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Estimating the Optimal Location for the Storage of Pellet Surplus

Andrzej Bochniak [1] and Monika Stoma [2,*]

[1] Department of Applied Mathematics and Computer Science, University of Life Sciences, Głęboka 28, 20-612 Lublin, Poland; andrzej.bochniak@up.lublin.pl
[2] Department of Power Engineering and Transportation, University of Life Sciences, Głęboka 28, 20-612 Lublin, Poland
* Correspondence: monika.stoma@up.lublin.pl

Abstract: This paper deals with the problem of managing the surplus that arises during the seasonal production of pellets, which will be sold in the period of increased demand. Dijkstra's algorithm is used in issues connected with finding a new storage place with a view of the optimisation of the transport costs of pellets produced by a company in 18 different towns in the Lubelskie Voivodeship in Poland. The most optimal location for the new pellet storage site has been determined, for which the total length of the traveled routes is the shortest, taking into account the actual shares of individual plants in the total production. The construction of the graph with the shortest paths was made on the basis of the existing network of available transport roads, and the nodes of the graph were their intersections. The most advantageous storage location of pellets was identified by the calculation the total transport cost using a minimum-cost tree of shortest paths. Based on the estimated transport assumptions, the lowest total cost of transport from all 18 plants was 3092.0 (km), which corresponds to an average distance to production plants of 89.7 km and 61.7 km to estimated selling distribution. The new storage point is suggested near the town of Piaski. Average cost of travel for all trees obtained for existing plant locations and subsequent distribution to points of sale was 4113.7 (km), while standard deviation 735.2 (km). Additionally, a relative increase in costs was estimated in the case of selecting other locations. Using spatial interpolation and geoprocessing tools, a map—showing the increase in pellet transport costs in relation to the most optimal solution—was developed. The constructed map allows for a better analysis of cost increases than a single point. It was stated that the increase in transport costs does not exceed 10% of lowest cost for 17.6% area of studied area. It was found that the most convenient area is shifted to the south of the voivodship and improperly adopted storage location can increase transport costs by up to 75%.

Keywords: biomass storage; Dijkstra's algorithm; minimizing transportation cost; geospatial analysis

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1. Introduction

Biomass may be used as raw material in the forest product industry and in the chemical industry, but also is used for biofuel production and heat/power production [1]. This is all the more important as the production of electricity based on wood pellets (solid biomass) can increasingly contribute to the achievement of climate goals. At the same time, care should be taken to aim at low-emission in various areas of the economy while maintaining growth economic and—with regard to electricity production—maintaining a sufficient generation capacity [2].

Wood pellets can be produced from several types of forest raw materials, from industry residues, forestry management residues, or pulp or timber grade pulpwood. Large-scale production of pellets is often designed with a mix of different raw materials, depending on local availability and cost.

Poland has a number of renewable energy resources, including energy from biomass. It may include raw materials of plant and animal origin that are biodegradable and come from agriculture and agro-food industry. Forest biomass, in the form of briquettes, pellets, wood chips, and bales, among others, is the basic solid fuel from biomass. Biomass is extremely varied in terms of state of matter, moisture content, calorific value, and specific weight. This raw material has a large volume and water content, therefore transport and storage of biomass is problematic [3].

In Poland, every region has a different energy potential. However, all regions have a problem with the optimisation of the process of obtaining biomass and its use for energy purposes, and hence with its transport. During transport, biomass may be damaged or its physical and chemical properties may be changed. Pellets may serve as an example—under the influence of moisture, their energy value is reduced, and their combustion deteriorates. Moreover, obtaining biomass is often difficult due to the dispersed nature of its availability Therefore, any process connected with the transport and storage has to be well thought-out and designed due to the expenses incurred. By using appropriate methods of storage and transport, the pellets can be prevented from uptake water by using sealed packaging or stored in constant conditions.

Determination of an appropriate and the shortest routes to transport pellets is a serious problem that distributors of this type of biomass face. When speed on the designated route and quality of the pellets delivered to a customer are important, the travel route has to be properly planned, and a storage space which is close to all users has to be designated. It should be remembered that, on the one hand, biomass logistics includes a number of cooperating processes, and on the other that each type of biomass requires a different logistic process, and raises other problems and requirements related to transport, storage, or delivery which should be taken into account when designing effective logistics systems

Various types of costs should also be taken into account, as both commercial and service activities are a key element of sustainable development due to their contribution to the productivity of natural and human resources although they also generate many positive benefits for the market, society, economy, and the environment. However, they also entail some negative problems [4]. Both aspects are particularly relevant to transport, which largely contributes to the economic development of societies, but is also responsible for negative impacts on the climate, the environment, and human health. These negative effects can occur both at the local level, e.g., air pollution or environmental degradation due to generated freight movements, and at the global level, e.g., climate change [5]. These effects can be assessed by determining the value of externalities or external costs, as each transport company, in connection with the cargo transport process carried out, generates two types of costs—internal costs (own costs and infrastructure costs) and social costs of transport, also referred to as external costs (environmental costs, e.g., pollution, noise, and costs related to congestion and accidents).

Internal costs include the operational-private costs of transport and the time costs of goods in transit [6]. These include, firstly, amortisation (of motor vehicles and other fixed assets), consumption of materials and energy (fuel consumption, consumption of lubricants and oils, and tyre wear), external services (operation of repair and service facilities), salaries, social security, taxes, and fees and other costs [7]. Own costs of an enterprise providing transport services depend on many different factors, the most important of which are: type of cargo, type and condition of rolling stock, direction and distance of transport, degree of use of rolling stock, condition of infrastructure, employment, weather conditions, and topography [8]. According to Irannezhad and team [4], internal transport costs mainly include operating costs dependent on time and distance and fixed cost of vehicles.

