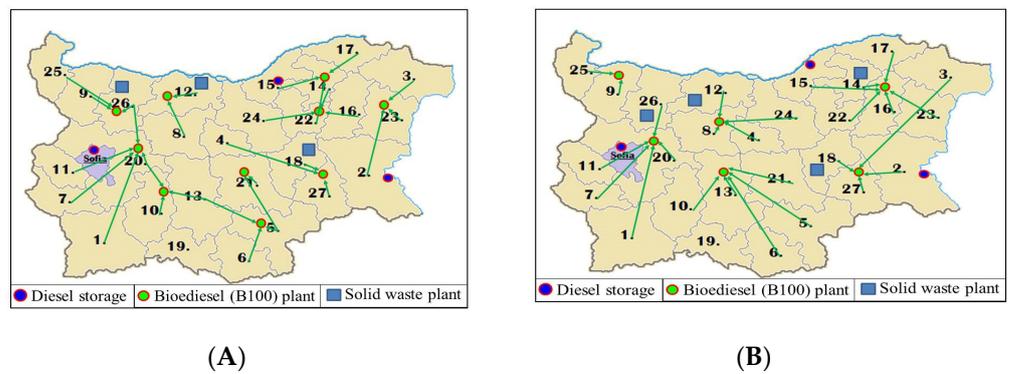
Figure 4. (**A**) Minimum total GHG emissions. (**B**) Minimum total annual costs. Optimal structure of IBDSC and logistics for delivery of animal fats and waste oils as feedstock for 2020.

Figure 5 shows that the GHG emissions with the highest values are generated from the processes related to biodiesel production. These are followed by emissions from its burning, as well as emissions from the cultivation of biomass as feedstock for biodiesel production. The GHG emissions due to transport of raw materials and products have the lowest values. The lower emission values under the criterion (A) Minimum total GHG emissions compared to (B) Minimum total annual costs are due to the fact that according to criterion (A), the preferred transport is rail, while criterion (B) relies on short-distance auto transport.

Tables 9 and 10 represent the optimal size, capacity and location of biorefineries and solid waste disposal facilities, using the two main criteria: (A) Minimum total greenhouse gas emissions and (B) Minimum total annual costs.

(A)

(B)
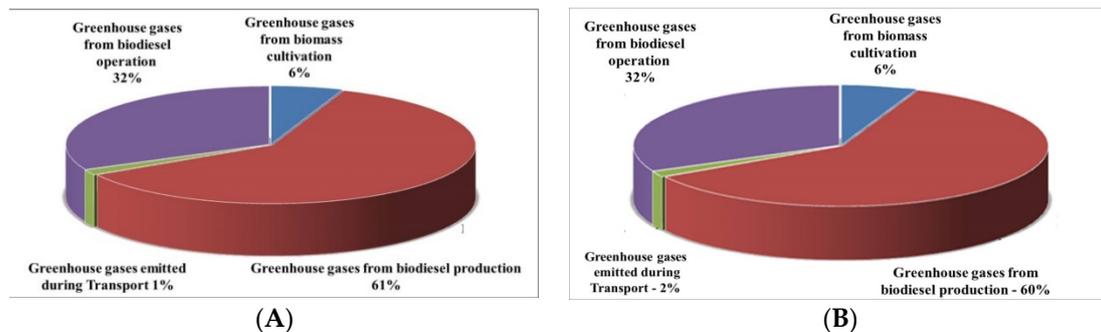
Figure 5. (**A**) Minimum total GHG emissions. (**B**) Minimum total annual costs. Distribution of total GHG emissions for the life cycle stages of biodiesel for the period 2016–2020.

Table 9. Optimal size, capacity and location of biorefineries and facilities for solid waste use using criterion: (A) Minimum total greenhouse gas emissions.

Years	2016	2017	2018	2019	2020
Proportion Biodiesel/Diesel	**6%**	**7%**	**8%**	**9%**	**10%**
Regions	Optimal Size and Capacity of Biorefineries, [t/y]				
Region-5			Size_1 7907.96	Size_1 7305.93	Size_1 8500.00
Region-10	Size_3 27,707.90	Size_3 30,577.38	Size_3 24,101.54	Size_3 24,409.93	Size_3 28,700.37
Region-12		Size_3 25,506.10	Size_3 15,703.19	Size_3 37,664.44	Size_3 39,045.68
Region-14		Size_1 8002.23	Size_1 7481.96	Size_1 8083.69	Size_1 8500.00
Region-20			Size_4 45,452.03	Size_4 25,692.48	Size_4 35,311.27
Region-21				Size_2 18,225.70	Size_2 17,933.16
Region-22	Size_3 23,167.91	Size_3 15,601.37	Size_3 18,219.92	Size_3 9527.73	Size_3 10,708.57
Region-23				Size_4 17,579.15	Size_4 20,990.37
Region-26	Size_4 48,667.82	Size_4 49,516.38	Size_4 36,244.69	Size_4 52,874.40	Size_4 71,105.31
Region-27	Size_3 18,981.74	Size_3 20,713.33	Size_3 30,569.45	Size_3 23,719.49	Size_3 28,364.28
Regions	Optimal Size and Capacity of Solid Waste Facilities, [t/y]				
Region-12		Size_W1 58,763.95	Size_W1 85,000.00	Size_W1 85,000.00	Size_W1 85,000.00
Region-18			Size_W1 38,420.15	Size_W1 85,000.00	Size_W1 85,000.00
Region-26	Size_W1 74,616.52	Size_W1 77,706.22	Size_W1 85,000.00	Size_W1 85,000.00	Size_W1 85,000.00

Table 10. Optimal size, capacity and location of biorefineries and facilities for solid waste use using criterion: (B) Minimum total annual costs.

