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Determination of the Optimal Location of Sewage Sludge Installation for the Needs of Production of Fertilizer Products

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1. Introduction

The limited availability of natural resources and the needs of the economy and societies result in increased production costs and an increased demand for resources. The search for new sources of supply and the pressure associated with environmental protection caused an increase in the interest in products that partly lost their value − waste, by-products or secondary raw materials. This change is reflected in the new paradigm of management − a circular economy. The transformation towards the circular economy means that enterprises are increasingly implementing new technological solutions that would enable material, biological, raw or energetic recovery and use of values from defective products and closing the circulation of materials.

The essence of the circular model of the economy is to reduce the mass of waste produced while increasing their level of recovery. As a result, the waste is treated as a raw material for the implementation of current production and enabling the company's product range to be expanded by introducing new products obtained from waste to the market. The changing approach to the use of waste and by-products of industrial and domestic processes has led to the development of a specific group of entities involved in the process of closing the circulation, defined in other publications and papers as *Circular Economy Plants* (Barla et al. 2018). Their main goal is the transformation of waste generated from one industry to raw materials used by another. These objects therefore mediate and clear the material flows between the links of value chains. They apply the technology adapted to the selected type of recovery and operation in conditions of uncertainty resulting from the volatility of the supply stream of waste constituting the object of processing and the demand for recovery processes. Conducting operations under conditions of high uncertainty means that it is necessary to take a number of decisions covering both economic and environmental aspects that translate into competitiveness and profitability of operations. One of the key decisions in the functioning of such plants concerns logistics regarding the spatial configuration of the supply network, the participants of which will provide the necessary materials for their operations.

In Poland the management of sewage sludge especially in medium and small wastewater treatment plants is a significant problem and requires continuous activities. Furthermore, the problem of configuration of the logistics network for the optimization of activities in the circular economy is a new subject and relatively rarely discussed in literature, there is especially a lack of references (Jąderko 2018) concerning wastewater management and waste management such as sewage sludge.

The management of municipal sewage sludge depends on many factors, however, the key legal issues are the legal conditions that shape the activities of water and sewage companies. International (National Waste Management Plan 2022) and national (Directive 2008/98/EC on waste) conditions assume increased sludge recycling and their application in agriculture, horticulture, green areas and land reclamation processes. Sludge recycling technologies within the framework of organic recycling have many advantages, which include loss of waste status, possibility of storing fertilizer and free transport as well as generating an additional source of income for the company or obtaining an appropriate level of organic recycling. It should be emphasized that the implementation of such solutions should be justified from the technological and logistical point of view and correspond to the idea of sustainable development.

The issue of supply chain modelling for effective management of sewage sludge corresponding to the concept of circular economy is a complex issue including both logistics and environmental engineering (Jąderko and Białecka 2015, Dos Santos 2019, Jąderko 2018), which requires:

- analysis of material flows in the waste management system (Makarichi et al 2018),
- processing of data related to the operational activities of waste management plants (Burger et al 2018),
- eco-design of biological wastewater treatment technology (Zhao et al 2019), energy waste utilization technology (Simeone et al 2016),
- use of logistic models of configuration and management of the logistics network.

The development of an integrated decision model supporting network management processes is an important and current research problem, which requires conducting a number of research works and testing various variants of solutions. The conducted study of the subject literature showed the need to develop decision models in the selection of optimal locations for circular plants, the main purpose of which is to treat rainfall as a raw material (Jąderko and Białecka 2016). So far, the only criterion for selecting the location of waste management facilities was to minimize costs (Merkisz-Guranowska 2012) while environmental and logistic factors were treated as complementary. The increase of entrepreneurs' demand for raw materials and problems related to ensuring the efficiency of their processing systems, in particular configuration aspects for logistics systems of sediment management, causes the need to develop a solution based on a systemic approach, taking into account a multi-criteria analysis. The research problem formulated in this way is the starting point for the considerations presented in the article.

2. Methods

The centre of gravity method (Łupicka 2002) is a classical method used in logistics for pre-locating production and storage facilities. It was applied in the tests in order to determine the optimal location of sewage sludge installation. The basic assumption of the method makes it possible to indicate the best location of the facility, taking into account the geographical coordinates of supply sources, transport costs and the volume of the shipped cargo. It is basically very simple to apply, but it also leads to a number of disadvantages including issues with stativity. Nevertheless, it has a wide application in determining the base solution and is a starting point for its further improvement (Krawczyk 2001).

From the point of view of the conducted research, the determination of optimal locations for sewage sludge transformation facilities requires a holistic approach that takes into account the interaction of a number of related elements. The adoption of the logistic concept of land for waste management (including sewage sludge), including in particular optimization methods and tools, allows streamlining the management of material flows, in this case waste with the simultaneous effective involvement of resources and capital.