External costs are the monetary valuation of externalities; they are side effects of transportation [5]. These include the costs of social and environmental impacts, such as the aforementioned local and global air pollution (impact of exhaust gases on human health and the environment—lorries that collect and distribute typically burn diesel fuel and cause air pollution, the individual components of which can cause local damage to surrounding buildings, green spaces, and human health), congestion costs (trucks tend to run in densely urbanized and/or industrialized areas. They may experience congestion and the resulting delivery delays. However, they can also cause delays for other vehicles, the costs of which are counted as externalities reflecting the loss of time of transport users due to congestion, extension of transport time, increase in fuel costs, etc.), costs related to accidents in transport (damage and property losses to the transport company and third parties, in addition to the loss of life and injuries of the persons affected), costs related to noise (generated, among others, by heavy goods vehicles involved in the collection and distribution of loads; unacceptable limits cause irritation and, if persistent, may cause a decrease in efficiency and have adverse health effects), and the cost of road infrastructure [6]. It should also be added that internalizing external costs allows pricing at the right social cost, leading to an efficient allocation of resources [5].

The external costs of transport are quite thoroughly researched, and the results have been presented in the extensive literature on the subject, including in the following works: [9–13].

With regard to the analysis of wood pellet delivery costs, attention should be paid to the studies by Miao et al. [14], which present an overview of the overall costs and processes involved with biomass feedstock harvesting, processing, and delivery to biofuel plants. Other works that include cost analysis of supply chain elements include research carried out by Ehrig and his team [15] or Boukherroub [16].

With a view to reducing the emission of environmentally harmful substances such as greenhouse gases and other particles and, in addition, due to the lower calorific value of pellets in relation to fossil fuels (per mass unit), in order to make the use of pellets profitable, the transport distances should not be too large. In the case of trucks, transport over short distances up to 100 km is suggested [17]. As shown by other authors from different countries, the route of biomass transport should be less than 1200 km [18]. Above this distance, the emissions of harmful substances from transport start to exceed that from the use of traditional energy sources.

It should be added that transport is a dynamically developing field; according to the forecasts, by 2050 at least 25 million km of new roads are expected worldwide, which means a 60% increase in the total length of roads compared to 2010 [19]. However, this is associated with the aforementioned costs and negative aspects, especially in relation to the environment—as global sources report, global greenhouse gas (GHG) emissions from the transport sector have more than doubled since 1971; moreover, they are growing faster than those of any other end-use energy sector, and more than three-quarters of this increase comes from road vehicles [20].

Therefore, the main goal of logistics management is to minimize the total cost of transport and proper organization of the supply chain. It depends on a given means of transport, transported products, choice of roads and connections, transport technology, duration of transport (the entire process), the method of loading, storage options, as well as economic, legal, or environmental conditions. However, in the case of a specific product, such as pellets, the costs of the supply chain are largely dependent on the specific conditions of the supply chain, including the regional availability of the raw material, which varies depending on the location of the pellet production plants [2]. Hence, it is extremely important to properly optimize the costs associated with the broadly understood process of transport and forwarding of goods, so that they do not exceed the profits related to the sale or provision of services.

The logistic system of biomass supplies should therefore be designed individually for individual solutions—at the level of communes or their associations (e.g., poviats). It should also be remembered that sometimes distances from the sources of raw materials, locations of energy production sites, or other conditions may cause the so-called space–time gap. Its existence requires further improvement of logistic processes consisting in the delivery of biomass with appropriate parameters, in the right quantity, in the right condition, in the right place, at the right time, for the right customer, at the right cost.

Choosing an appropriate storage site of pellets may be determined using various methods, including the construction of a minimum-cost tree with the use of Dijkstra's algorithm. It is used to determine the shortest distance of all connections.

Therefore, the aim of the study is to find an optimal storage location of pellet surplus in the Lubelskie Voivodeship, which in turn will lead to a reduction in transport costs of this type of biomass. It also aims to present the essence, possibilities, and advantages that stem from the use of Dijkstra's algorithm in this kind of problem.

2. Materials and Methods

2.1. Data

The research was conducted in one of the voivodeships of central and eastern Poland—the Lubelskie Voivodeship. Due to its area of 25,122 km^2 it is the 3rd largest voivodeship of the country. However, it is a sparsely populated area characterised by a low level of urbanisation; it also has the most sparse city network in Poland. On the other hand, compared to other economic sectors, it is characterised by the highest rates in the contribution of agricultural production in the country. The agricultural character of the voivodeship (agricultural area constitutes 63% of the voivodeship area), diverse agricultural production, as well as a large forest area (23% of the whole voivodeship area) result in biomass being the most accessible source of energy, and the possibilities for its use open up in almost the whole voivodeship.

The analysis of the determination of the biomass storage site was carried out on the example of a certain company, which distributes pellets in the Lubelskie Voivodeship in Poland. The company has 18 sites for obtaining chips (from which pellets are produced), which also serve as storage facilities in the Lubelskie Voivodeship. The company plans to build an additional storage of pellets in the Lubelskie Voivodeship, which would serve as a storage point for seasonal surpluses for existing plants and to contribute to the reduction in transport costs of biomass. The distances for a single transport do not exceed 220 km, assuming transport from the most distant parts of the voivodeship or, respectively, 110 km to the center. The conducted analyses also took into account the estimated sales of the company in percentage terms.

The spatial data processing and visualization was made in the QGIS program ver. 3.16 [21]. Publicly available free vector layers of administrative borders for Poland and the Lubelskie Voivodeship and poviats were obtained from the website of Head Office of Geodesy and Cartography (GUGiK) [22]. Data on the main road network in the voivodeship was downloaded using the Quick OSM plugin.

