P-Graph approach for the economical optimisation of biomass supply network that meets requirements on greenhouse gas emissions savings - a case study of rural areas

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This work presents a novel P-graph-based model for optimizing a biomass supply network. The objective of this optimization is twofold: to find the most cost-effective biomass supply network with a minimum cost, while also fulfilling the required greenhouse gas (GHG) emissions savings defined in Directive 2018/2001 (80% savings compared to fossil fuel comparators) for the use of biogas.
To achieve this goal, an extension to a P-graph-based biomass supply network was developed, which allows the optimization of the network while limiting GHG emissions associated with the use of biogas. The model includes a summary of GHG emissions for each stage of biogas production and consumption, compared to threshold values. Additionally, seasonal variation in biomass supply was integrated into the model by using a multiperiod approach.
The model was developed and solved in P-Graph Studio, with input data defined using the Geographic Information System (GIS) tool, including feedstock availability, an optimal location for a biogas site, and transportation distance. The approach was tested in a case study located in a rural area. This model can benefit a wide range of stakeholders, including biogas plant operators, policymakers, researchers, and energy regulatory authorities.

1. Introduction

A drastic acceleration of the energy transition and an increase in natural gas independence is required in light of the changing geopolitical and energy market realities. Anaerobic digestion (AD) of by-products, residues and waste materials has not only been recognised as technology for the generation of sustainable alternative fuel but is also an environmentally friendly waste treatment method [1]. Biogas production in the European Union (EU) has steadily increased during the last decade, going from 6,227 biogas plants in 2009 [2] to 20,000 in 2021 [3]. Up to 72 % of the feedstock used for biogas production comes from the agricultural sector [4], mostly from maize silage. The competitive use of biogas feedstocks with food and feed production raised not only environmental but also socio-economic concerns, reflected in new sustainability requirements, defined by EU legislation. The revised Renewable Energy Directive (D2018/2001), which came into force in December 2018, established sustainability and the greenhouse gas (GHG) emission-reduction standards that biogas used in transportation, electricity, heating, and cooling must meet. Concerning GHG savings, the Directive defines that the GHG savings from the use of biomass for electricity, heating and cooling production should be at least 70% for installations starting operation from the beginning of the year 2021 until the end of 2025 and 80 % for installations starting operation from 2026 [5]. Furthermore, the European Commission (EC) set a cap on food and feed crops toward the EU renewable objective, starting at 7% in 2021 and gradually decreasing to 0% in 2030, in order to reduce the impact of Indirect Land-Use Change (ILUC). With the given new requirements, the utilization of materials previously regarded as waste is receiving increased attention, as it not only improves the sustainability of biogas production but also improves waste management and resource efficiency. Hence, biogas production can serve as a treatment plant that converts waste resources into high-value products, consequently contributing towards the objectives of the European Circular Economy Action Plan [6]. In their paper, the European Biogas Association highlighted the untapped opportunities for GHG savings through the utilization of industrial waste, loaded with organic matter, for biogas production [7], as waste management measures have a significant effect on climate change mitigation [8]. Furthermore, lignocellulose biomass is now recognised as a significant untapped source of renewable energy, that may substantially contribute towards fulfilling the global demand for renewable energy [9].

A transition toward more sustainable biogas and biofuel production seeks more research on the more sustainable alternatives (such as residues and by-products) which should replace the currently dominant maize silage in biogas production by fulfilling the sustainability and greenhouse emission criteria [10]. The potential of biomass residues that is accessible for the production of biogas is limited by factors like their low energy density, scattered production and competitiveness with other uses [11]. Assessment of this potential is the necessary first step and it should include spatial dimension. The application of GIS technologies has been recognised as being particularly beneficial for mapping biomass potential during the past ten years since it can deliver insightful information about the spatial distribution of the biomass potential and input data for biomass potential analysis.

One of the main barriers to enhanced biomass utilisation in energy supply is the economic viability of a biomass supply network. Different methods for optimising the biomass supply network have been presented in the literature to overcome this obstacle. It has been recognised that graph theory methods are being employed more frequently to solve biomass supply network modelling issues. Graph theory is the study of graphs, which are mathematical constructions used to represent pairwise relationships between objects. Implementation of graph theory methods offers several advantages for supply network modelling. Some of the advantages of graph theory methods are a representation of decision structures (solutions), the algorithmic generation of a mathematical model and the derivation of multiple alternative solutions [12]. In comparison to the other methods, such as Mixed-Integer Linear Programming (MILP), there is a reduced complexity of the solution procedure.

1.1 Literature review

It is becoming evident that energy systems modelling is progressively embracing different types of integrative approaches [13]. Murele et al. [14] investigated the influence of the integration of biomass into coal-based energy supply networks. Results of the optimisation aimed to minimise the cost of the energy supply network, obtained through the General Algebraic Modelling System software (GAMS), indicate that a biomass fraction of 7.9% in the mixed solid fuel will provide an optimal solution, as it would result in a balanced cost decrease of the emission cost and increase of the supply network. Simon et al. [15] developed a model that simulates the supply curve of wood biomass from the sustainable management of natural forests. The findings indicate that the maximum admissible distance to the nearest transportation route and the associated transportation expenses are the two factors that exert the greatest impact on both the supply and cost of wood biomass. Rentizelas et al. [16] applied the Data Envelopment Analysis method for assessing the cost, energy and GHG emission efficiency of international biomass supply network pathways. The selection of the most efficient pathway depends on the total cost, energy consumption and emissions, as well as priorities of the decision maker. Shen et al. [17] developed a novel mathematical optimisation approach that allows the reduction of redundancy of data series to solve the multi-echelon biomass supply problem. This multi-echelon biomass supply problem includes economic, environmental and social indicators, optimised by maximising economic viability and social benefit while minimising environmental emission through a weighted-sum approach and max-min aggregation approach.

The use of P-graphs in energy system modelling has intensified during the past two decades. In their recent paper, Xu et al. [18] implemented the P-graph approach to define optimal energy export strategies of islands, whose objective is to minimise construction, operating and environmental cost (related to greenhouse gas footprint). Results showed that the best operational path and the best economical cost are in the case of export by electricity. Similar to this, the paper published in April 2023, written by Ji et al. [19] presents the implementation of the P-graph approach for the optimisation of multi-period renewable energy systems with hydrogen and battery energy storage. For the developed biomass energy supply scenario, the results show that the renewable energy systems with hydrogen storage and battery storage are, respectively, 21.5 % and 5.3 % cheaper than those without energy storage. The developed model investigates CO_2 generation and includes it in the optimisation through the cost of CO_2 emissions. Aviso et al. [20] implemented a P-graph approach to the development of optimal and sub-optimal biochar-based carbon networks. Here, the objective was to optimise the network in terms of overall carbon sequestered annually, without exceeding constraints on soil contamination. Lam et al. [21] have proposed a model to integrate palm biomass and waste motor oil into the waste-to-energy model. The method to solve the combinatorial of the biomass supply chain in Federal Land Development Authority Jengka was presented by Varbanov et al. [22]. Here, the authors have proposed possible locations for building a new biomass processing facility in the considered region, which should be used for the utilization of waste from oil palm biomass processing. Malladi et al. [23] have created a decision support tool to optimise the short-term logistics of forest-based biomass through the minimisation of the biomass logistic cost. The method to solve the combinatorial of the biomass supply chain in Federal Land Development Authority Jengka was presented by Varbanov et al. [22]. Here, the authors have proposed possible locations for building a new biomass processing facility in the considered region, which should be used for the utilization of waste from oil palm biomass processing. Malladi et al. [23] have created a decision support tool to optimise the short-term logistics of forest-based biomass through the minimisation of the biomass logistic cost. Van Fan et al. [24] applied the P-graph approach to detect cost-optimal and suboptimal pre-and post-treatment pathways for the anaerobic digestion of lignocellulosic waste. The result of the optimisation for the lignocellulosic waste showed that alkali CaO pre-treatment proved to be the cost-optimal pre-treatment option of the lignocellulosic waste, while H2S + membrane separation proved to be the cost-optimal post-treatment (biomethane upgrading) option. Benjamin [25]. developed a P-graph approach to perform a critical analysis of an integrated network of biomass processing industries under scenarios that involve both supply and demand side disturbances. This methodology enables the reduction of the net product stream output that results from the occurrence of climate change-induced events (supply-side disruptions) and seasonal fluctuations in demand, to be assessed. Vance et al. [26] implemented the P-graph method for the development of economically optimal and suboptimal structures of biomass network that includes corn silage, grass silage, corn straw and wood as feedstock material for combined heat and power (CHP) units. For the obtained results (ranked structures) ecological footprint was assessed, indicating the amount of land required to support and assimilate a given human population's consumption and wastes. The structures whose ecological footprint was lower than the given threshold were considered sustainable.

The objective of this work is to develop a novel P-graph-based method for economical optimisation of the biomass supply network, that meets requirements on greenhouse gas emissions savings and considers the seasonality of biomass availability, a P-graph based model was developed. The threshold of this requirement is defined in Directive 2018/2001 and it equals 80% savings compared to fossil fuel comparator. As represented in the literature review, studies in this field determine the economically optimal and sub-optimal biomass networks and thereafter compare the ecological footprint/environment constraints upon the optimisation process. Furthermore, the seasonality of biomass supply and biogas demand is mostly neglected, although it may have a significant impact on the viability of utilisation of feedstocks with high seasonal fluctuations, such as industrial by-products and agricultural residues. To address this research gap, the contributions which this study delivers, in comparison to earlier research are the following:

- a P-graph-based model which enables the optimisation of a biomass supply network that simultaneously limits the GHG emissions that a biomass network can generate and defines the optimal and sub-optimal economical structures, which are in line with the requirements of the GHG emission savings;
- the developed model integrates the seasonality of biomass supply, through the implementation of the multi-period approach. Hence, the limitations on greenhouse gas emissions are automated and fulfilled for each period.

2. Problem statement

To investigate the possibilities of the P-graph approach to perform an economical optimisation of the biomass supply chain, that meets requirements on greenhouse gas emissions savings and considers the seasonality of biomass availability, the P-graph-based model was developed. The main assumptions of the problem can be defined as follows.