Years	2016	2017	2018	2019	2020
Proportion Biodiesel/Diesel	**6%**	**7%**	**8%**	**9%**	**10%**
Regions	Optimal Size and Capacity of Biorefineries, [t/y]				
Region-8				Size_3 40,210.52	Size_3 37,685.86
Region-9					Size_3 35,865.99
Region-13			Size_3 35,559.64	Size_3 28,560.47	Size_3 32,178.49
Region-16		Size_4 31,857.90	Size_4 34,632.79	Size_4 38,235.05	Size_4 45,722.29
Region-20	Size_4 70,525.36	Size_4 74,000.00	Size_4 72,884.91	Size_4 74,000.00	Size_4 70,161.58
Region-27	Size_3 48,000.00	Size_3 44,058.89	Size_3 42,603.40	Size_3 44,076.90	Size_3 47,544.80

Table 10. *Cont.*

Years	2016	2017	2018	2019	2020
Proportion Biodiesel/Diesel	**6%**	**7%**	**8%**	**9%**	**10%**
Optimal Size and Capacity of Solid Waste Facilities, [t/y]					
Region-12			Size_W1 41,021.98	Size_W1 74,203.72	Size_W1 63,026.74
Region-14				Size_W1 46,322.35	Size_W1 59,259.36
Region-18	Size_W1 40,018.77	Size_W1 79,844.32	Size_W1 82,398.17	Size_W1 84,793.56	Size_W1 80,383.87
Region-26	Size_W1 34,597.76	Size_W1 56,625.85	Size_W1 85,000.00	Size_W1 84,837.31	Size_W1 85,000.00

Tables 11 and 12 represent the obtained results using the two main criteria: (A) Minimum total greenhouse gas emissions and (B) Minimum total annual costs.

Table 11. Results obtained from the optimization problem solution using criterion: (A) Minimum total greenhouse gas emissions.

Years	2016	2017	2018	2019	2020
Proportion Biodiesel/Diesel	6%	7%	8%	9%	10%
Optimization criterion value (72) (A) Minimum total greenhouse gas emissions, $\left[\text{kg}_{CO_2 eq.}/d\right]$ 11,960,007,897.41 Objective function value (70) (B) Minimum annual costs, [M\$] 1318.237 Objective function value (74) (C) Total number of jobs, [Jobs/y] 2670.00					
Total operating costs of IBDSC, [M\$/y]	188.522	210.435	294.457	309.574	315.249
Total costs of biodiesel production, [M\$/y]	415.982	60.884	82.355	112.845	118.489
Total GHG emissions, $\left[\text{Mt}_{CO_2 eq.}/y\right]$	1834.796	1957.235	2682.917	2676.472	2808.587
Total number of jobs, [Jobs/y]	620	480	570	590	410
Total amounts of produced biodiesel and diesel [t/y]					
Biodiesel from 1G feedstock	27,738	50,732	77,479	115,165	109,872
Biodiesel from 2G feedstock	90,786	99,184	108,201	109,917	159,286
Biodiesel totally	118,525	149,916	185,680	225,082	269,159
Price for biodiesel production [\$/t]	350.96	406.12	443.53	501.35	440.22
Petroleum diesel	19,45,321	2,086,596	2,237,010	2,384,211	2,537,784
Distribution of arable land [ha]					
Land for cultivation of sunflower and rapeseed for biodiesel production	19,403	35,493	54,211	80,587	76,881
Land for cultivation of sunflower and rapeseed for food	1,464,199	1,493,331	2,002,839	1,897,456	1,897,456
Free arable land	1,997,387	1,952,166	1,423,940	1,502,946	1,506,652

Table 12. Results obtained from the optimization problem solution using criterion: (B) Minimum total annual costs.

Years	2016	2017	2018	2019	2020
Proportion Biodiesel/Diesel	6%	7%	8%	9%	10%
Objective function value (72) (A) Minimum total greenhouse gas emissions $\left[\text{kg}_{CO_2eq.}/\text{d}\right]$ 13,323,159,067.04 Objective function value (70) (B) Minimum annual costs, [M$] 1054.008 Objective function value (74) (C) Total number of jobs, [Jobs/y] 1880					
Total operating costs of IBDSC [M$/y]	143.011	162.518	240.838	249.525	258.115
Total costs of biodiesel production [M$/y]	37.884	54.603	73.411	95.662	104.277
Total GHG emissions $\left[\text{Mt}_{CO_2eq.}/\text{y}\right]$	2101.136	2224.594	2969.221	2944.325	3083.884
Total number of jobs [Jobs/y]	440	260	370	420	390.
Total amounts of produced biodiesel and diesel [t/y]					
Biodiesel from 1G feedstock	27,738	50,732	77,479	107,865	106,940
Biodiesel from 2G feedstock	90,786	99,184	108,201	117,217	162,218
Biodiesel totally	118,525	149,916	185,680	225,082	269,159
Price for biodiesel production [$/t]	319.63	364.22	395.36	425.01	387.42
Petroleum diesel	1,945,321	2,086,596	2,237,010	2,384,211	2,537,784
Distribution of arable land [ha]					
Land for cultivation of sunflower and rapeseed for biodiesel production	19,411	35,505	54,227	75,496	74,845
Land for cultivation of sunflower and rapeseed for food	1,464,199	1,493,331	2,002,839	1,897,456	1,897,456
Free land	1,997,379	1,952,153	1,423,924	1,508,037	1,508,688