2.2. Dijkstra's Algorithm

Graph theory and algorithms created for them are widely used in many areas of life. One of the main uses is finding the shortest paths between given points of a system, as well as control of the flow of data or goods in a studied system. Dijkstra's algorithm, used in this research, is a popular and well-known algorithm used for finding the shortest paths between vertices of the graph. The literature presents its use in ICT in designing IT networks to minimize the cost of its creation and to determine optimal locations of its substations [23]. The algorithm is also used in designing a network of routes for vehicles and the selection of the location of a distribution center [24,25]. It may be also used in city transit in examining the accessibility of specific locations in the public transport network [26]. Due to its popularity, the algorithm also has available visualizations useful in the effective learning of its operation, e.g., in e-learning [27]. However, in the case of larger data sets, when a network includes thousands of points, the use of this algorithm may prove to be ineffective. Due to this, certain modifications are used to improve the efficiency of the algorithm [28,29], or other heuristic or genetic algorithms are used [30]. In the case of uncertainties in the issue while modifying the algorithm, fuzzy set theory may be applied [31]. The literature also includes the reduction in costs in the division of a system into several subsets. It is used, among others, in the military, where the algorithm is considered in planning military maneuvers and regrouping several facilities [32,33]. Thanks to its general character, it may also be used in the problem of finding optimal storage locations of biomass and assessing the cost of its transport.

The search of the best location of a place which may be used for storage of pellets was based on construction of the minimum cost tree consisting of shortest paths. In graph theory, a graph is a pair $G = (V, E)$, where V is a set of vertices (nodes) and E is a set of edges (arches). An edge is an ordered pair of vertices (v_i, v_j) such that $v_i, v_j \in V$. In practice, weighted graphs are generally used. A weighted graph is defined as a structure $G = (V, E, w)$, where weights of edges are given by a weight function w: $E \rightarrow R$ which assigns a real number to each edge. Most frequently, it gives a positive real value, which is the cost of moving directly from one vertex u to another v, i.e., w: $E \rightarrow [0, \infty)$. For simplicity, the cost of an edge can be thought of as the distance between those two vertices.

A tree is an undirected graph in which any two vertices are connected by exactly one path. For a given connected, undirected graph G, a spanning tree is in turn a subgraph of G which includes all its vertices and is a tree. For example, the vertices of the graph can represent cities and costs of running edges represent distances between pairs of cities connected directly by the road.

In the analyzed problem the issues connected with the shortest paths with one source in which the graph $G = (V, E)$ is given, and the $s \in V$ vertex is distinguished and called the source. Moreover, the weights of all edges of the graph are nonnegative, i.e., $w(\nu_i, \nu_j) \geq 0$. The shortest path from s to v must be found for each vertex v in the graph.

The cost of a path $p = \nu_0, \nu_1, \ldots, \nu_k$ between two vertices is the sum of costs of the edges in that path (Formula (1)).

$$w(p) = \sum_{i=1}^{k} w(\nu_{i-1}, \nu_i) \tag{1}$$

The cost δ of the shortest path from vertex u to v is defined as follows (Formula (2)):

$$\delta(u,v) = \begin{cases} min\{w(p)\} & if\ path\ p\ from\ u\ to\ v\ exists \\ \infty & elsewhere \end{cases} \tag{2}$$

The shortest path from u to v is each path p for which $w(p) = \delta(u,v)$.

One of the classic and most used algorithms for calculating the shortest path from an origin to a destination is Dijkstra's algorithm [31]. It was first enunciated by Edsger Wybe Dijkstra [34] and is one of the most used and discussed algorithms in the literature of graphs. Its temporal complexity is O (∣E∣ + ∣V∣·log ∣V∣), where ∣E∣ is the number of edges and ∣V∣ is the number of vertices of the graph. For a given source vertex (node) in the graph, the algorithm finds the path with lowest cost (i.e., the shortest path) between that vertex and every other vertex. If vertices denote cities, edges represent roads, and weights mean distances between cities, then the algorithm finds the shortest routes between one chosen city and all others [35–37].

Dijsktra's algorithm is not efficient for searching for the shortest path in large graphs [38], so various modifications to this algorithm have been proposed by several authors. Some of these algorithms use heuristics to reduce the run time needed for searching for the shortest path with and without data processing. Delling et al. [39] show an overview of routing algorithms; all approaches show important advances in shortest path search and make a low response time in large graphs possible using heuristics. However, in the analyzed case the size of the graph is not large, so the time needed to complete Dijkstra's algorithm is short.

Dijkstra's algorithm is based on iterations over the set of vertices. At each iteration, the algorithm finds a vertex for which the distance from the root vertex to the selected vertex is minimal [40]. In subsequent iterations, the set S of vertices is remembered, for which the weights of the shortest paths from the source s has been calculated, i.e., the shortest path to the source for each vertex has been already determined. In simple terms, Dijkstra's algorithm involves a multiple repetition of the following operations:

1. estimation of the shortest path for each vertex $u \in V$–S;
2. selection of another vertex for which the minimum weight of a shortest path has been estimated (in other words, selecting the closest vertex);
3. addition of vertex u to the set S;

4. implementation of the so-called relaxation of edges stemming out of the vertex u [27].

The aim of relaxation is to check if after the addition of vertex u to set S, the distance of each neighbor v of vertex u to root vertex s becomes shorter than the path earlier estimated. If the path from s to v via u is shorter, then it is changed (detailed information on the operation of the algorithm can be found in, e.g., [41]).