- GHG emission-saving requirements
  1. The assumption is used that biogas produced in anaerobic digestion is future utilised in a CHP engine, which supplies the electric and heat demand of the process. This is a so-called case 1 in D2018/2001. This assumption was used for the calculation of the maximal allowed total GHG emissions.
- To ensure the compliance of resulting structures (optimal and suboptimal) with GHG saving requirements defined in Directive 2018/2001 80% GHG emission savings compared to the fossil fuel comparator), authors calculated the maximal allowed GHG emissions in their previous work [27]. For a typical case, where electrical and heat efficiency is 36% and 43% respectively, the maximal total GHG emissions equals 16.95 gCO_2/MJ biogas. In the developed model, this value is set as a threshold. Seasonality of feedstock availability
  1. Feedstock availability through a year is represented through multi-period representation. Here, the assumption is used that biomass available for biogas production is the one generated in the specific period (month/s). There is a threefold reason for this. The first one is that some of the considered feedstock can not be stored for a longer period of time, due to potential changes in feedstock conditions, which could result in the adverse performance of biogas production. The second is

that seasonal feedstock storage may result in additional methane emissions generated during the storage period, which could result in exceeding the threshold of GHG emissions, due to the high global warming potential of methane. The final one is the cost of the investment and maintenance of the seasonal storage.

ii. In case the required biogas production exceeds the biogas potential contained in the biomass, the assumption was used that this gap will be covered with the wheat straw, due to favourable storage properties.

- Cost of biomass supply network

  i. The cost of anaerobic digestion is considered to be the same for each biomass supply network. Therefore, this cost is not included in the cost of the biomass supply network, as it does not differ for different structures of biomass supply networks.

  ii. The cost of a feedstock, transport and processing is considered and calculated as a specific cost (cost per unit of mass or energy).

The objective function of the optimisation is to minimise the cost of the biomass supply network while fulfilling the given constraints regarding GHG savings and maximising the utilisation of seasonally available biomass. The hypothesis of this work is that an economically optimal residual biomass supply network for biogas production, that meets sustainability and greenhouse gas emissions saving criteria, could be determined with the P-graph approach.

3. Method

The method used for this work can be divided into two major sections. The first part of the research is conducted with the GIS tool and the second part of the research is conducted with the P -graph tool. The flowchart presented in Figure 1 represents the steps of the method, which are explained in detail below.

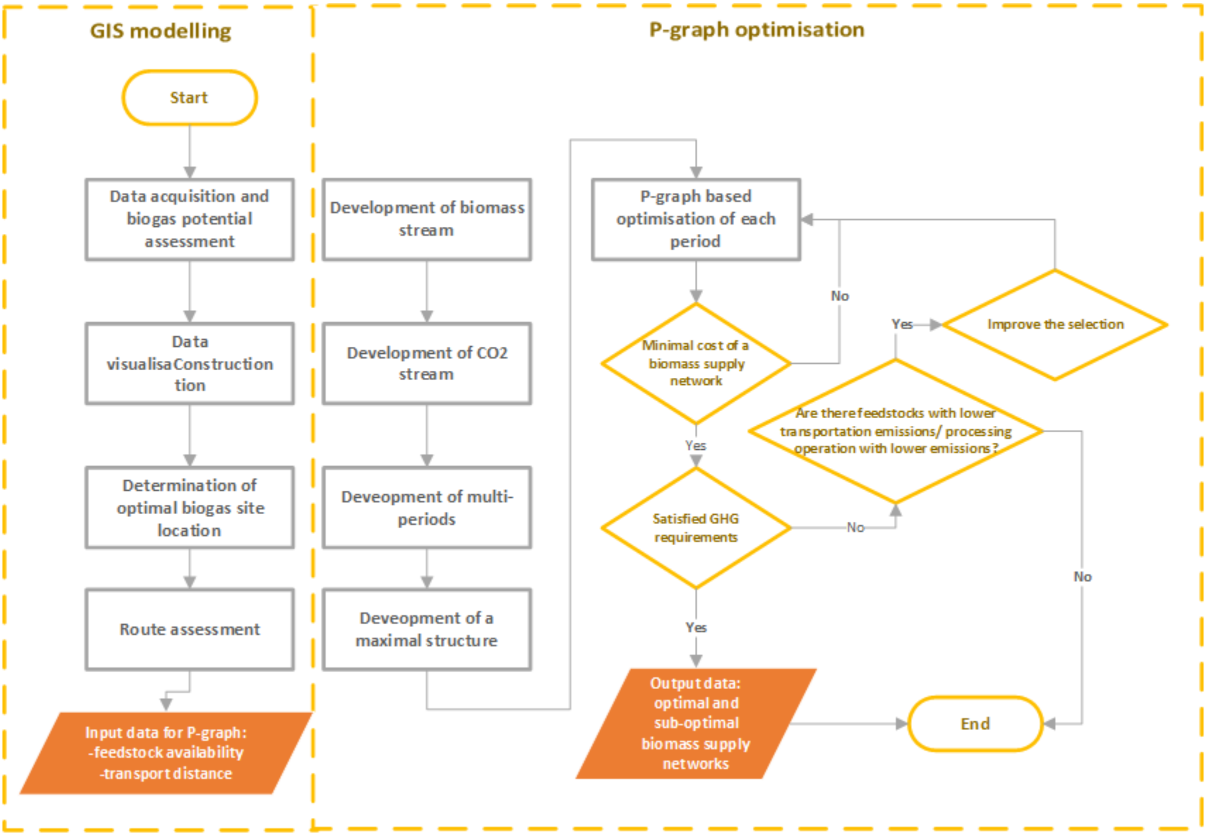


Figure 1 Flowchart representation of the method

3.1 GIS assessment of biomass and biogas potential

GIS assessment of biomass potential is the process of using a GIS tool to create maps that present the distribution and density of biomass potential in a particular area. For this purpose, the QGIS tool [28] was used. QGIS is a free and open geographic information system tool that allows users to develop, analyse, edit and print geospatial data. The conducted assessment was implemented to obtain input data for P-Graph Studio (P-graph software). It includes several steps, which are described in more detail in the subsections below.

<u>Data acquisition and biogas potential assessment</u>

Residues and by-products that are located in rural regions are the raw materials (feedstocks) taken into consideration in this work. More precisely, the following categories can be created from the examined feedstocks for this work:

- Agricultural residues (maize stover, wheat straw);
- Manure (Cattle, pig, chicken manure);
- By-products from the food industry (Grape pressings, sugar beet pulp).

To assess the biogas potential, the theoretical potential of the selected feedstock must first be assessed. This theoretical potential is based on the ratio of residue to processed commodities and the amount of processed commodities. Only a portion of the theoretical potential, also called technical potential can be utilised for the production of bioenergy due to competition with other purposes (feed, land protection, etc). Hence, a sustainable removal rate was applied for wheat straw. This factor equals 40% for wheat straw [29]. For livestock, the theoretical potential is a function of the number of livestock (head) and the amount of manure produced annually per head.

Based on the theoretical potential of fresh feedstocks, a specific biogas yield from fresh feedstock, and the methane content of biogas, the biogas potential of the evaluated feedstocks is determined. Input data for the calculation of the biogas potential from wheat straw and cow manure can be obtained from public reports and agricultural geoportals provided by a national Ministry of Agriculture and the related Agencies. To assess the biogas potential from grape pressings and sugar beet pulp, input data can be obtained through publicly available annual reports. Table 1 lists the biogas yield and biogas methane content for the considered feedstocks.

Table 1 Biogas yield and methane content of considered residues and by-products

Residues/ by-products	$\boldsymbol{y}$ **(m^3/t_{FM})**	$\boldsymbol{s_{CH_4}}$ **(%)**	**Reference**
Wheat straw	125	52.5	[30]
Grape pressings	160	80	[31]
Sugar beet pulp	96	50	[32]
Cow manure	22.1*		[33]

* In literature, the value is given for a methane yield (m^3 CH_4/t)

Previous studies [34], [35]. of the authors go into a greater level of detail on this step.

Data visualisation

The geographic distribution of biomass potential and the distance to a possible biogas site limit the viability of using residues and by-products from an economic and GHG savings perspective. Data visualisation highly depends on the type of represented feedstocks. Feedstocks that are being generated at farms (manure) and in the food industry can be represented by a point vector layer since the production of feedstocks occurs at a specific location. To link the attribute (non-spatial) information on the biogas potential to spatial information, geocoding can be applied, which represents converting addresses into geographic coordinates and thus enable utilisation of the data in the GIS tool.

On the other hand, agricultural residues occur in the wider area. A top-down approach was applied to visualise and evaluate the distribution of this potential, and the potential of wheat straw was dispersed in the areas that fall under distinct land cover classifications. Data included in the GIS tool can be afterwards used for map development. GIS biomass maps can visualise information on biomass and biogas potential and be used for distance determination and optimal biogas site location determination.

Determination of optimal biogas site location

The optimal location for a biogas plant is determined using geographic and attribute (non-spatial) data. This biogas plant can be understood as a centralised production site that produces biogas from feedstock supplied by the concerned industry, farms and agricultural sites. The goal function of this optimisation is to minimize transport distance between a biogas site and concerned feedstock providers. For this optimisation, the “Mean coordinate” spatial query, available in QGIS was used. As the input data for the optimisation, biogas potential was used as the weighted factor. In a case where biogas potential is represented in both point and polygon vector layers, it is important to align the type of layers and merge those layers into one, which can be used for optimal biogas site location determination. In this work, the potential of the agricultural residues, initially represented in the polygon vector layer was transferred to the point layer by using the “Centroids” query in QGIS. The generated points can be understood as the collection sites of agricultural residues.

Route assessment

The "Shortest path" query in QGIS can be used to examine routes (transport distance). This query allows the automatic assessment of the shortest (or fastest, upon user preferences) route between feedstock providers and biogas plants. The input data used for this assessment includes a network layer representing transport routes (roads) in the considered, a layer representing feedstock providers including the information a respective biogas potential and a layer including the location of the optimal biogas site location. The transport routes (road networks) can be imported to QGIS with the "QucikOSM" plugin. Specific transportation costs can be determined with equation (1):

$$C_{trans} = \frac{d * (K_{full} + K_{empty})}{B_{biogas}} * b * T \tag{1}$$

Where C_{trans} stands for specific transport cost (EUR/GJ), d for transport distance (km), K_{full} for fuel consumption of a full truck (L/km), K_{empty} for fuel consumption of empty truck (L/km), b for fuel price (EUR/L), B_{biogas} for biogas potential of transported feedstock (GJ) and T for transport cost correction factor. In this work, we used the assumption that T equals 3, which means that the cost of fuel is one-third of the total transport cost.