5. Conclusions

Based on the analysis conducted, the following conclusions can be drawn:

1. The available agricultural land in Bulgaria meets the needs for production of a sufficient amount of first-generation feedstock for the production of the required amount of biodiesel (B100) in order to meet Bulgarian needs and reach the required quota of 10% for liquid biofuel by 2020.

2. The optimal land required for sunflower and rapeseed cultivation is concentrated in a small number of regions of the country, selected independently of the optimization criteria for the optimal design of IBDSC.

3. The optimal mix of first-generation bioresources, applying the approach based on the "Minimum total annual costs" criterion for the design of IBDSC for 2020, requires 14% of the agricultural land to be used for sunflower cultivation and 2% to be used for rapeseed cultivation. Applying the approach based on the "Minimum total GHG emissions" criterion requires 12% of the agricultural land to be used for rapeseed cultivation and 3% for sunflower cultivation. Applying the approach based on using both criteria, second-generation bioresources (waste cooking oils and animal fats) are used as the main raw material to meet the requirements of the required quota of 10% for biodiesel by 2020.

4. An important conclusion for transportation is that rail is the optimal mode of transport to use for both types of bioresources (sunflower and rapeseed; animal fats and waste oils) and fuels (biodiesel (B100) and petroleum diesel).

5. The average price of biodiesel (B100) for the period (2016–2020) applying the approach based on the "Minimum total annual costs" criterion is 378 $/t, while applying

the approach based on the "Minimum total GHG emissions" criterion in the same circumstances gives a price of 428 \$/t, i.e., 14% higher.

6. Applying the approach based on the "Minimum total GHG emissions" criterion showed that GHG emissions have a 6.6% lower value compared to the use of the criterion "Minimum total annual costs", while the price of biodiesel is 14% higher.

7. The estimated value of capital investment for the entire period (2016–2020) is \$96.779 million, applying the approach based on the "Minimum Total Annual Costs" criterion, and \$127.257 million for the solution obtained when the "Minimum Total GHG Emissions" criterion is used based on the same input data.

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Appendix A

- Sets/Indexes

I Set of first-generation feedstock (sunflower and rapeseed), *i*;
Y Set of second-generation feedstock (waste cooking oil and animal fat), *y*;
LF Set of type of vehicles for transportation, *lf*;
P Set of type of plants for biodiesel (B100) production and thier capacities, $p = \overline{1, N_p}$;
S Set of type of facilities for solid waste use and thier capacities, $s = \overline{1, N_s}$;
GF Set of the regions into which the territory of Republic of Bulgaria is divided, *gf*;
A Set of proportions biodiesel (B100) and diesel, subject to blending for each of the customer areas, *a*;
T Set of time intervals *t*.

- Subsets/Indexes

B Set of types of vehicles for transportation of biodiesel (B100) and diesel, which is subset of *LF* ($B \subset LF$), *b*;
L Set of types of vehicles for transportation of biomass, which is subset of *LF* ($L \subset LF$), *l*;
LC Set of types of vehicles for transportation of WCO and animal fat, which is subset of *LF* ($LC \subset LF$), l_c;
M Set of types of vehicles for transportation of solid waste, which is subset of *LF* ($M \subset LF$), *m*;
E Set of types of vehicles for transportation of waste biomass, which is subset of *LF* ($E \subset LF$), *e*;
Z Set of types of vehicles for transportation of sunflower and rapeseed for food, which is subset of *LF* ($Z \subset LF$), *z*;
F Set of regions for biodiesel (B100) production, which is subset of *GF* ($F \subset GF$), f;
C Set of areas for blending and use of biodiesel, which is subset of ($C \subset GF$), *c*;
D Sets for the supply and production of petroleum diesel, which are subsets of ($D \subset GF$), *d*;
W Set of regions for collection and treatment of solid waste, which is subset ($W \subset GF$), *w*;
K Set of regions for treatment and use of glycerol, which is subset of *GF* ($K \subset GF$), *k*;

R Set of regions for treatment and use of sunflower husk, which is subset of GF ($SH \subset GF$), r;
U Set of regions for collection and treatment of waste biomass, which is subset of ($U \subset GF$), u;
V Set of regions for using sunflower and rapeseed for food, which is subset of ($V \subset GF$), v;
H Set of regions for collection of WCO and animal fat, which is subset of ($H \subset GF$), h;
G Set of regions for bioresources cultivation (sunflower, rapeseed, etc.) ($G \subset GF$), g;

Input parameters

- Constant parameters or those that can change very slowly over time:

Environmental parameters

$EFBP_{ip}$ Emission factor for biodiesel (B100) production from biomass $i \in I$ according to technology $p \in P$, $\left[\mathrm{kg_{CO_2 eq.}} \, \mathrm{eq}\right\}/\mathrm{t \, biofuel}]$;