2.3. Transport Cost Calculation

After determining the shortest paths by Dijkstra's algorithm for a given graph G and a selected root vertex s, a tree T of shortest paths for the root vertex s to any other vertex v can be constructed. The cost of a tree is the sum of costs of all paths from optimal location to any of the current pellet production sites. In case of different shares, weights u_i of individual points can be considered, which is associated with more or less frequent need to cover a given route. The weighted average length of the path from the selected central vertex to the n other vertices was determined using the Formula (3):

$$\overline{d}_s(s) = \sum_{i=1}^{n_s} u_i \cdot w(s, \ldots, \nu_i) / \sum_{i=1}^{n_s} u_i \tag{3}$$

The above formula relates to the average distance travelled from the pellet production sites to the new surplus storage site; n_s denotes number of production sites. Similarly, the weighted average distance between the designated storage point and individual poviats p_i (exactly to their centroids) can be expressed according to the expected sales shares r_i by Formula (4):

$$\overline{d_p}(s) = \sum_{i=1}^{n_p} r_i \cdot w(s, \ldots, p_i) / \sum_{i=1}^{n_p} r_i \tag{4}$$

Finally, the total cost of transport can be determined using Formula (5):

$$c(s) = \sum_{i=1}^{n} N_{si} \cdot f_i \cdot \overline{d_{si}}(s) + \sum_{i=1}^{n} N_{pi} \cdot f_i \cdot \overline{d_{pi}}(s) \tag{5}$$

where n refers to number of vehicle types, N_s and N_p to the numbers of paths travelled to new storage site and to poviats, respectively, using vehicle of type i and f_i to its relative fuel consumption. In the following research, N_s = 18 and $N_p = 24$ was adopted, which correspond to the number of production plants and number of poviats, respectively. One type of vehicle was considered.

2.4. Research Methodology

The methodology adopted in the research is presented in Figure 1. It considers the choice of a suitable storage of pellet surplus, which can be used in the period of increased demand.

The construction of the graph, and the implementation of Dijkstra's algorithm and the tree with the minimum cost of transport, were made in MATLAB based on spatial data determined in the QGIS program (locations of pellet production points, junctions determined by the intersection of main roads, and distances between nodes as measures of transport costs). Based on the obtained pellet transport cost estimates, a map was developed showing their increase in relation to the optimal solution. Spatial interpolation was performed with the use of spline functions.

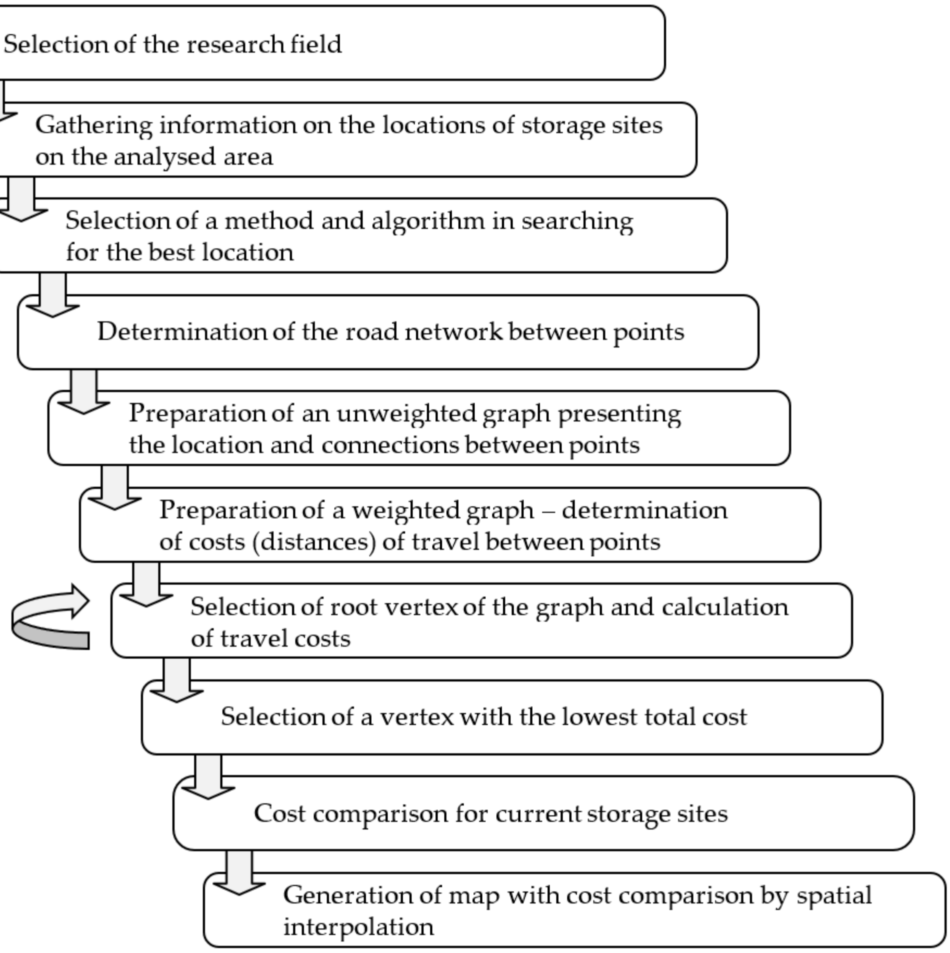

Figure 1. The order of procedures in the research methodology.

3. Results

As mentioned before, the research was carried out for the Lubelskie Voivodeship (central-eastern Poland). The analysis aimed to find a location for the storage of pellet surpluses with the shortest distances from individual production points and to the later distribution to points of sale in the period of increased demand for energy. A total of 18 localities in which pellets are stored were the vertices of the graph. The localities in the graph were connected with edges indicating actual road connections, including express, national, voivodeship, poviat, and municipality roads. The map of the studied road network was presented in Figure 2. The markings of locations used in Figures 2–7 and on the map are characterized in Table 1.

Table 1. Symbols of places on the map and graphs.