3.2 Optimisation of biomass supply network by P-graph

Due to the combinatorial nature of the problem, biogas production can be accomplished by a wide range of alternative structures. The determination of the optimal network structure is most frequently referred to as process-network synthesis (PNS) flowsheet design. The P-graph method is a graph-theoretical approach used for solving PNS problems [36]. Hence, for this step, the P-graph-based algorithms and the concomitant software (P-Graph Studio) will be used.

3.2.1 P-graph studio and P-graph based algorithms

P-graphs are bipartite graphs, each comprising material nodes (M) and operating unit nodes (O) and arcs between them. Determination of the feasible structures will be performed in three major steps.

In the first step, the maximal structure of feasible solutions for biogas production is developed. The maximal structure comprises all the combinatorically feasible structures capable of yielding the specified products from the specified raw materials. The feasible solution structure generated by process-network synthesis must have several basic features that are taken as axioms, the introduction of which improves the efficiency of the combinatorial search during the process. In the P-graph-based methods, the algorithm MSG (Maximal Structure Generation) yields the maximal structure, i.e., the superstructure, for the Process Network Synthesis (PNS) problem. MSG Algorithm is a polynomial algorithm based on the axioms which define representations of the final product, interim products, raw materials, operating units and arcs. Those axioms are explained in detail by Friedler et al. [37]. The maximal structure will be analysed in the second step. Here, algorithm SSG (Solution Structure Generation) will be used for the generation of all the solution structures representing the combinatorically feasible flowsheets from the maximal structure. Algorithm SSG systematically and combinatorically selects a series of active sets and carries out decision mappings. Finally, ABB (Accelerated Branch and Bound) algorithm will be used to generate the n-best feasible solution structures. Algorithm ABB is a branch and bound algorithm for solving combinatorial problems. It traverses the maximal structure, keeping track of all partial solutions in corresponding tree branches and bounding until it finds a branch whose objective function is better than the current best solution.

3.2.2. Biomass supply network design

The first step in creating a P-graph for a biomass supply network is to identify the potential feedstocks that can be used in the considered area and to map out the transportation network. Those data (type of feedstock, technical potential, biogas potential transport distance) were exported from the GIS tool in the previous steps.

Material nodes are representing raw materials (wheat straw, grape pressings, manure and sugar beet pulp), interim materials and the final product (biogas). Operating unit nodes are representing biomass transport, biomass processing and anaerobic digestors. Anaerobic digesters are enclosed structures where the anaerobic breakdown of raw material (feedstock) takes place. The biomass supply network developed in this paper is presented in simplified form (for only one input raw material) in Figure 2.

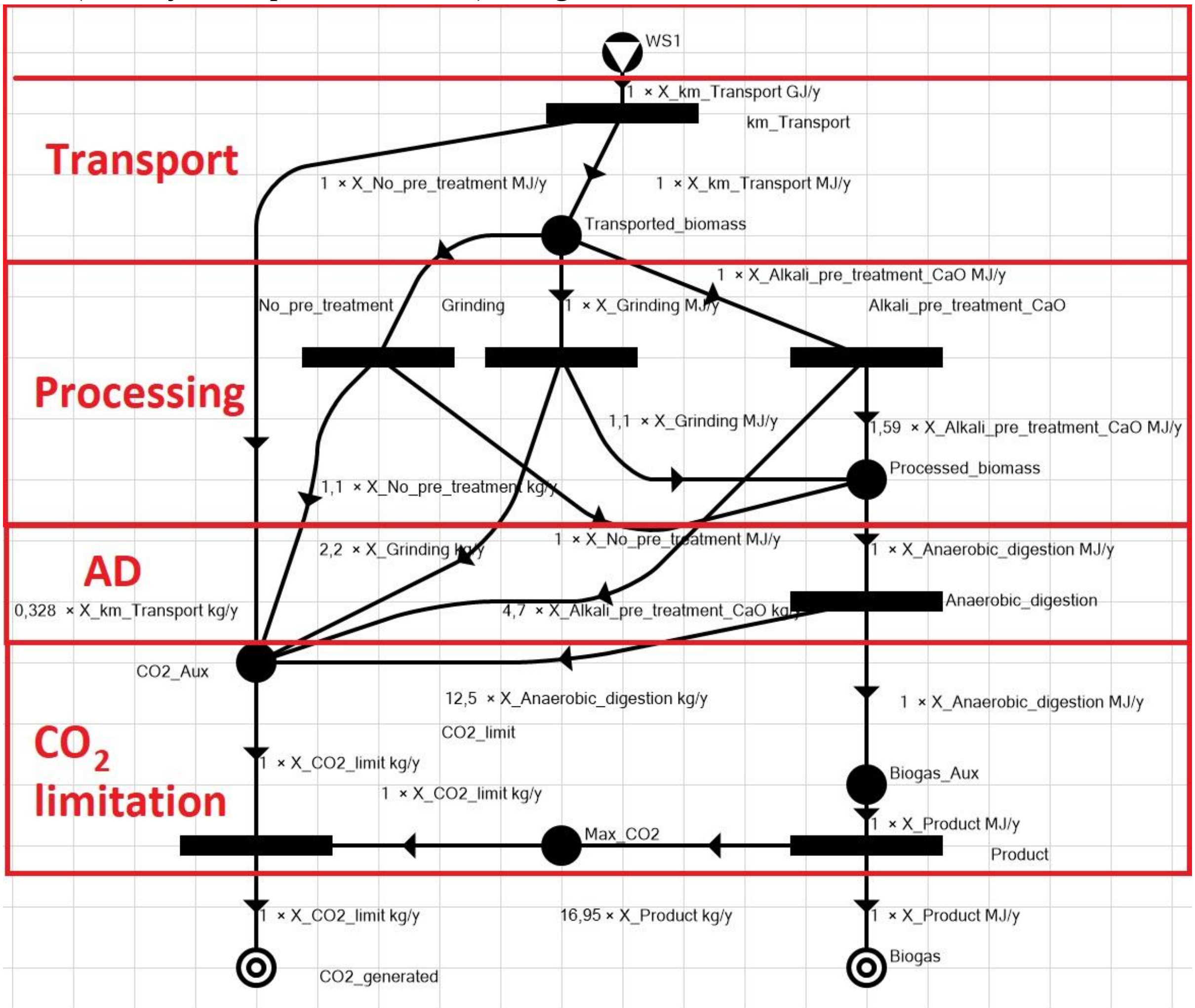
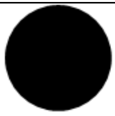


Figure 2 PNS network of the utilisation of wheat straw for biogas production

Elements included in the PNS network are presented in Table 2.

Table 2 P-graph representation of elements included in the PNS network

Element	P-graph representation
Feedstock sites: Cattle farm (CF)/ Wineries (W)/ Sugar factory (SF)/ Wheat straw collection site (WS)	
Intermediate products: Transported biomass/Processed biomass Auxiliary products: Maximal allowed CO_2 (Max CO_2), Summarised CO_2 generation (CO_2_Aux), Summarised Biogas production (Biogas_Aux)	
Operating units: Transport; Pre-processing: No pre-treatment/ Grinding and bailing/ Alkali pre-treatment; Anaerobic digestion (AD) Auxiliary units: CO_2 limitation (CO_2 limit)/ Biogas limitation (Product)	
Final products: Biogas/ Generated CO_2 (CO_2 gen)	

As can be seen from Figure 2 PNS network developed for utilisation of considered feedstocks (here wheat straw was taken as an example) includes two main streams- stream of biomass and stream of CO_2. In the context of biomass stream, it refers to the feedstock that is being transported, processed and utilised in an anaerobic digestor for biogas production. In the context of CO_2 streams, it refers to the emissions associated with the transport and processing of biomass, as well as the emissions associated with the biogas in use (here represented as emissions associated with anaerobic digestor). When developing CO_2 streams special attention was taken to ensure that all GHG emissions (including CO_2 and non-CO_2 emissions) are covered and assessed in line with the method defined in Directive 2018/2001 [38]. This ensures the compliance of resulting structures (optimal and suboptimal) with 80% GHG savings defined in Directive 2018/2001 to be legally binding for biogas sites starting operation from 2026. As a threshold, the value of 16.95 gCO_2/MJ_{biogas} net emissions is used in the model.
The stages in biomass and CO_2 streams are represented in red squares in Figure 2. All of those stages include operating units, while the resulting outputs are represented as interim materials except in the case of biogas, which is represented as the final product. Here, it is interesting to highlight part of the PNS network that represents the processing stage and part of the PNS network representing CO_2 limitation. In the processing stage for wheat straw three options are represented- no processing (only bailing at the field is included here), grinding and alkali pre-treatment (CaO). Implementation of one of those three options leads to different biogas yields obtained from the concerned feedstocks. As presented by Van Fan et al. [24], grinding will result in a 10% enhanced biogas yield of lignocellulosic waste, while alkali pre-treatment would lead to 59% higher biogas yield compared to the option without pre-treatment. On the other hand, grinding and alkali pre-treatment increases the cost of the pre-processing and associated GHG emissions. Those ratios are presented in arcs for the representing processing options of biomass stream. As expected, the cost and associated GHG emissions are the highest for alkali pre-treatment. For cases like this, where final cost and total GHG emissions depend on numerous factors, it is very beneficial to conduct a P-graph optimisation. Finally, it is important to note that the biogas potential of feedstocks refers to the reference biogas yield (in a case where there is no pre-treatment) and not the energy value of the feedstock composed in the chemical composition of the feedstock.

Part of the PNS network representing CO_2 limitation sets the threshold for GHG generation (and resulting savings) of the production of biogas and its use. For this purpose, two auxiliary products (intermediate materials) are included in the PNS network design- CO_2_Aux and Biogas_Aux. The maximal flow of those two auxiliary products is set to zero, indicating that they are completely consumed. As can be seen from Figure 2, CO_2_Aux summarizes all of the G emissions generated by processes represented by operating units. Biogas_Aux is used for setting the threshold (maximum) on GHG emissions that the use of fuel (biogas) can generate to be in line with the GHG savings. This limit is represented in PNS Network as Max_CO_2. In case if during the optimisation process, CO_2_Aux emissions are higher than Max_CO_2 emissions, the P-Graph Studio makes a new iteration to find a structure whose emissions are lower than Max_CO_2.