$EWCO_{yp}$ Emission factor for biodiesel (B100) production from WCO and animal fat $y \in Y$ according to technology $p \in P$, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t_{biofuel}}\right]$;

ESU_i Emission factor for pollution caused by waste biomass $i \in I$, if not used for other purposes, $\left[\dfrac{\mathrm{kg_{CO_2 eq.}}}{\mathrm{t_{solid \, waste}}}\right]$;

$ESF1_{ft}$ Emissions released from solid waste use, if performed at the plant $f \in F$, $\left[\dfrac{\mathrm{kg_{CO_2 eq.}}}{\mathrm{t_{solid \, waste}}}\right]$;

$ESW1_{wst}$ Emission factor for pollution caused by solid waste when they used in plant $w \in W$ according to technology $s \in S$, if not used for other purposes, $\left[\dfrac{\mathrm{kg_{CO_2 eq.}}}{\mathrm{t_{solid \, waste}}}\right]$;

$EFDP_d$ Emission factor for petroleum diesel production in region $d \in D$, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t_{diezel}}\right]$

$EFTRA_{il}$ Emission factor for biomass $i \in I$, transported using vehicles of type $l \in L$, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t \, km}\right]$;

$EFTWA_{yl_c}$ Emission factor for WCO $y \in Y$, transported using vehicles of type $l_c \in LC$, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t \, km}\right]$;

$EFTWC_y$ Emission factor for WCO $y \in Y$, which causes environmental pollution, if it is not used for biodiesel (B100), $\left[\dfrac{\mathrm{kg_{CO_2 eq.}}}{\mathrm{t_{WCO}}}\right]$;

$EFTB_b$ Emission factor for transportation of biodiesel (B100) and petroleum diesel using vehicles of type $b \in B$, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t \, km}\right]$;

$EFTRW_m$ Emission factor for transportation of solid waste using vehicles of type $m \in M$, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t \, km}\right]$;

$EFTRU_e$ Emission factor for transportation of waste biomass using vehicles of type $e \in E$, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t \, km}\right]$;

$EFTRV_z$ Emission factor for transportation of sunflower and rapeseed for food using vehicles of type $z \in Z$, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t \, km}\right]$;

ECB Emissions (CO_2), released during burning biodiesel (B100), $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t_{biodiesel}}\right]$;

ECG Emissions (CO_2), released during burning petroleum diesel, $\left[\mathrm{kg_{CO_2 eq.}}/\mathrm{t_{diesel}}\right]$

Economic parameters

PO Price of petroleum diesel, [\$/t];
$cost\_Gl$ Price of glycerol, [\$/t];
$cost\_Ml$ Price of the cake used as animal feed, [\$/t];
C_{CO_2} Tax on carbon emissions, expressed in terms of unit equivalent of CO_2, generated during IBDSC operation, $\left[\mathrm{\$/kg_{CO_2 eq.}}\right]$;
IA_{il} Fixed costs for transportation of biomass $i \in I$ using vehicles of type $l \in L$, [\$/t];
IB_{il} Variable costs for transportation of biomass $i \in I$ using vehicles of type $l \in L$, [\$/t km];

IAW_{yl_c} Fixed costs for transportation of WCO $y \in Y$ using vehicles of type $l_c \in LC$, [\$/t];

IBW_{yl_c} Variable costs for transportation of WCO $y \in Y$ using vehicles of type $l_c \in LC$, [\$/t];

OA_b Fixed costs for transportation of biodiesel (B100) using vehicles of type $b \in B$, [\$/t] ;

OB_b Variable costs for transportation of biodiesel (B100) using vehicles of type $b \in B$, [\$/t km];

OAD_b Fixed costs for transportation of petroleum diesel using vehicles of type $b \in B$, [\$/t];

OBD_b Variable costs for transportation of petroleum diesel using vehicles of type $b \in B$, [\$/t km];

OAW_m Fixed costs for transportation of solid waste using vehicles of type $m \in M$, [\$/t];

OBW_m Variable costs for transportation of solid waste using vehicles of type $m \in M$, [\$/t km];

OAU_e Fixed costs for transportation of biomass using vehicles of type $e \in E$, [\$/t];

OBU_e Variable costs for transportation of biomass using vehicles of type $e \in E$, [\$/t km];

OAV_z Fixed costs for transportation of sunflower and rapeseed for food using vehicles of type $z \in Z$, [\$/t];

OBV_z Variable costs for transportation of sunflower and rapeseed for food using vehicles of type $z \in Z$, [\$/t km].