Symbol	City	Symbol	City
BP	Biała Podlaska	MP	Międzyrzec Podlaski
Bi	Biłgoraj	Pi	Piszczac
Ch	Chełm	Pu	Puławy
JL	Janów Lubelski	RP	Radzyń Podlaski
Jo	Józefów	So	Sosnowica
Ks	Krasnystaw	Sw	Świdnik
Kr	Kraśnik	TL	Tomaszów Lubelski
Lb	Lubartów	Wl	Włodawa
Lk	Łuków	Zw	Zwierzyniec

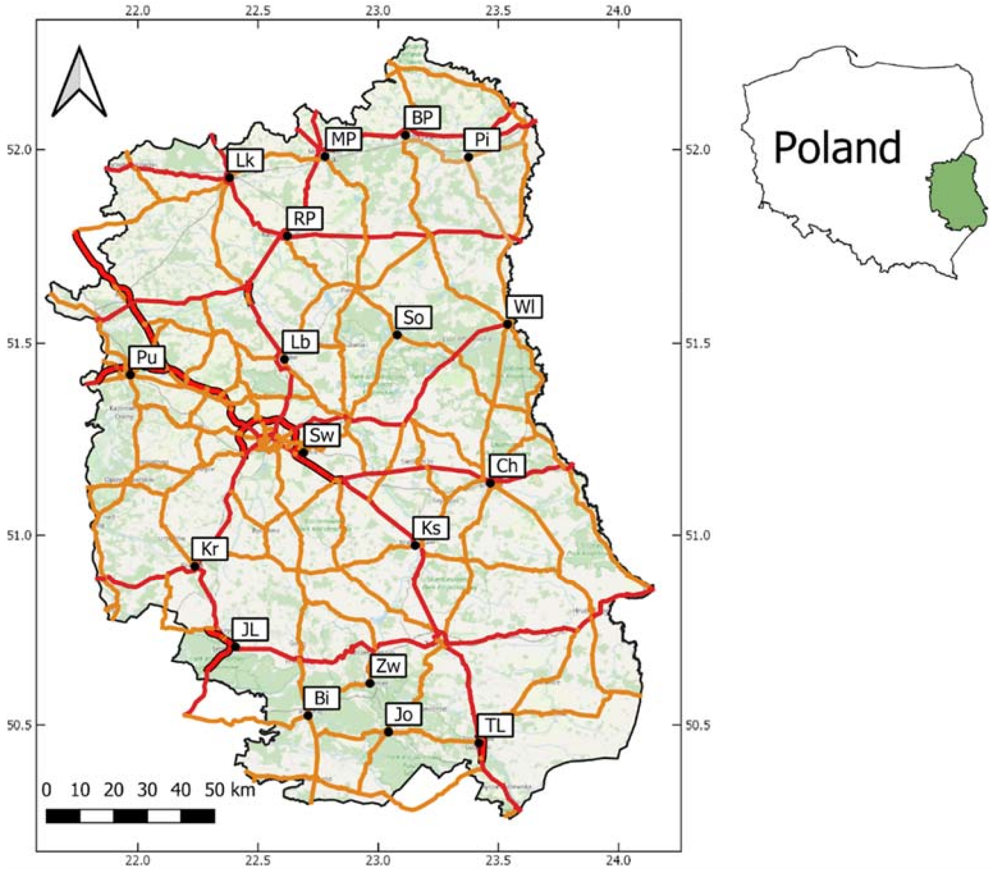

Figure 2. Locations of biomass depots and the network of main roads in Lubelskie Voivodeship.

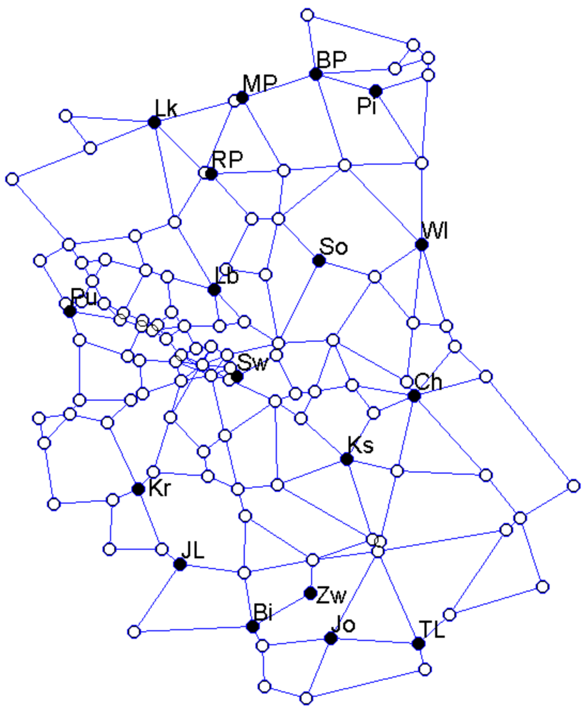

Figure 3. Graph presenting locations of pellets production and road connections.

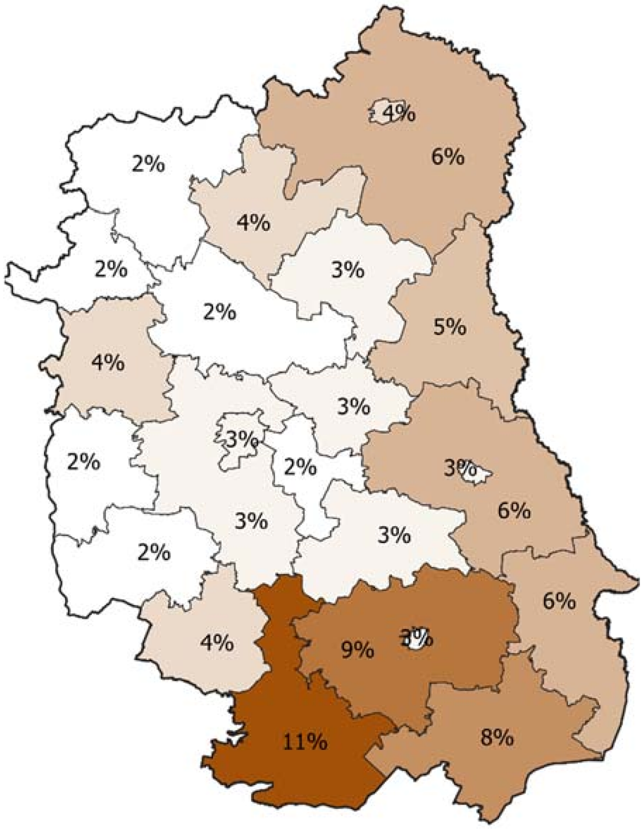

Figure 4. Estimated sale shares of stored by poviat.