The cost of a PNS network includes the sum of the cost of the raw materials and the cost of the transport and processing cost. As the main objective of this work is to compare the economic feasibility of the structures, the cost of the anaerobic digestion was not considered here, as it is considered to be equal for all of the considered feedstocks. The goal function of the optimisation is to minimise the cost of a biogas supply network (structure). The optimal solution is the one which can deliver the required biogas production, for a minimal cost and by staying below the permissible limit on GHG production. In addition to an optimal solution the n- best solutions will be ranked.

3.2.3 Multi-period P-graph Optimisation

To incorporate the seasonal variation of biomass supply and biogas demand during the year, the model was extended to multi-periods. The multi-period P-graph modelling allows dividing a year into custom-selected periods of time, which can be of arbitrary length. A multi-period optimisation approach, provides more reliable data compared to a single-period model, as it takes into account fluctuations of inputs (feedstocks) supply during the year, as well as differences in output (biogas) demand throughout the year. For the considered problem, periods are selected based on the availability of considered feedstock types. Hence, months with equal feedstock supply are grouped into the same period. The multi-period extension was implemented by configuring the Multiperiodic settings of the PNS network using P-Graph Studio.

4. Case study

The presented method was demonstrated in the case study of the rural area of Osijek-Baranja County. The county is situated in the northeastern part of the country and has intensive livestock production and use of land for agricultural production. Figure 3 represents the sites and agricultural land considered in this case study.

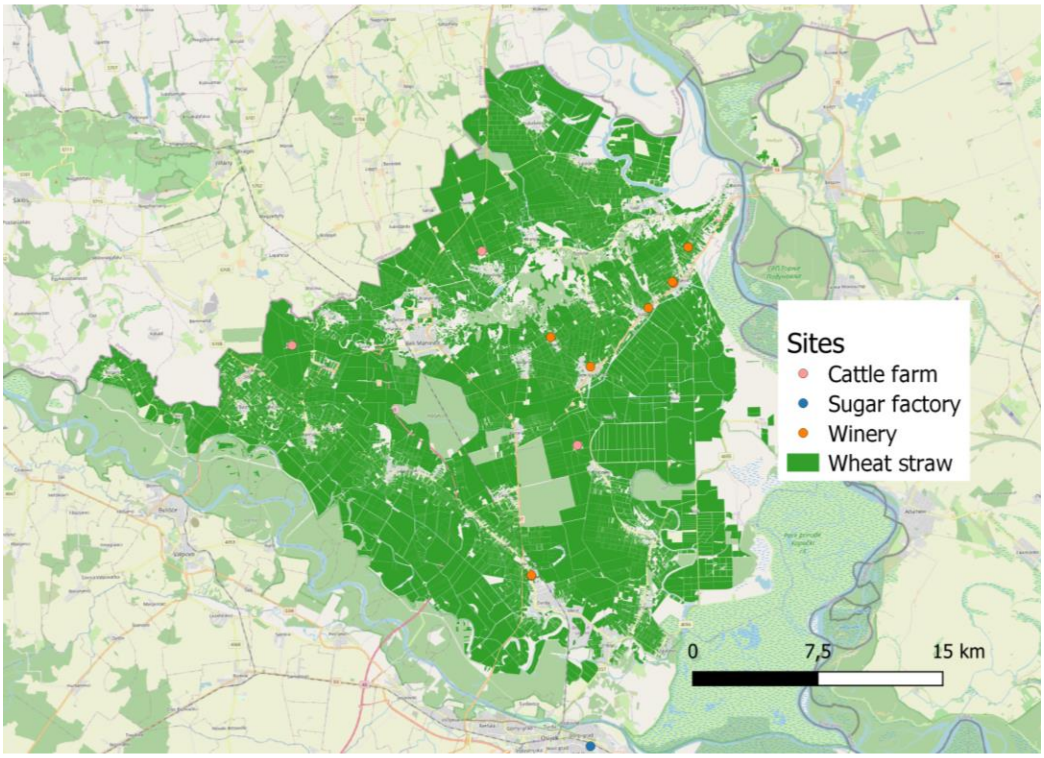


Figure 3: Case study sites and agricultural land

For the feedstock cost, the input data from Table 3 were used.

Table 3 Specific feedstock cost

Feedstock	Cattle manure	Grape pressings	Sugar beet pulp	Wheat straw
Cost (€/t)	5	5	25 [39]	25 [40]

5. Results

According to the method provided in the section above, the biogas potential from wheat straw, manure, grape pressings, and sugar beet pulp was determined for the farms, wineries, sugar factories, and wheat straw collection sites. The spatial distribution of biogas potential is presented in Figure 4.

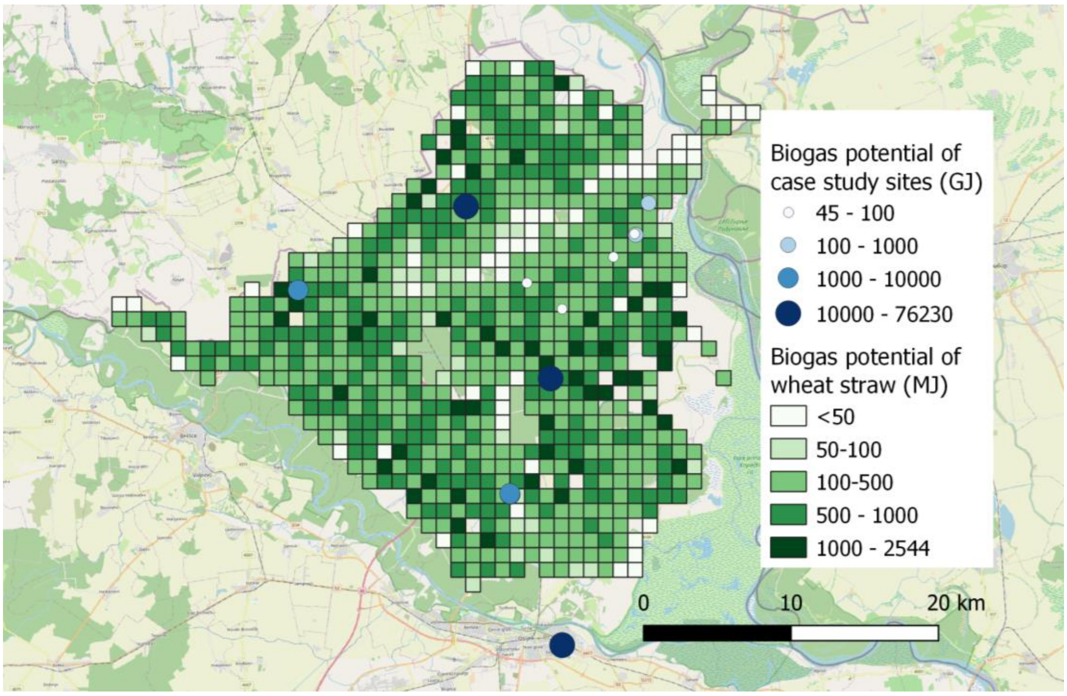


Figure 4: Biogas potential

The optimal location for the biogas site was defined based on the locations of feedstock suppliers with the highest biogas potential. In accordance with the optimal location, the transport distance between industry/farm/collection sites and the optimal location of the biogas site was calculated as represented in Figure 5.

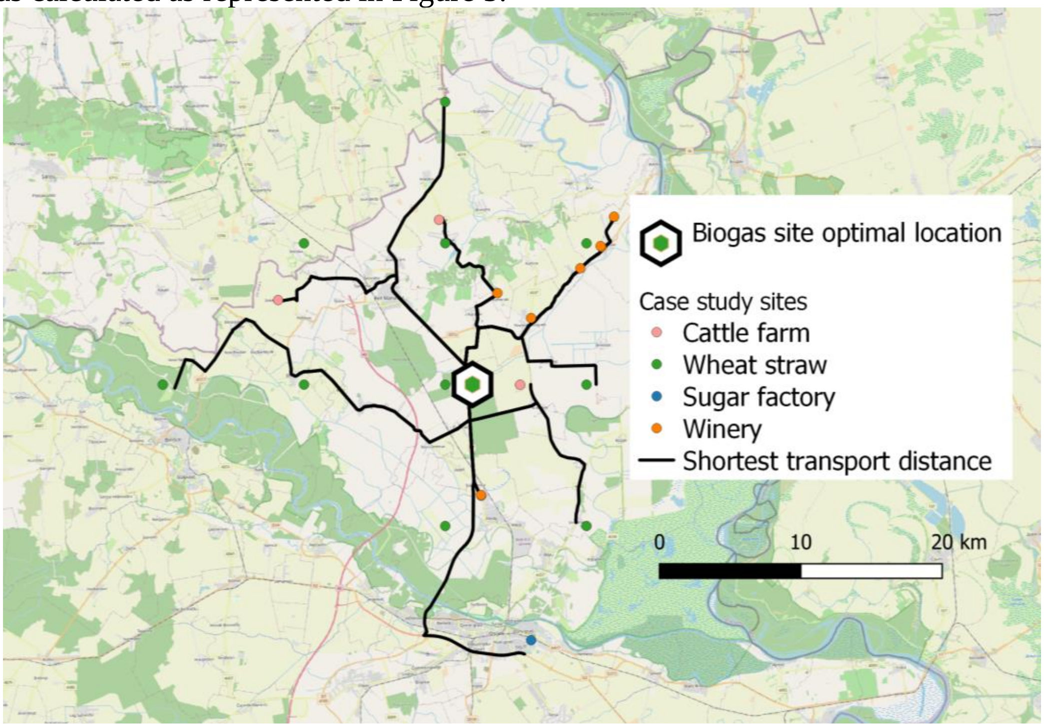


Figure 5 Transport road route and optimal biogas site location

In accordance with the resulting GIS layer (Figure 5), the P-graph representation and the maximal structure are developed. The data set obtained with QGIS includes biogas potential and transport distance for 18 feedstock-providing sites. Table 4 lists sites included in the P-graph representation and the transport distance between each feedstock-providing site and biogas site.