Technical parameters

QT_{il}^{MIN} Minimum transport capacity l, used for transportation of biomass i, [t];

QTB_b^{MIN} Minimum transport capacity $b \in B$ used for transportation of biodiesel, [t];

Gl_i Amount of glycerol obtained in the process of processing feedstock in the production of biodiesel, [t/t];

GlW_y Amount of glycerol obtained in the process of processing WCO in the production of biodiesel, [t/t];

Ml_i Amount of cake obtained in the process of processing 1 ton feedstock in the f biodiesel, [t/t];

MlW_y Amount of grist obtained in the process of processing of 1 ton WCO in the production of biodiesel, [t/t];

PB_p^{MAX} Maximum annual capacity of plant of type $p \in P$ for the production of biodiesel (B100), using sunflower and rapeseed of type $i \in I$ and WCO of type $y \in Y$, [t/y];

PB_p^{MIN} Minimum annual capacity of plant of type $p \in P$ for the production of biodiesel (B100), using sunflower and rapeseed of type $i \in I$ and WCO of $y \in Y$, [t/y];

PBS_{ip}^{MAX} Maximum annual capacity of plant of type $p \in P$ for the production of biodiesel (B100), using sunflower and rapeseed of type $i \in I$, [t/y];

PBS_{ip}^{MIN} Minimum annual capacity of plant of type $p \in P$ or the production of biodiesel (B100), using sunflower and rapeseed of type $i \in I$, [t/y];

$PBSs_{yp}^{MAX}$ Maximum annual capacity of plant of type $p \in P$ for the production of biodiesel (B100), using WCO of type $y \in Y$, [t/y];

$PBSs_{yp}^{MIN}$ Minimum annual capacity of plant of type $p \in P$ for the production of biodiesel (B100), using WCO of type $y \in Y$, [t/y];

P_s^{MIN} Minimum annual capacity of the type facility $s \in S$ for solid waste processing, [t/y]

P_s^{MAX} Maximum annual capacity of the type facility $s \in S$ for solid waste processing, [t/y]

ENO Energy equivalent per unit of petroleum diesel, [GJ/t];

ENB Energy equivalent per unit of biodiesel (B100), [GJ/t];

ADD_{dcb} Delivery distance between regions $d \in D$ and $c \in C$ using vehicles of type $b \in B$, [km];

ADG_{gfl} Delivery distance between regions $g \in G$ and $f \in F$ using vehicles of type $l \in L$, [km];

ADF_{fcb} Delivery distance between regions $f \in F$ and $c \in C$ using vehicles of type $b \in B$, [km];

ADU_{gue} Delivery distance between regions $g \in G$ and $u \in U$ using vehicles of type $e \in E$, [km];

ADW_{fwm} Delivery distance between regions $f \in F$ and $w \in W$ using vehicles of type $m \in M$, [km];

ADV_{gvz} Delivery distance between regions $g \in G$ and $v \in V$ using vehicles of type $z \in Z$, [km];

AHF_{hfl_c} Delivery distance between regions $h \in H$ and $f \in F$ using vehicles of type $l_c \in LC$, [km];

QTB_{il}^{MIN} Minimum capacity of vehicles of type $l \in L$ used for transportation of sunflower and rapeseed $i \in I$, [t];

$QTW_{yl_c}^{MIN}$ Minimum capacity of vehicles of type $l_c \in LC$ used for transportation of WCO $y \in Y$, [t];

QTE_b^{MIN} Minimum capacity of vehicles of type $b \in B$ used for transportation of biodiesel (B100), [t];

$JobB_p$ Necessary jobs for building biodiesel refinery of size $p \in P$;

$JobO_p$ Necessary jobs for operation of biodiesel refinery of size $p \in P$ per year;

$JobG_{ig}$ Necessary jobs for cultivation of feedstock of type $i \in I$ in region $g \in G$ per year;

$JobW_s$ Necessary jobs for building solid waste use facilities of size $s \in S$;

$JobOW_s$ Necessary jobs for operation of the solid waste use facilities of size $s \in S$ per year;

M_{ft}^{JobP} Factor for changing the employment assessment depending on the region $f \in F$ in which the plant is built;

M_{wt}^{JobW} Factor for changing the employment assessment depending on the region $w \in W$ in which the plant is built.

- Parameters depending on time interval

    These parameters are influenced by market fluctuations and other external factors and have a different value for each time interval $t \in T$, but do not change in it.

Environmental parameters depending on the time interval

$EFBC_{igt}$ Emission factor for cultivation of biomass $i \in I$ in region $g \in G$, $\left[kg_{CO_2eq.} / t_{biomass} \right]$;

TEI_t^{MAX} Maximum overall environmental impact, $\left[kg_{CO_2eq.} \right]$

Economic parameters depending on the time interval

ς_t Interest rate, %;

ε_t Discount factor;

M_{tf}^{const} Factor for the change of the base price, depending on the region $f \in F$ according to the location of the plant ($M_f^{const} \geq 1$), [Dimensionless];

PGl_{it} Sales price of glycerol obtained from the feedstock i, [\$/t];

$PGlW_{yt}$ Sales price of glycerol obtained from WCO y, [\$/t];

PMl_{it} Price obtained from the sale of the feedstock i, used for food, [\$/t];

$PMlW_{yt}$ Price obtained from the sale of a pure product obtained from WCO y, [\$/t];

PG_t Price of petroleum diesel for each time interval $t \in T$, [\$/t];

PSU_{it} Price of waste biomass for each time interval $t \in T$, [\$/t];

M_{wt}^W Coefficient of adjustment in the price of the solid waste facility in the region for each time interval $t \in T$;

$Cost_{pft}^F$ Capital investment for building the facility $p \in P$ for the production of biodiesel (B100) in all areas $f \in F$ for each time interval $t \in T$, [\$];

$CostB_{pt}$ Capital costs for building facility for biodiesel production (B100) with productivity $p \in P$ according to a given technology, [\$];

$CostW_{st}$ Capital costs for building facility for solid waste use with productivity $s \in S$ according to a given technology, [\$];