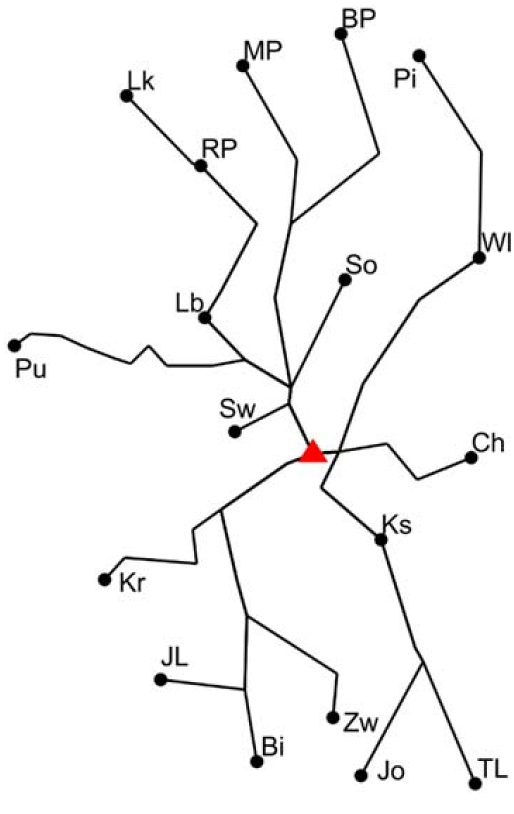

Figure 5. The minimum cost tree rooted in optimal location.

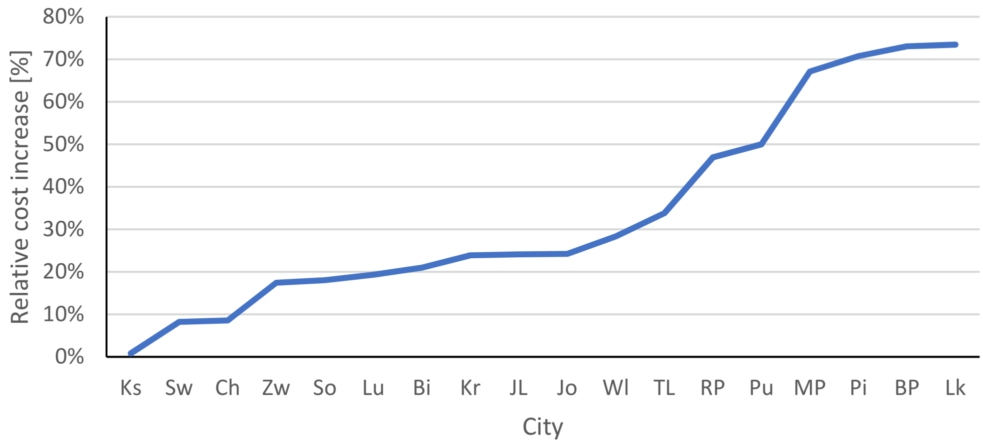

Figure 6. Relative cost increase for original locations in comparison with the optimal one.

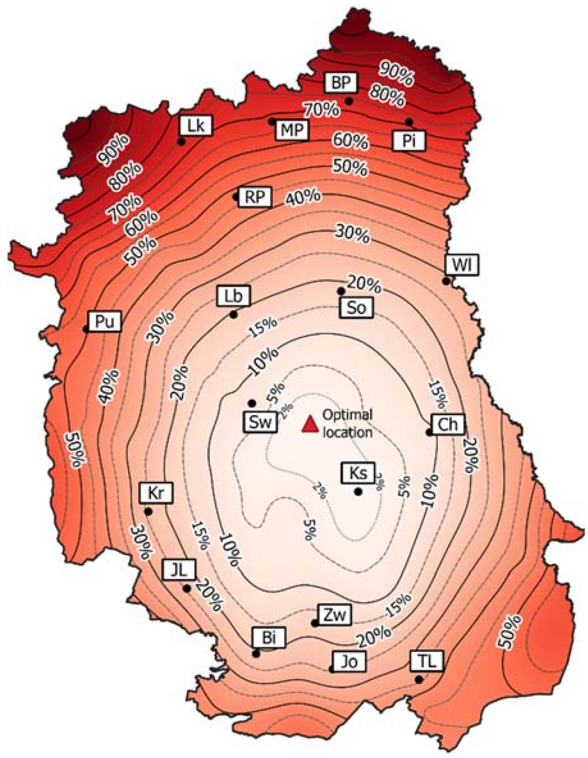

Figure 7. Map with contours for relative cost increase in comparison with the optimal one.

During the next stage, the road network was simplified. The exact topography and the actual shape of roads is not needed for graph algorithms; it was approximated with the use of straight lines. The graph constructed in this way is presented in Figure 3. The vertices of the graph show the current locations of the pellet production points (vertices filled with black color) and the points of intersection of main roads in the Lubelskie Voivodeship as approximate locations of a potential pellet storage point (filled with white color). In total, the graph contains 122 vertices.