The purpose of the article was to develop a decision model for the selection of the optimal location of sewage sludge installation on the example of Silesia, Poland. The following works were carried out successively:

- identification of key elements of sewage sludge management system,
- analysis and quantitative-qualitative assessment of sewage sludge streams and other substrates necessary for the production of fertilizer granules,
- analysis of criteria excluding the selection of the installation location,
- gathering spatial data resulting from defined criteria,

- determination of the optimal location for the installation (using the method of determining optimal solutions for the location of objects − centre of gravity),
- analysis of the possibilities of technology adaptation in the analysed region.

The decision-making model developed on the basis of the presented research stages, taking into account the optimization of the installation location, allowed to include technological and logistical, ecological, infrastructural, economic-legal and social criteria as part of the planning process of the circular economy plant location.

3. Identification of key system elements

The stabilized municipal sewage sludge (waste code 19 08 05) is created in wastewater treatment plants. Their quantity and quality depend on the content of pollutants in sewage, the technology adopted and implemented, and the degree of decomposition of organic substances in the process of so-called stabilization.

At present, the dominant trend for the management of municipal sewage sludge is the use (according to data: Local Data Bank, data for 2017):

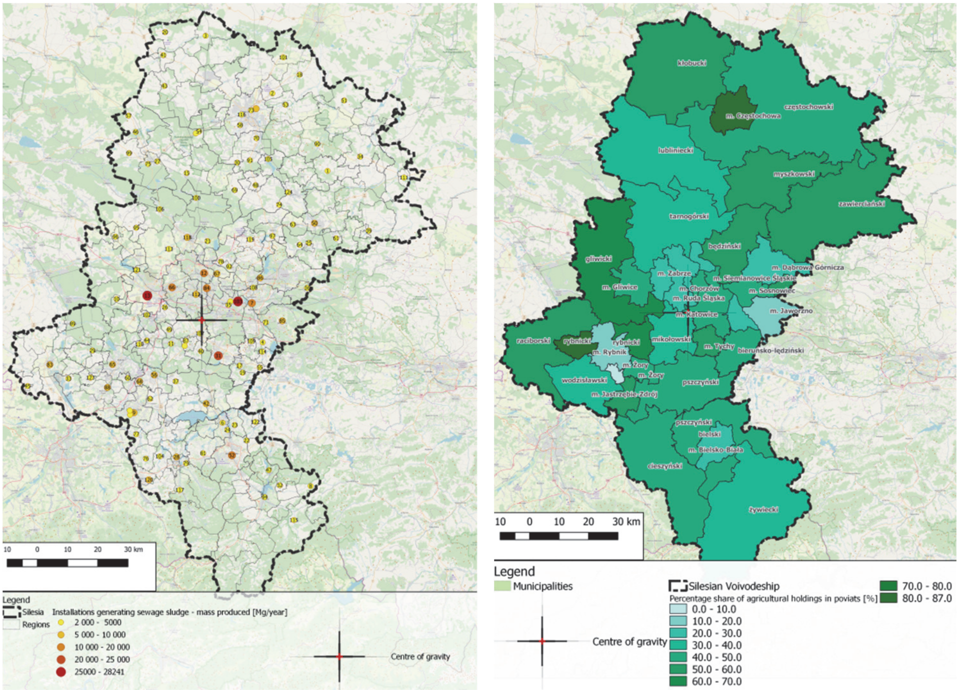
- in agriculture: 2 513 Mg s.m.,
- for the reclamation of land, including land for agricultural purposes: 2 482 Mg s.m.,
- for growing plants intended for the production of compost: 5 322 Mg s.m.,
- by thermal transformation: 5 428 Mg s.m.,

and:

- are stored together: 64 Mg s.m.,
- and the remaining ones are accumulated in the treatment plant.

In Silesia, there are currently 26 (Voivodship reports on waste management 2017)waste recovery or disposal installations, including municipal sewage sludge. The inventory of sources of sewage sludge production constituting a potential source of supply has shown that in 2017 in Silesia, 340,315.24 Mg (64 039 Mg s.m.) of (Local Data Bank, data for 2017) municipal sewage sludge was generated (waste code 19 08 05). The mass of generated sewage sludge in Silesia compared to the total capacity of the waste management installation of this group of waste (265,576.62 Mg/year), confirms the necessity to increase the efficiency or implementation of technologies allowing sludge management.

The identification of key elements of the system allowed to indicate: (1) installations producing sewage sludge in Silesia as sources of technology for the production of organic fertilizers from sewage sludge (124 facilities included in the analysis) and (2) the share of agricultural holdings constituting the fertilizer market. Geographical data is presented in Figure 1.



(1) (2)

Fig. 1. (1) Installations generating sewage sludge (2) surface share of farms in Silesia
Source: Own elaboration

Using the centre of gravity method to determine the optimal location required the collection of spatial and quantitative data corresponding to individual waste holders. The collected data made it possible to adapt the designs to a specific group of materials – waste, and allowed to determine the geographical coordinates for the optimal location of the sludge treatment plant in organic fertilizers.