TDC_t^{MAX} Maximum total costs of IBDSC for each time interval $t \in T$, [\$];

INS_{ft} Government incentives for biodiesel production (B100) depending on the region $f \in F$ for each time interval $t \in T$, [\$/t];

UPC_{igt} Production costs per unit of biomass type $i \in I$ in region $g \in G$ for each time interval $t \in T$, [\$/t];

UPW_{yht} Costs for obtaining WCO of type $y \in Y$ in region $h \in H$ for each time interval $t \in T$, [\$/t];

UPB_{ipft} Production costs per unit of biodiesel (B100) from biomass of type $i \in I$ in a biorefinery of size $p \in P$, built in region $f \in F$ for each time interval $t \in T$, [\$/t];

$UPBw_{ypft}$ Production costs per unit of biodiesel (B100) from WCO of type $y \in Y$ in a biorefinery of size $p \in P$, built in region $f \in F$ for each time interval $t \in T$, [\$/t];

UPD_{dt} Production costs per unit of petroleum diesel in refinery, built in region $d \in D$ for each time interval $t \in T$, [\$/t];

UPW_{swt} The price paid for use of a unit of solid waste in a solid waste facility of size $s \in S$, built in region $w \in W$, for each time interval $t \in T$, [\$/t];

$UPSW_{ft}$ The price paid for use of a unit of solid waste, if this is realized in the plants $f \in F$ for the production of biodiesel (B100)for each time interval $t \in T$, [\$/t];

$UPWCO_{yht}$ The price paid for use of a unit of WCO of type $y \in Y$ in region $h \in H$ for each time interval $t \in T$.

Technical parameters depending on the time interval

K_{tc}^{mix} Proportion of biodiesel (B100) and petroleum diesel during blending for each of the customer's areas. The ratio of biodiesel (B100) and petroleum diesel has a higher energy equivalent for both fuels for each time interval $t \in T$, [Dimensionless];

γ_{it} Biomass to biodiesel conversion factor depending on the type of biomass $i \in I$, [t$_{biodiesel}$/t$_{biomass}$];

YO_{tc} Consumption of petroleum diesel in different years in customer areas $c \in C$, [t/y];

PBI_{tig}^{MAX} Maximum amount of biomass of type $i \in I$, which can be cultivated in a region $g \in G$ per year, [t/y];

PBI_{tig}^{MIN} Minimum amount of biomass of type $i \in I$ which can be cultivated in a region $g \in G$ per year, [t/y];

QI_{igt}^{MAX} Maximum amount of biomass for region $g \in G$, [t/d];

QB_{ft}^{FOOD} Maximum amount of biodiesel from the region $f \in F$, [t/d];

QD_{td}^{MAX} Maximum amount of petroleum diesel from the region d, [t/d];

QB_{ti}^{Food} The total amount of feedstock of type $i \in I$, which should be provided for all regions $g \in G$ for food security, [t];

QT_{til}^{MIN} Optimal transport capacity $l \in L$ used to transport biomass, [t];

QTB_{tb}^{MIN} Optimal transport capacity $b \in B$ used to transport biodiesel, [t];

A_{gt}^{S} Free arable land in the region $g \in G$ for cultivation of biomass for each time interval $t \in T$, [ha];

A_{gt}^{Food} Free arable land in region $g \in G$ for cultivation of sunflower/rapeseed for food security for each time interval $t \in T$, [ha];

β_{igt} Production rate of biomass $i \in I$ cultivated in region $g \in G$ for each time interval $t \in T$, [t/ha];

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

α_t Period of operation of IBDSC for a year, [d/y];

γ_{ipt} Biomass to biodiesel (B100) conversion factor for biomass of type $i \in I$, according to $p \in P$ for each time interval $t \in T$, [t$_{biodiesel}$/t$_{biomass}$];

γw_{ypt} WCO to biodiesel (B100) conversion factor for WCO of type $y \in Y$, according to $p \in P$ for each time interval $t \in T$, [t$_{biodiesel}$/t$_{WCO}$];

SW_{ipt} Amount of solid waste generated during the production of one tonne of biodiesel (B100), using biomass of type $i \in I$ and technology ot type $p \in P$ during time interval $t \in T$, $\left[\frac{t_{solid\ waste}}{t_{biofuel}} \right]$;

YO_{ct} Demand for petroleum diesel in customer areas over the years $c \in C$ for each time interval $t \in T$, [t/y];

PBI_{igt}^{MAX} Maximum amount of biomass of type $i \in I$, which can be cultivated in region $g \in G$ per year for each time interval $t \in T$, [t/y];

PBI_{igt}^{MIN} Minimum amount of biomass of type $i \in I$, which can be cultivated in region $g \in G$ per year for each time interval $t \in T$, [t/y];

$PBIs_{yht}^{MAX}$ Maximum amount of WCO of type $y \in Y$, which can be provided in region $h \in H$ per year for each time interval $t \in T$, [t/y];

$PBIs_{yht}^{MIN}$ Minimum amount of WCO of type $y \in Y$, which can be provided in region $h \in H$ per year for each time interval $t \in T$, [t/y];

QI_{igt}^{MAX} Maximum permissible flow rate of feedstock of type $i \in I$ from region $g \in G$ for each time interval $t \in T$, [t/d];