Each edge connecting vertices was assigned with a cost reflecting the distance between chosen localities. For each vertex, the shortest path to each pellet production locality was determined with the use of Dijkstra's algorithm.

As already mentioned, the large number of small farms, which is characteristic of rural, poorly industrialized areas with a lower level of economic development, does not have a positive effect on the conclusion of contracts for the supply of biomass. Therefore, when designing a logistics system, models should be developed that take into account the companies that purchase and process biomass already on the market, as well as, on the one hand, the availability of a given type of biomass on the market and, on the other hand, the demand for it. Therefore, when estimating the costs of pellet logistics, the estimated demand for pellets in individual poviats of the voivodship was additionally taken into account (Figure 4).

As shown in Figure 4, in the analyzed Lubelskie Voivodeship, several areas with different estimated demand for pellets can be observed, with the greatest demand in the south of the voivodeship, due to the large number of farms and the large potential of bio-mass sources. In turn, the lowest demand is estimated in the central and western part of the voivodeship, due to the higher population density and industrialization, resulting in a greater number of households connected to the central heating network.

According to the next step of the research procedure, after determining the shortest paths, a tree with minimum transport cost was constructed. Total costs for individual trees rooted in the current locality were presented in Table 2 (if a new location is near to an existing one). The columns present the production share of a given plant, the average distance to other pellet production sites, the total cost including all 18 locations, and the absolute and relative increase in transport costs in relation to the optimal location.

Table 2. The cost of trees rooted at given cities by Dijkstra's algorithm in relation to optimal place.

City	Prod. Share u (%)	Average Distance $\overline{d_s}$ (km)	Average Distance $\overline{d_p}$ (km)	Tree Cost c (km)	Cost Increase (km)	Relative Cost Increase (%)
Krasnystaw (Ks)	4.8	89.7	61.5	3092.0	24.9	0.8
Świdnik (Sw)	1.9	97.4	65.4	3321.6	254.5	8.3
Chełm (Ch)	4	96.1	66.7	3331.8	264.6	8.6
Zwierzyniec (Zw)	4.9	102.2	73.6	3605.8	538.6	17.6
Sosnowica (So)	5.2	103.3	73.6	3625.5	558.4	18.2
Lubartów (Lu)	5.1	104.4	74.4	3665.2	598.0	19.5
Biłgoraj (Bi)	15	96.7	82.3	3715.6	648.5	21.1
Kraśnik (Kr)	1	103.2	81.2	3805.7	738.6	24.1
Janów Lubelski (JL)	8.1	103.4	81.4	3813.3	746.1	24.3
Józefów (Jo)	12.6	102.2	82.3	3816.1	749.0	24.4
Włodawa (Wl)	7.2	107.5	83.7	3944.0	876.8	28.6
Tomaszów Lubelski (TL)	5.4	110.9	88.2	4113.0	1045.9	34.1
Radzyń Podlaski (RP)	1.1	127.9	92.4	4519.4	1452.2	47.3
Puławy (Pu)	5.7	128.4	95.9	4613.0	1545.9	50.4
Międzyrzec Podlaski (MP)	5.5	143.1	107.0	5143.6	2076.5	67.7
Piszczac (Pi)	4.5	146.1	109.4	5255.4	2188.3	71.3
Biała Podlaska (BP)	7	148.6	110.5	5326.4	2259.3	73.7
Łuków (Lk)	1	150.0	109.9	5338.4	2271.3	74.1

On the basis of the calculated costs, it was found that the lowest total cost (3067.2 km) was indicated for the trees rooted in the vertex number 101, located near the town of Piaski (GPS coordinates 51.1594 N, 22.9459 E). For this root vertex, the average distance to all the production plants was 88.1 km, and average distance to all poviats 61.7 km. The graph presenting a tree with the lowest cost is shown in Figure 5. The location for which the presented tree has a minimum cost, obtained with the use of Dijkstra's algorithm, is marked with a red triangle.

Considering only existing production plant localities, the smallest difference with the optimal one occurred in the case of Krasnystaw—Ks (total tree cost equals 3092.0 km). This location is closest to the optimal location. The average distance to other plants is 89.7 km, and this is only a 0.8% increase in cost in relation to the optimal one. On the other hand, Łuków (Lk) and Biała Podlaska (BP) are the worst sites for potential storage locations of biomass in the form of pellets in the Lubelskie Voivodeship, due to the costs obtained for these localities; the average distance to all production sites is 150.0 km, and the total cost is 5338.4 km for Łuków and 148.4 km and 5326.4 km, respectively, for Biała Podlaska.

The average cost of travel for all trees obtained for individual locations amounted to 4113.7 (km), while standard deviation amounted to 735.2 (km). A visual comparison regarding the relative difference of costs for towns with storage locations of biomass was presented in Figure 6.

The relative increase in costs in comparison to the optimal one is the smallest in in the case of Krasnystaw (Ks) at 0.8%; slightly higher, 8.3%, for Świdnik (Sw); and 8.6% for Chelm (Ch). On the other hand, Łuków (Lu) and Biała Podlaska (BP) had the largest relative cost increase, which is, respectively, 74.1% and 73.7% higher than the optimum. It shows that these towns do not provide an optimal storage location of biomass and had to be rejected. If the relative difference of costs is large, a given locality does not qualify as a place to create a storage location of biomass.

For visualization purposes, based on the obtained pellet transport cost estimates determined for trees for all possible graph nodes, a map was developed showing their increase in relation to the optimal solution. Spatial interpolation was performed with the use of spline functions. The constructed map is shown in Figure 7. The map shows contours specifying the equal cost of pellet transport in the case of the location of a new storage place.