Table 4: P-graph legend and transport distance

Site	Cattle farm				Winery				
Abbreviation	CF1	CF2	CF3	CF4	W1	W2	W3	W4	W5
Distance (km)	9	16	21	8	8	8	17	15	19
Site	Sugar factory	Wheat straw collection site							
Abbreviation	SF	WS1	WS2	WS3	WS4	WS5	WS6	WS7	WS8
Distance (km)	26	32	17	18	24	14	1	12	16

The P-graph representation of the maximal structure of the case study is represented in

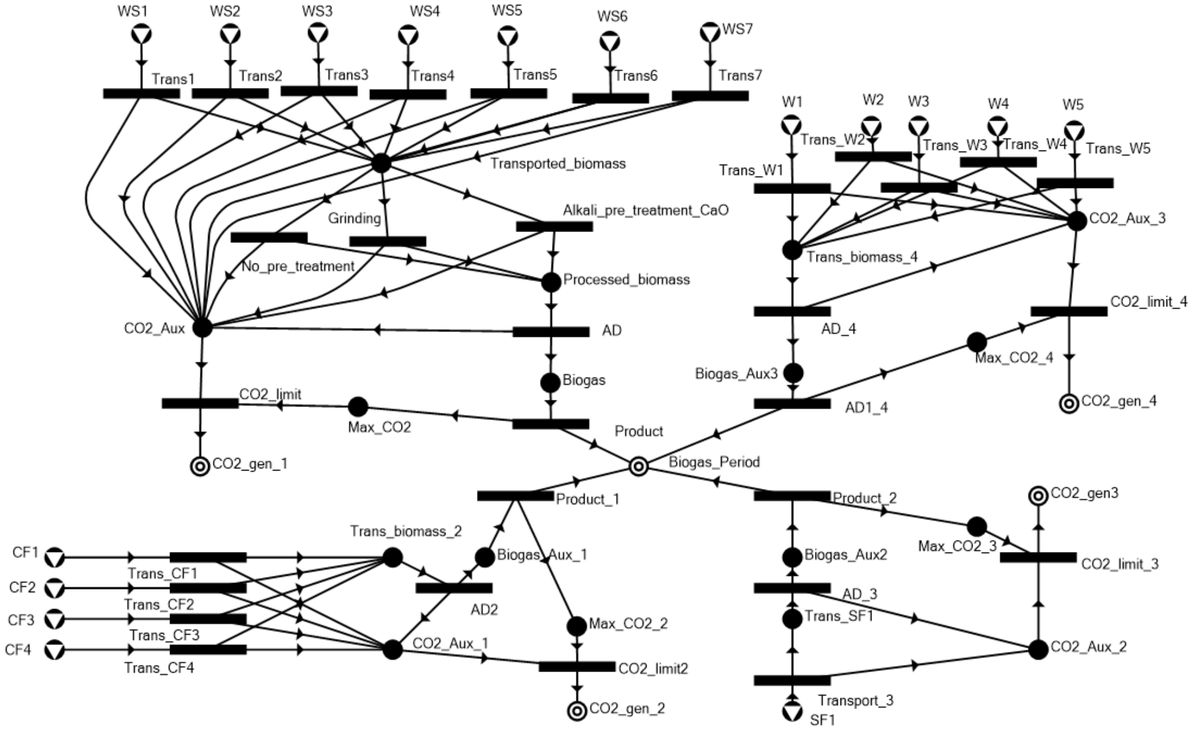


Figure 6. As described in the method, the material nodes are represented by raw materials (manure, industrial by-products and agricultural residues) and the final product (biogas). Operating unit nodes are representing anaerobic digestors.

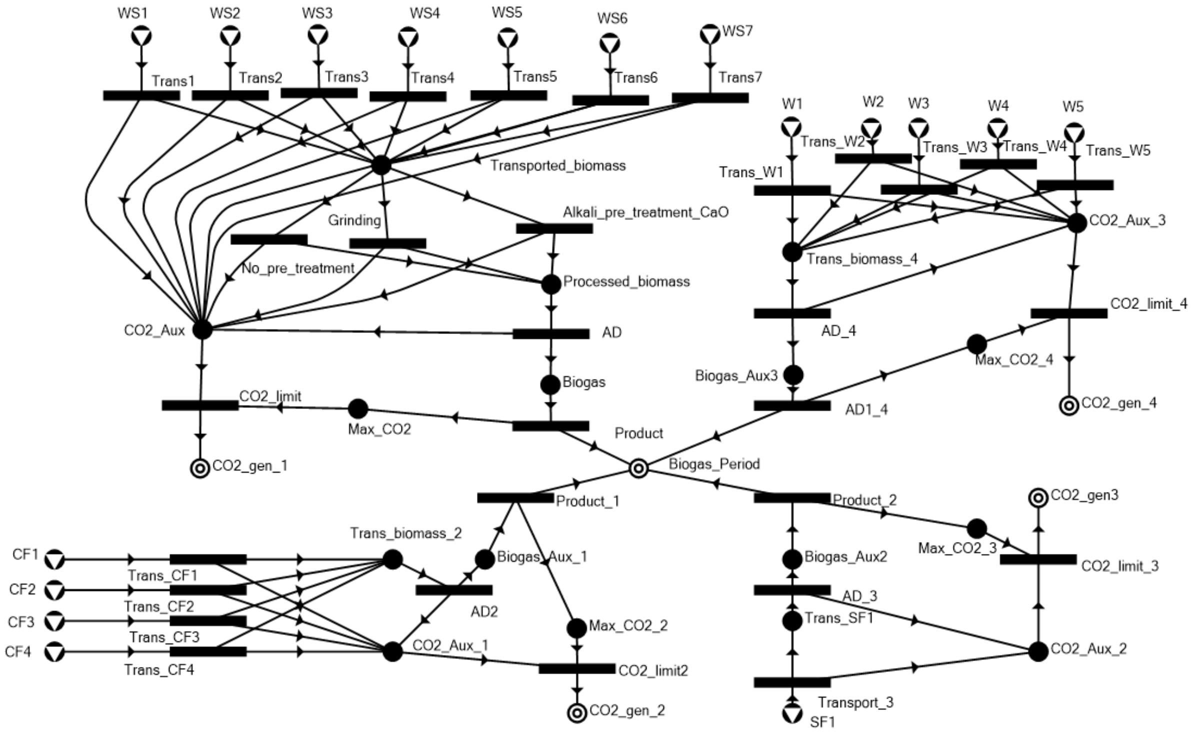


Figure 6: P-graph representations of the maximal structure of the case study

Four groups of feedstock providers can be recognised in the maximal structure. Those are wheat straw collection sites (upper left corner), cattle farms (bottom left corner), sugar factory (bottom right corner) and wineries (upper right corner). As can be seen in

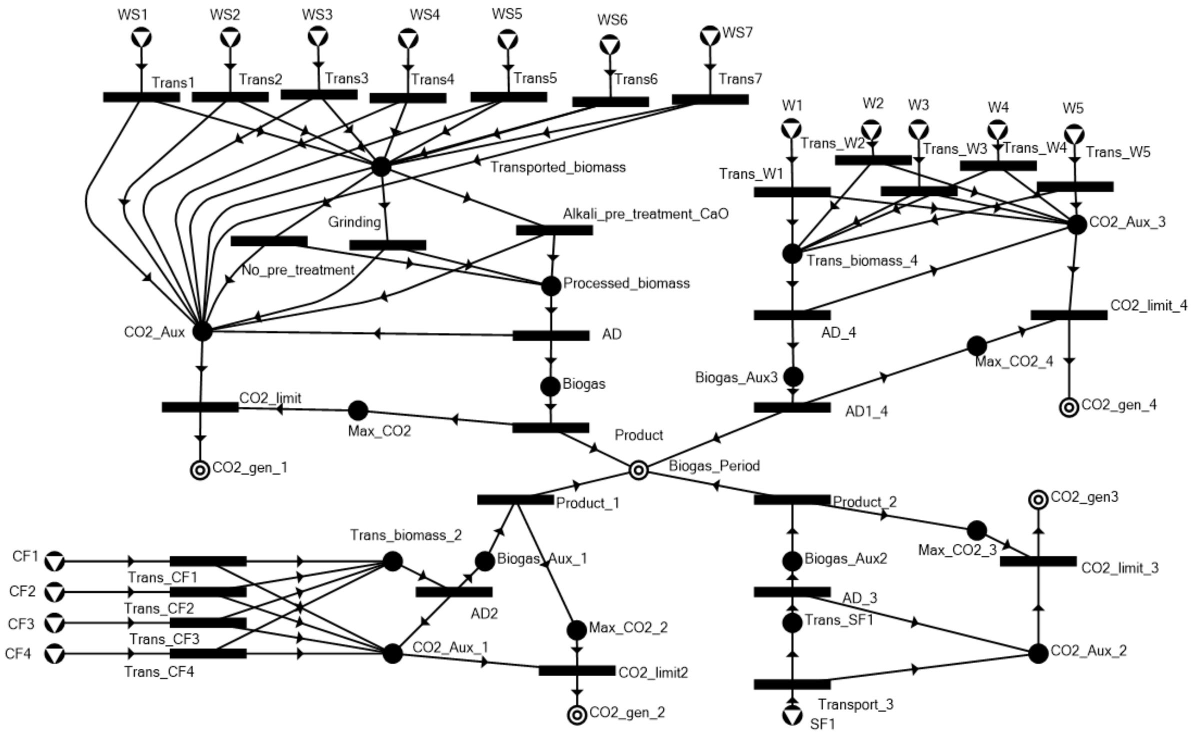


Figure 6, all biomass streams lead to one final product (biogas), as this paper considers one site as a biogas production site, while CO_2 streams are set to define CO_2 generated by each feedstock group.

As described in the Method section, based on maximal structure, all feasible structures were defined. For the optimal solution, the objective was to minimise the cost of the biomass supply network and to limit the associated GHG emissions below the given threshold. This was done for two cases, both having the required biogas production of 120,000 GJ/y, but in the first case the optimisation is performed on the annual level, while in the second case, the multiperiod approach was implemented to include the seasonal variation of feedstock supply. The biogas production of 120,000 GJ corresponds to the production of anaerobic digestors which deliver biogas to CHP with 1.5 MW_{el}.
The optimal structure for annual biogas production of 120,000 GJ/y is presented in Figure 7.