QIs_{yht}^{MAX} Maximum permissible flow rate of WCO of type $y \in Y$ from region $h \in H$ for each time interval $t \in T$, [t/d];

QI_{yht}^{MAX} Maximum amount of WCO and animal fat h$\in$ *H*, [t/d];

QB_{ft}^{MAX} Maximum permissible flow rate of biodiesel (B100) from region $f \in F$ for each time interval $t \in T$, [t/d];

QD_{dt}^{MAX} Maximum permissible flow rate of petroleum diesel from region $d \in D$ for each time interval $t \in T$, [t/d];

QW_{ft}^{MAX} Maximum permissible flow rate of solid waste from region $f \in F$ for each time interval $t \in T$, [t/d];

QU_{gt}^{MAX} Maximum permissible flow rate of waste biomass from region $g \in G$ for each time interval $t \in T$, [t/d];

QV_{gt}^{MAX} Maximum permissible flow rate of sunflower/rapeseed for food security from region $g \in G$ for each time interval $t \in T$, [t/d];

QB_{it}^{Food} total amount of bioresources of type $i \in I$, which should be provided by the regions $g \in G$ to provide food security for each time interval $t \in T$, [t/y];

QTL_{ilt}^{MIN} Optimal capacity of vehicles of type $l \in L$, used to transport biomass of type $i \in I$ for each time interval $t \in T$, [t];

QTB_{tt}^{MIN} Optimal capacity of vehicles of type $b \in B$, used to transport biodiesel (B100) and petroleum diesel for each time interval $t \in T$, [t];

QTE_{et}^{MIN} Optimal capacity of vehicles of type $e \in E$, used to transport waste biomass for each time interval $t \in T$, [t];

QTZ_{Zt}^{MIN} Optimal capacity of vehicles of type $z \in Z$, used to transport sunflower/rapeseed for food security for each time interval $t \in T$, [t]; QTM_{mt}^{MIN} Optimal capacity of vehicles of type $m \in M$, used to transport solid waste for each time interval $t \in T$, [t];

$QTW_{l_c yt}^{MIN}$ Optimal capacity of vehicles of type $l_c \in LC$, used to transport WCO of type $y \in Y$ for each time interval $t \in T$, [t].

Decision variables

- Positive continuous variables

QB_{tfcb} Biodiesel flow rate produced from feedstock of type $i \in I$ transported by vehicles of type $b \in B$ from region $f \in F$ to $c \in C$ in each time interval $t \in T$, [t/d];

QD_{tdcb} Petroleum diesel flow rate transported by vehicles of type $b \in B$ from region $d \in D$ to $c \in C$, in each time interval $t \in T$, [t/d];

QED_{tc} Amount of petroleum diesel that will be delivered to meet the energy needs of a region $c \in C$, for each time interval $t \in T$, [t/y];

QEB_{tc} Amount of biodiesel produced from biomass that will be delivered to meet the energy region $c \in C$, for each time interval $t \in T$, [t/y];

A_{tig} Land occupied by sunflower/rapeseed in region g, for each time interval t, [ha];

A_{tig}^{F} Land occupied by sunflower/rapeseed $i \in I$ needed for food security in region $g \in G$, for each time interval $t \in T$, [ha];

TC_t Price of transport, for each time interval $t \in T$, [\$];

TCI_t Total capital investment, for each time interval $t \in T$, [\$];

TI_t Total environmental impact, for each time interval $t \in T$, [kg$_{CO_2eq.}$];

TEI_t Total impact of GHG emissions, for each time interval $t \in T$, [kg$_{CO_2eq.}$];

PBB_{igt} Crop biomass of type $i \in I$, which should be provided from region $g \in G$ in the time interval $t \in T$;

QI_{igflt} Flow rate of crop biomass of type $i \in I$, transported by vehicles of type $l \in L$ from region $g \in G$ to $f \in F$, for each time interval $t \in T$, [t/d];

QIP_{igflpt} Flow rate of crop biomass of type $i \in I$, transported by vehicles of type $l \in L$ from region $g \in G$ to $f \in F$, according to technology $p \in P$, for each time interval $t \in T$, [t/d];

QIw_{yhflct} Flow rate of WCO biomass of type $y \in Y$, transported by vehicles of type $l_c \in LC$ from region $h \in H$ to $f \in F$, for each time interval $t \in T$, [t/d];

$QIPw_{yhfl_cpt}$ Flow rate of WCO biomass of type $y \in Y$, transported by vehicles of type $l_c \in LC$ from region $h \in H$ to $f \in F$ according to technology $p \in P$, for each time interval $t \in T$, [t/d];

QB_{fcbt} Flow rate of biodiesel (B100), produced from biomass of type $i \in I$ and $y \in Y$, transported by vehicles of type $b \in B$ and $l_c \in LC$ from region $f \in F$ to $c \in C$, for each time interval $t \in T$, [t/d];

QBP_{ifcbpt} Flow rate of biodiesel (B100), produced from crop biomass of type $i \in I$ and transported by vehicles of type $b \in B$ from region $f \in F$ to $c \in C$, according to technology $p \in P$, for each time interval $t \in T$, [t/d];

$QBPw_{yfcbpt}$ Flow rate of biodiesel (B100), produced from WCO biomass of type $y \in Y$ and transported by vehicles of type $b \in B$ from region $f \in F$ to $c \in C$, according to technology $p \in P$, for each time interval $t \in T$, [t/d];