It can be seen on the map that, despite the fact that the location of the optimal storage site is determined approximately in the center of gravity of the entire voivodeship, the area where the relative cost increase does not exceed 10% is quite stretched. This area has 42,122.36 km^2, which is approximately 17.6% of the entire area of the voivodship (25,122.35 km^2). This area is shifted to the south of the voivodeship, where two larger production plants are located and an increased demand for energy from pellets is present.

4. Discussion

The transport, storage, and reloading of pellets are very important issues for all market participants—producers, distributors, consumers, and the entire society. This is due to both economic reasons and the quality of the final product [42–44]. Inadequate storage and transport conditions may reduce the calorific value and other quality features of wood pellets, such as mechanical strength, degree of crushing, or ash content, which are key determinants of the selection of the appropriate type of fuel [45].

It should be added that a large part of the current use of pellets is facilitated by the intense activities of global trade, and the growing use of bioenergy in combination with the spatial distribution of biomass demand and supply will further increase trade in solid biomass [46]. In the literature on the subject, one can find the results of research that allow us to assess the economic feasibility of transporting biomass and biofuel; however, this transport is carried out on a large scale and over long distances. Large-scale and long-distance transport of biomass is a cost-effective transport option for biofuel plants and for coal plants which consider biomass co-firing [47–49]. On the other hand, it should be remembered that the large distance between the production site and the locations of end users may cause pellets to be subject to variable storage conditions, which in turn may cause their physical and chemical degradation [50].

Therefore, in the research and analysis carried out, the focus was on the issues of biomass transport on a local scale. In order to indicate the optimal pellet storage location, Dijkstra's algorithm was used. Dijkstra's algorithm is a well-known algorithm used to find the shortest paths between vertices of a graph. Shortest path search has been widely studied. Many applications can be found in different fields of science, especially in Geographic Information Systems. Additionally, various modifications of this algorithm with the use of heuristics are proposed in order to reduce its execution time [40].

The selection of the optimal location for a new storage point for pellet surplus—presented in this paper—concerns the problem in which this point becomes the central point of distribution of goods. Additionally, actual shares of pellet production in each plant have been taken into account, so each edge has the different weight. The weights take into account, e.g., the intensity of following specific routes. The construction of the minimum-cost tree also depends on the way the goods are distributed to selling points. One can consider a model in which distribution is also possible between individual (closest) locations, as well as the demand for the product in the vicinity of production and storage points. However, when it comes to the place of production of pellets, one of the most important factors when choosing the right place is the availability of the raw material. This aspect affects not only the price of the raw material, but also the costs of transporting the raw material to the pellet plant [2].

Similar studies were carried out in, for example, the USA, where attempts were made to develop mathematical logistic models allowing for the estimation of distribution channels, transport, and quantities for the domestic demand for wood pellets. Lacoa and his team [51] investigated two cases: distribution to power plants and distribution to retail stores. Models developed using Dijkstra's algorithm can be used as tools to minimize the costs of wood pellet distribution in a selected area.

It should be added that more and more often in computer-aided systems of choosing the optimal distribution routes for goods, multi-criteria mathematical models are used, which take into account many qualitative and quantitative parameters; this requires their additional standardization and determination of their priority level [52]. An example is the work of Aghalari et al. [53], in which they presented the problem of optimizing the entire biomass-to-pellet supply system. They have developed a two-stage stochastic model that takes into account various elements such as: harvesting, storage, transportation, or quality inspection. However, they focused largely on the impact of biomass quality and its transport to processing points.

With regard to transport processes, it can therefore be concluded that biomass can be transported in many ways. When choosing the optimal form of transport in terms of economic and ecological aspects, one should take into account many factors, including, first of all: the type and form of biomass, its quantity, but also the distance to the destination, and the requirements and needs of customers. Taking into account the typical locations of biomass sources and the considered distances in the analyzed area, it seems that the most beneficial in many respects will be the use of road infrastructure and road transport. Then, with regard to storage processes, it should be mentioned that many types of biomass are characterized by seasonal availability, as they are collected and then processed at a specific time of the year, hence they must be stored. Therefore, building small, local depots seems to be a good solution. Storage points (warehouses) may be located in specially dedicated places for this purpose.

5. Conclusions

After analyzing the literature, and on the basis of this research, it was possible to draw the following conclusions:

1. Dijkstra's algorithm allowed finding the shortest path between vertices (localities).
2. The optimal location for a new storage place for pellets was indicated near the city of Piaski. The lowest total cost of tree rooted in this place was 3067.2 km, which relates to the average distance 88.1 km to a single plant and 61.7 km to poviat.
3. From 18 current localities of the company's sites in the Lubelskie Voivodeship, the closest optimal costs were obtained for Krasnystaw (0.8% higher), Świdnik (8.3% higher), and Chełm (8.6% higher).
4. Average cost of travel for all trees obtained for individual locations amounted to 4113.7 (km), while standard deviation amounted to 735.2 (km).
5. The area with the most convenient locations is shifted from the center towards the southern part of the voivodship, and the increase in transport costs does not exceed 10% of lowest cost for 17.6% area of the Lubelskie voivodship.
6. Improperly adopted storage location can increase transport costs by up to 75%.

The results obtained in the analysis in order to estimate the potential storage location of biomass in the form of pellets on a technical level may serve as the basis for further research. It may be carried out for different territorial units with the use of tools of technical and economic optimization of various undertakings of production and processing of biomass into useful forms of energy. Dijkstra's algorithm allows us to find the shortest path between vertices (localities). Individual edges of a graph may have different weights that define the cost of going from one vertex to another on a given edge, which allows the determination of the potential of the optimization procedure on the economic level. This is all the more important as reducing supply chain costs can contribute to increased use of pellets. This manuscript concerns mainly one of the components of the entire pellet production chain, which is the cost of transport. In the next step, the authors intend to take into account other factors in order to model and optimize the problem as a whole. Free GIS software will also be used for implementation so that the whole problem is solved in one analytical program.

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