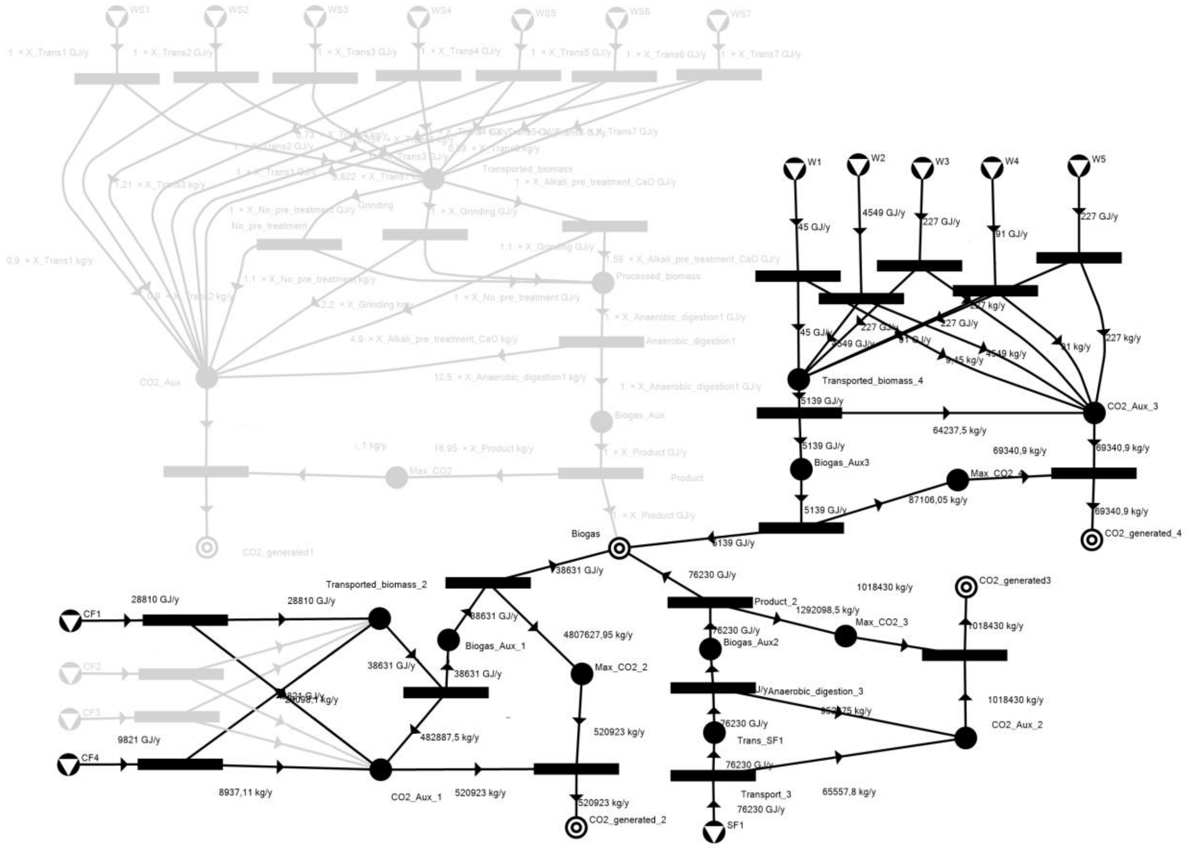


Figure 7: The optimal structure for annual biogas production of 120,000 GJ/y

The cost of the biomass supply network (including feedstock and transport costs) is 292,016 EUR. This equals 2.43 EUR/GJ. The data from the optimal structure are presented in Table 5, to improve the visibility of the numbers presented in Figure 7.

Table 5 The optimal structure for annual biogas production of 120 000 GJ/y

Abbreviation	CF1	CF4	SF1	W1	W2	W3	W4	W5
Delivered feedstock (GJ)	28,810	9,821	76,230	45	4,549	227	91	227

As can be seen from the results, the model first selects the wineries and sugar factory, after that cattle farms and finally wheat straw. It is interesting to see that the model would select sugar beet pulp prior to the manure from the further farms, as feedstock cost is lower for manure. The reason for this selection is the relatively low bulk density of the biogas potential of manure, compared to the bulk density of a biogas potential of sugar beet pulp. Hence, higher transport may surpass the difference in feedstock cost.

GHG emissions linked to each stage of the production and use of biogas are assessed. Contribution to GHG emission generation is presented in Table 6 by each feedstock group, as well as the GHG savings compared to the fossil fuel comparators (for both heat and electricity).

Table 6 GHG emission generation- case 1 (biogas production 120,000 GJ)

Feedstock	**Wheat straw**	**Manure**	**Sugar beet pulp**	**Grape pressings**
Biogas produced from feedstock (GJ)	-	38,631	76,230	5,139
Associated GHG emissions (kg CO_2eq)	-	520,923	1,018,430	68,769
Associated GHG emission savings (kg CO_2e)	-	4,143,757	-	-
Neto GHG emissions	-	-3,622,834	1,018,430	68,769
Specific GHG emissions (kg CO_2eq/GJ)	-	-93.8	13.36	14
GHG savings compared to fossil fuel comparator for heat, Case 1, closed digestate	-	210.70%	84.25%	83.49%
GHG savings compared to fossil fuel comparator for electricity, Case 1, closed digestate	-	165.35%	90.70%	90.26%

As can be seen from the specific GHG emissions presented in Table 6, GHG emissions are below the threshold (which is set to 16.95 kg CO_2/GJ biogas), which can be considered as a confirmation that the developed model presented as feasible structures only those which fulfil GHG savings.

Integration of GHG emissions limitation, in line with Directive 2018/2001, represents an added value and a step beyond the current state of the art in P-graph optimisation. To enhance the understanding of GHG emission limitation and improve the visibility of Figure 7, part of the PNS network (for the case of optimal structure) whose function is to limit GHG emission is presented enlarged in Figure 8.

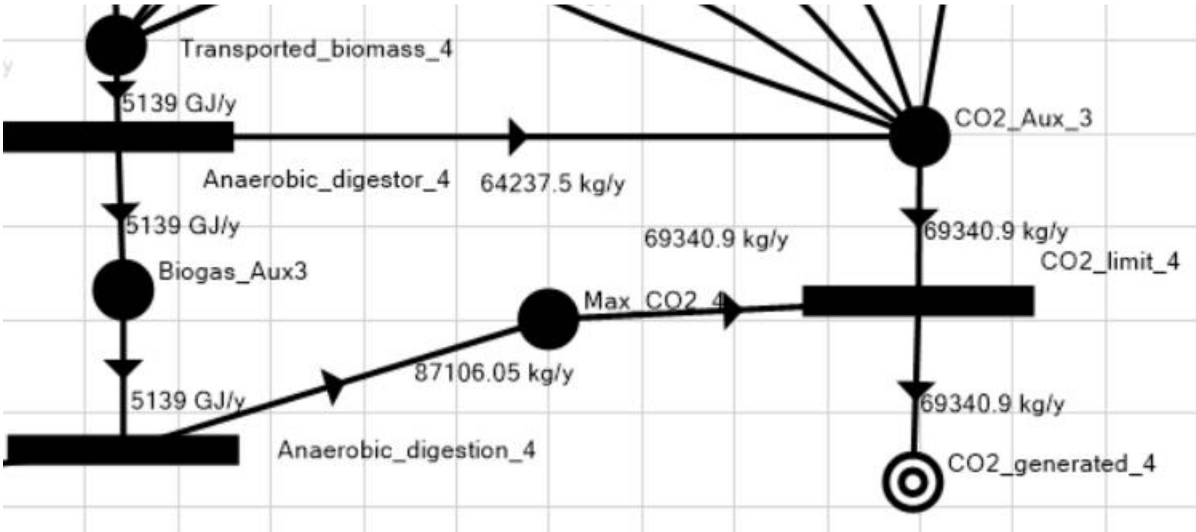


Figure 8 GHG emission limitation in PNS network (optimal structure)

For the given example, the selected feedstock group is grape pressings. CO_2_Aux is an auxiliary node represented as an interim product, whose main objective is to summarise GHG emissions that occur in biogas production and use lifecycle. This value equals 69 340.9 kg/y in Figure 8. The obtained value is then compared with the maximal allowed GHG emissions. The maximum allowed GHG emissions are calculated based on the biogas generation (GJ), obtained from the auxiliary node Biogas_Aux, which is multiplied by the specific limitation of GHG emissions per GJ of biogas. This value equals 87106.05 kg/y in Figure 8. Those two values meet at note Max_CO_2. For the case where GHG emissions that occur in a biogas lifecycle are higher than the maximum values, the model makes a new iteration and searches for a new economically optimal structure whose GHG emissions are below the given limit.

To enhance the accuracy of the results, the seasonal aspect of biomass production was integrated into the model. To integrate this, a year was divided into several periods, each representing certain months. The list of periods, corresponding months and generated types of biomass in a specific period is listed in *Table 7*.

Table 7 The list of periods with corresponding biomass generation

Period/ month	**1/ January-May**	**2/ June-July**	**3/ August**	**4/ September**	**5/ October-November**	**6/ December**
Wheat straw	NO	YES	NO	NO	NO	NO
Manure	YES	YES	YES	YES	YES	YES
Grape pressings	NO	NO	NO	YES	NO	NO
Sugar beet pulp	NO	NO	NO	YES	YES	NO

For each considered period, the assumption is used that biomass available for biogas production is the one generated in the specific period (months). There is a threefold reason for this. The first one is that some of the considered feedstock can not be stored for a longer period of time, due to potential changes in feedstock conditions, which could result in the adverse performance of biogas production. The second is that seasonal feedstock storage may result in additional methane emissions generated during the storage period, which could result in exceeding the

threshold of GHG emissions, due to the high global warming potential of methane. The final one is the cost of the investment and maintenance of the seasonal storage.
For the considered biogas production, in case the required biogas production exceeds the biogas potential contained in the biomass, the assumption was used that this gap will be covered with the wheat straw, due to favourable storage properties. Required biogas production, for the case of the annual production of 120, 000 GJ is presented in Table 8.

Table 8 Required biogas production in the concerned periods

Period/ month	**1/ January-May**	**2/ June-July**	**3/ August**	**4/ September**	**5/ October-November**	**6/ December**
Required biogas production (GJ)	55,848	19,029	0	11,096	22,561	11,466

As can be concluded from Table 8, annual maintenance of the biogas site is scheduled for August. The optimal structure for each period is presented in Figure 9, Figure 10, Figure 11, Figure 12 and Figure 13.