QD_{dcbt} Flow rate of petroleum diesel, transported by vehicles of type $b \in B$ from region $d \in D$ to $c \in C$, for each time interval $t \in T$, [t/d]; QW_{fwmt} Flow rate of solid waste, transported by vehicles of type $m \in M$ from region $f \in F$ to $w \in W$, for each time interval $t \in T$, [t/d];

QWS_{fwmst} Flow rate of solid waste, transported by vehicles of type $m \in M$ from region $f \in F$ to $w \in W$, in plant with size $s \in s$, for each time interval $t \in T$, [t/d];

QU_{iguet} Flow rate of straw collected from crop biomass of type $i \in I$ and transported for processing by vehicles of type $e \in E$ from region $g \in G$ to $u \in U$, for each time interval $t \in T$, [t/d];

QV_{igvzt} Flow rate of sunflower/rapeseed to provide food security transported by vehicles of type $z \in Z$ from region $g \in G$ to $v \in V$, for each time interval $t \in T$, [t/d];

QED_{ct} Amount of diesel that should be provided to meet the energy needs of the region $c \in C$, for each time interval $t \in T$, [t/y];

QEB_{ct} Amount of biodiesel (B100) produced from WCO biomass, which is provided to meet the energy needs of the region $c \in C$, for each time interval $t \in T$, [t/y];

A_{igt} Free arable land for cultivation of crop biomass of type $i \in I$, for the production of biodiesel (B100) in the region $g \in G$, for each time interval $t \in T$, [ha];

A^F_{igt} Free arable land for cultivation of crop biomass of type $i \in I$, needed to meet the food security in the region $g \in G$, for each time interval $t \in T$, [ha];

TC_t Transportation costs, for each time interval $t \in T$, [$];

TCI_t Capital investment, for each time interval $t \in T$, [$];

TI_t Total environmental impact, for each time interval $t \in T$, [kg$_{CO_2eq.}$];

TEI_t Total impact of GHG emissions, for each time interval $t \in T$, [kg$_{CO_2eq.}$].

- Binary variables

X_{igflpt} 0-1 variable, takes value "1", if crop biomass of type $i \in I$ is transported from region $g \in G$ to $f \in F$ by vehicles of type $l \in L$ for production according to technology $p \in P$, and takes "0" otherwise in time interval $t \in T$;

Xs_{yhfl_cpt} 0-1 variable, takes value "1", if WCO biomass of type $y \in Y$ is transported from region $h \in H$ to $f \in F$ by vehicles of type $l_c \in LC$ for production according to technology $p \in P$, and takes "0" otherwise in time interval $t \in T$;

Y_{fcbt} 0-1 variable, takes value "1", if biodiesel(B100) is transported from region $f \in F$ to $c \in C$ by vehicles of type $b \in B$, and takes "0" otherwise in time interval $t \in T$;

WS_{fwmt} 0-1 variable, takes value "1", if solid waste is transported from region $f \in F$ to $w \in W$ by vehicles of type $m \in M$, and takes "0" otherwise in time interval $t \in T$;

WU_{guet} 0-1 variable, takes value "1", if straw is transported from region $g \in G$ to $u \in U$ by vehicles of type $e \in E$, and takes "0" otherwise in time interval $t \in T$;

WV_{igvzt} 0-1 variable, takes value "1", if crop biomass of type $i \in I$ for food security is transported from region $g \in G$ to $v \in V$ by vehicles of type $z \in Z$, and takes "0" otherwise in time interval $t \in T$;

ZW_{swt} 0-1 variable, takes value "1", if solid waste use facility with size $s \in S$ is built in region $w \in W$, and takes "0" otherwise in time interval $t \in T$;

ZWF_{swt} 0-1 variable, takes value "1", if solid waste use facility with size $s \in S$ should operate in the region $w \in W$, and takes "0" otherwise in time interval $t \in T$, which includes the facilities built in the previous time interval and the new ones built during this interval, calculated by an equation $ZWF_{swt} = ZWF_{sw(t-1)} + ZW_{swt}$ for the first year ($t = 1$) the configuration is set by initialization $ZWF_{sw'1'} = ZW_{sw'1'}$;

Z_{pft} 0-1 variable, takes value "1", if plant for biodiesel(B100) production with size $p \in P$ should be built in the region $f \in F$, and takes "0" otherwise in time interval $t \in T$;

ZF_{pft} 0-1 variable, takes value "1", if plant for biodiesel(B100) production with size $p \in P$ should operate in the region $f \in F$, and takes "0" otherwise in time interval $t \in T$, which includes the plants built in the previous time interval and the new ones built during this interval, calculated by following recursive equation $ZF_{pft} = ZF_{pf(t-1)} + Z_{pft}$ for the first year ($t = 1$) the configuration is set by initialization $ZF_{pf'1'} = Z_{pf'1'}$;

PD_{dt} 0-1 variable, takes value "1", if diesel is produced in the region $d \in D$, and takes "0" otherwise in time interval $t \in T$;

DT_{dcbt} 0-1 variable, takes value "1", if diesel is transported from region $d \in D$ to $c \in C$ by vehicles of type $b \in B$, and takes "0" otherwise in time interval $t \in T$.

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