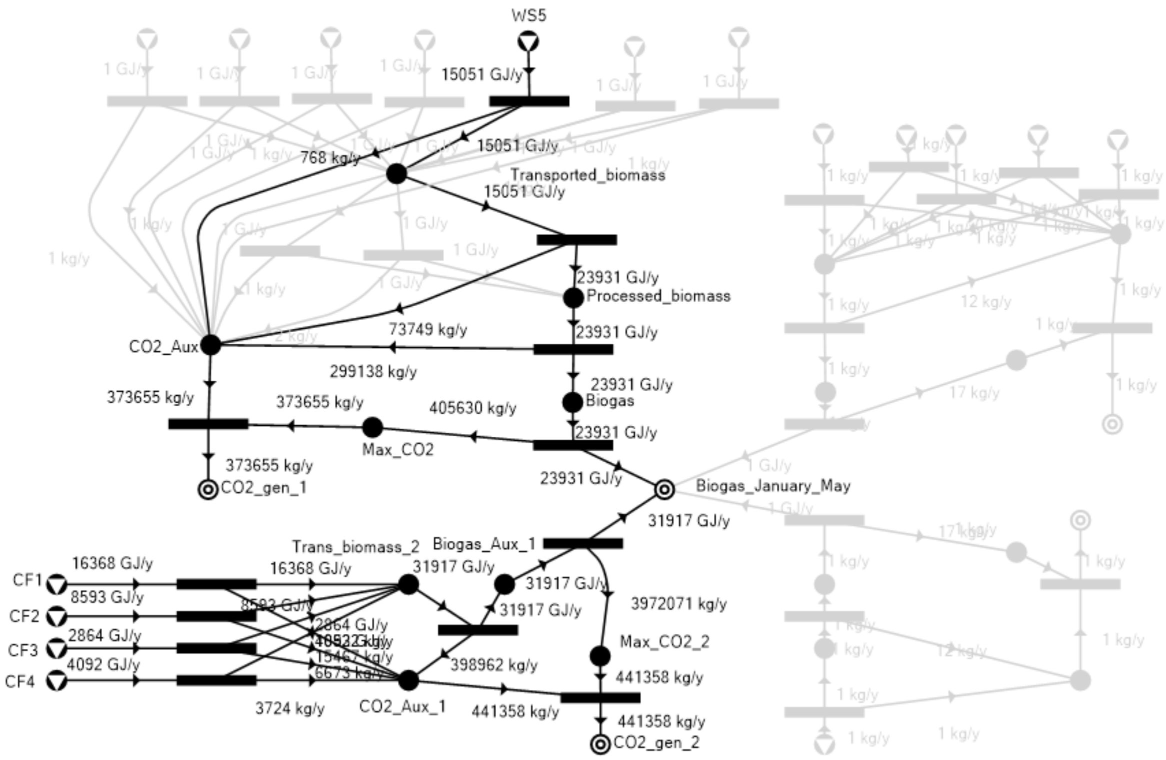


Figure 9 Optimal structure of biogas production from January until May

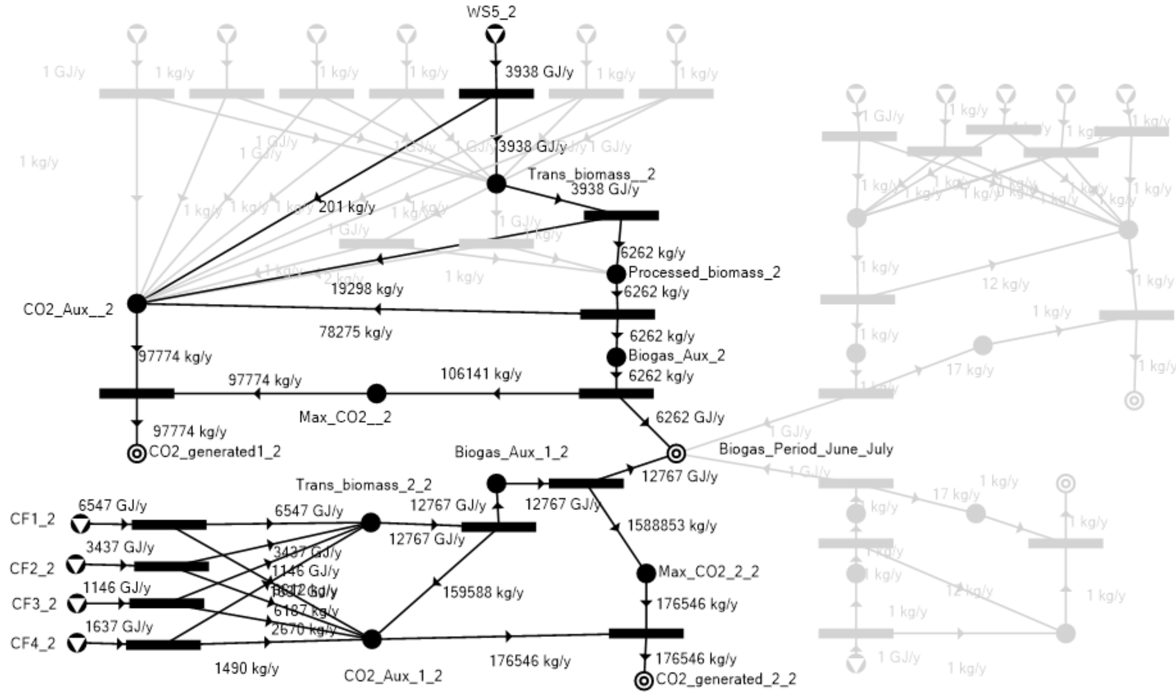


Figure 10 Optimal structure of biogas production in June and July

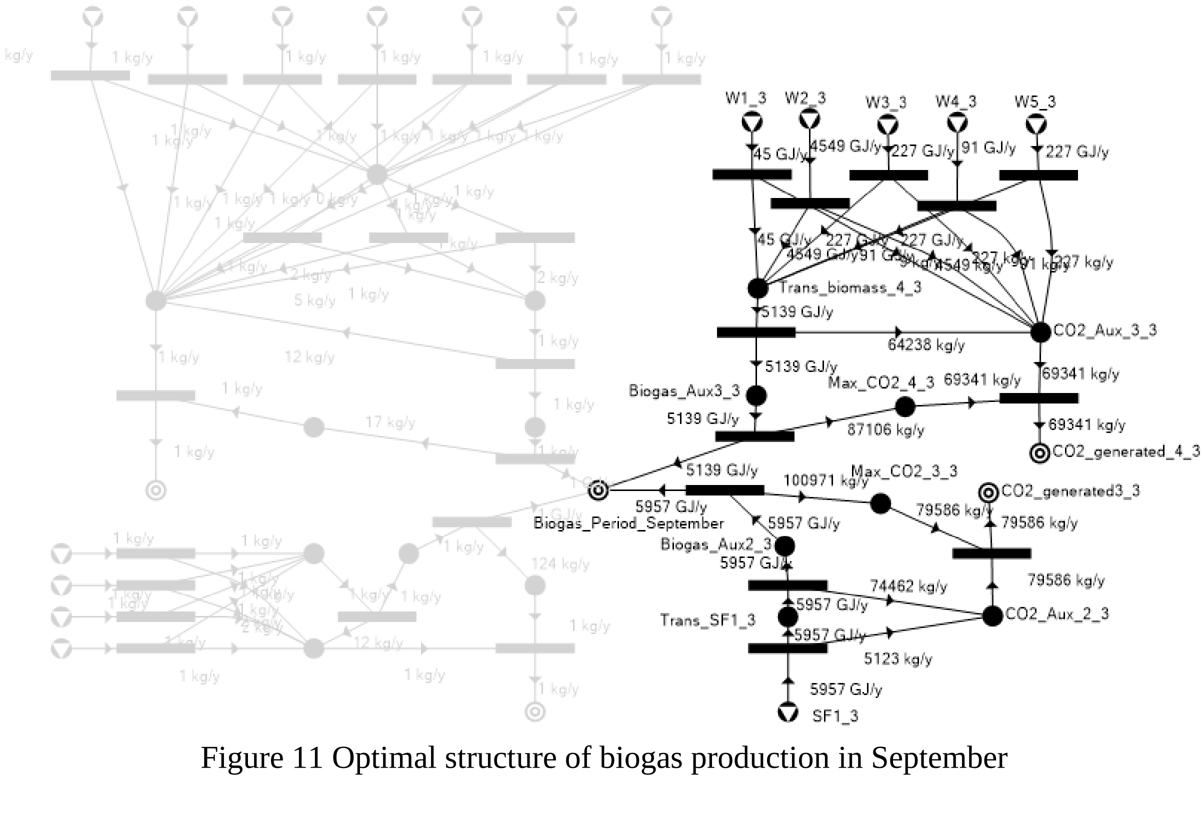


Figure 11 Optimal structure of biogas production in September

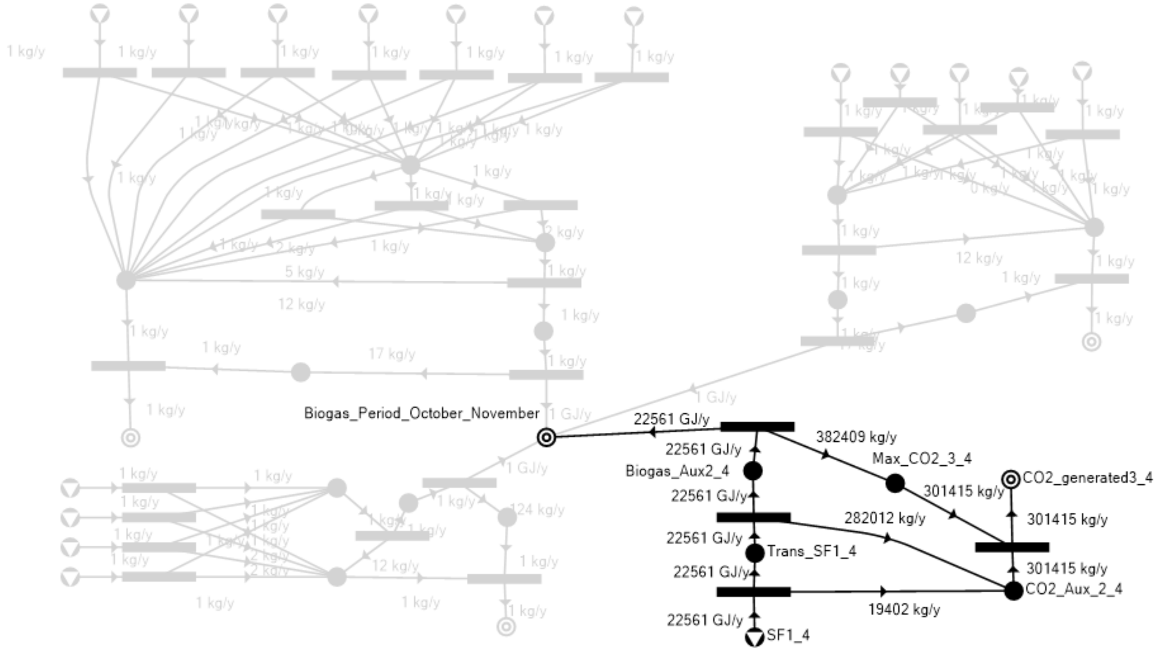


Figure 12 Optimal structure of biogas production in November and October

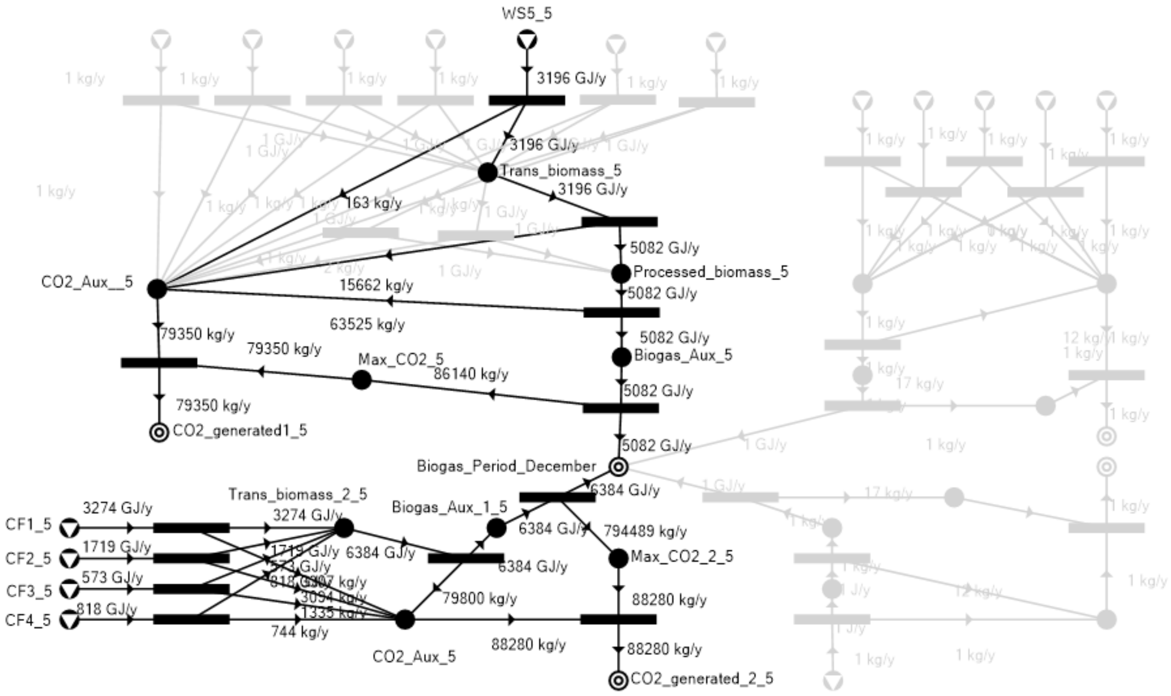


Figure 13 Optimal structure of biogas production in December

The values on delivered feedstock presented in optimal structures (Figure 9-Figure 13) provided for each period are shown in Table 9, to improve the visibility of the numbers.

Table 9 The summary of optimal structures determined for each considered period

	Delivered feedstock (GJ)						
	January-May	**June-July**	**August**	**September**	**October-November**	**December**	**Total**

WS5	15,051	3,938	-	-	-	3,196	22,185
CF1	16,368	6,547	-	-	-	3,274	26,189
CF2	8,593	3,437	-	-	-	1,719	13,749
CF3	2,864	1,146	-	-	-	573	4,583
CF4	4,092	1,637				818	6,547
SF1	-	-	-	5,957	22,561	-	28,518
W1	-	-	-	45	-	-	45
W2	-	-	-	4,549	-	-	4,549
W3	-	-	-	227	-	-	227
W4	-	-	-	91	-	-	91
W5	-	-	-	227	-	-	227

The optimal structures of periods from January-May, June-July and December are very similar. Although in the second period, there is a significant biogas potential of the wheat straw sites, the model will select manure, even from further farms. The total values of delivered feedstocks significantly differ from the first case where the optimal structure was defined on an annual basis. Compared to the first case where the model did not commit the wheat straw sites, in the second case wheat straw contributes to 18.3 % of biogas production. Furthermore, in the second case, the contribution of manure is significantly (34%) higher, even from the more distant farms, which would result in higher transport costs. On the other hand, most of the potential of sugar beet pulp was untapped in the second case (63%). Those chances negatively affected the total cost of the biomass supply network, which equals 733,684 € (6.11 €/GJ biogas). The increase in biomass supply cost is, to some extent, an expected result, as during the periods in which feedstock with high energy density and low prices were not available, the model committed the sites with higher transport distances and/or sites with higher feedstock and processing costs. Furthermore, although the multi-period approach resulted in less favourable results in terms of cost, it can be stated that this approach results in more accurate results and provides insights into the sensitivity of the cost of biomass supply network for the case where economically favourable feedstocks are not available, since they are being generated in a very short period of time during the year.

As for the first case, the contribution to GHG emission generation, as well as GHG savings compared to fossil fuel comparators, is presented in Table 10 by each feedstock group.

Table 10 GHG emission generation

Feedstock	**Wheat straw**	**Manure**	**Sugar beet pulp**	**Grape pressings**
Biogas produced from feedstock (GJ)	35,275	51,068	28,518	5,139
Associated GHG emissions (kg CO_2eq)	550,778	706,184	381,001	69,341
Associated GHG emissions savings (kg CO_2eq)	-	5,477,813	-	-
Net GHG emissions (kg CO_2eq)	550,778	-4,771,628	381,001	69,341
Specific GHG emissions (kg CO_2eq/GJ)	15.61	-93.44	13.36	13.49

GHG savings compared to fossil fuel comparator for heat, Case 1, closed digestate	89.12%	210.22%	84.25%	84.08%
GHG savings compared to fossil fuel comparator for electricity, Case 1, closed digestate	81.57%	165.06%	90.70%	90.60%

As in the first case, specific GHG emissions were below the given threshold, which can be considered as a confirmation that the model successfully limits the GHG emissions in both single-period optimisation and multi-period optimisation. It is also interesting to note that, due to the higher contribution of manure to biogas production, the net GHG emissions are significantly lower for the second case. As mentioned earlier, when defining the optimal structure, P-graph Studio defines and ranks sub-optimal structures as well. Hence, the results could be used for the development of a Pareto front that would define both the cost of the structure and the generated GHG emissions.

The developed model does not automatically prioritize the structures with the lowest GHG emissions, as it considers GHG emissions savings as constraints, not as the variable to be minimised. Although this may be considered as the limitation of the model, the minimisation of the GHG emissions was not selected as the target group of this model is the biogas industry, whose objective is commonly to fulfil the requirements given by the legislation and to minimise the cost of the biomass supply network. However, in case if biogas industry would receive some additional incentive to future reduce GHG savings, or in general decides to achieve savings higher than the given threshold, the developed model easily allows the comparison of the cost and GHG emissions of optimal and sub-optimal structures, thus enabling efficient assessment of trade-offs. Based on the obtained results, it can be considered that for the case of the minimisation of GHG emissions, the model would prioritize manure as the feedstock (even from more allocated farms), due to the high GHG emission savings resulting from the improved manure management.

As the developed model determined economically optimal and sub-optimal structures, simultaneously limiting GHG emissions in both single-period optimisation and multi-period optimisation, it can be stated that the hypothesis of this work is confirmed.

6. Conclusions

This paper presents a novel multi-period P-graph-based model for optimizing biomass supply networks, which goes a step further in integrating environmental constraints in the PNS network. The model developed in this work enables the economical optimisation of a biomass supply network, while simultaneously limiting the CO_2 emissions that the biomass supply network can generate, in line with the EU Directive 2018/2001 requirements. Furthermore, through the extension of the model to multi-periods, the developed model considers the seasonality of biomass supply during the year. The study also demonstrates the linkage between GIS mapping and route assessment with the graph theory approach for biomass supply chain optimization. The presented model was applied to the biogas production from agricultural residues, livestock and industrial by-products, including wheat straw, sugar beet pulp, grape pressings and manure.

The model was tested in a case study of a rural area in Osijek-Baranja county, which resulted in the determination of optimal and sub-optimal economical structures that fulfil GHG savings requirements. The results indicate that the model prioritizes feedstock from wineries and sugar factories, followed by cattle farms and wheat straw. Moreover, the specific cost of the biomass supply network (feedstock, processing and transport) was calculated to be 2.62 EUR/GJ in the case of optimisation on an annual level and 5.1 EUR/GJ in the case of multi-period optimisation, due to higher demand feedstocks with higher transportation, processing and/or feedstock cost. Overall, the paper confirms the hypothesis that an economically optimal residual biomass supply network for biogas production that meets sustainability and greenhouse gas emissions saving criteria can be determined with the P-graph approach. Future research could consider expanding the scope of the analysis by incorporating a wider range of feedstock varieties.

Acknowledgements

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List of Abbreviations

ABB- Accelerated Branch and Bound
AD-Anaerobic digestion
CHP- Combined heat and power
EC-European Commission
EU- European Union
GIS -Geographic Information System
GHG-Greenhouse Gas
ILUC -Indirect Land-Use Change
MILP-Mixed-Integer Linear Programming
MSG- Maximal Structure Generation
PNS -Process-Network Synthesis
SSG-Solution structure generation

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