The optimal location was determined according to the following formula:

$$\boldsymbol{X}^* = \frac{\sum_{i=1}^{I} \boldsymbol{M}_i \boldsymbol{X}_i}{\sum_{i=1}^{I} \boldsymbol{M}_i} \tag{1}$$

$$\boldsymbol{Y}^* = \frac{\sum_{i=1}^{I} \boldsymbol{M}_i \boldsymbol{Y}_i}{\sum_{i=1}^{I} \boldsymbol{M}_i} \tag{2}$$

where:
(Xi, Yi) − coordinates of the i-th source of sewage sludge − waste holder
Mi − the mass of generated sediments from the i-th source of sewage sludge − waste holder.

Table 1 Data summary
Source: Own elaboration

Item	Waste holder (*)	Mass of generated waste [Mg]	Geographical coordinates	
			X	Y
1	Rejonowe Przedsiębiorstwo Wodociągów i Kanalizacji S.A.	16756.51	50.2603059	19.13713299999995
2	Jastrzębski Zakład Wodociągów i Kanalizacji S.A.	8,145	49.94133730000001	18.602509499999996
3	Przedsiębiorstwo Wodociągów i Kanalizacji Sp. z o.o.	28240.92	50.281858	18.66275189999999
…	….	…	…	…
124	Waste holder no. 124	M_{124}	X_{124}	Y_{124}

(*) due to the wide range of data, selected items developed for the needs of database research were presented

4. Results and discussion

Considering the necessity to include the spatial mapping of the studied area, where the installation will eventually be created, the spatial layers should contain the following thematic maps to select a group of proposed location options for the implementation of technology, including the administrative map of the region; topographic map; hydrological map; road network map; map of residential buildings; map of protected areas; map of sources of supply of substrates necessary for the production of fertilizers from sewage sludge.

According to the adopted methodology and the centre of gravity method applied, the optimal location of sewage sludge installation for the production of fertilizer products is Mikołów (geographical coordinates: 50,21057311; 18,90949076). The point determining the optimal location has been presented on the map.

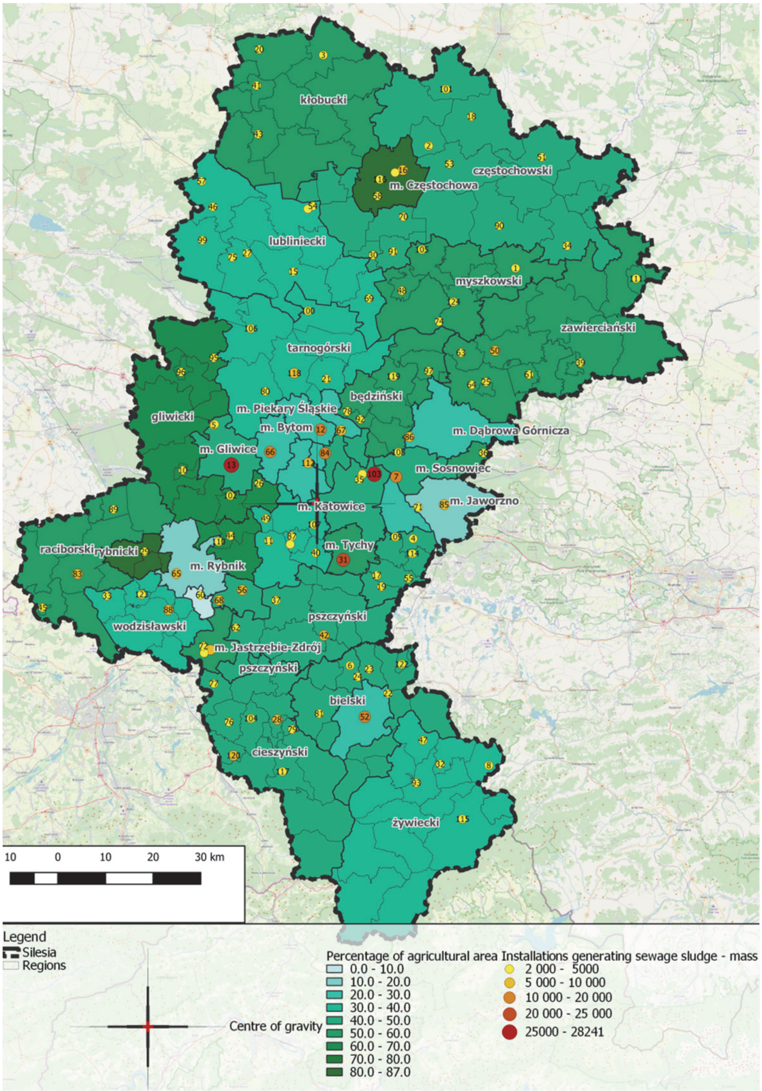


Fig. 2. Optimal installation location
Source: Own elaboration

The optimal location of the installation has also been presented on the thematic maps, which are the main determinants of choosing the best solution and exclusion criteria. It should be emphasized that the centre of gravity method presents the predisposed area for the construction of the facility or implementation of the installation, however, making a final decision requires detailed analyses allowing to determine a set of location variants as starting points for further research. An important advantage of the method used is the possibility of including the distance to the collection points of waste, which from the point of view of both economic and ecological issues is one of the key selection criteria.

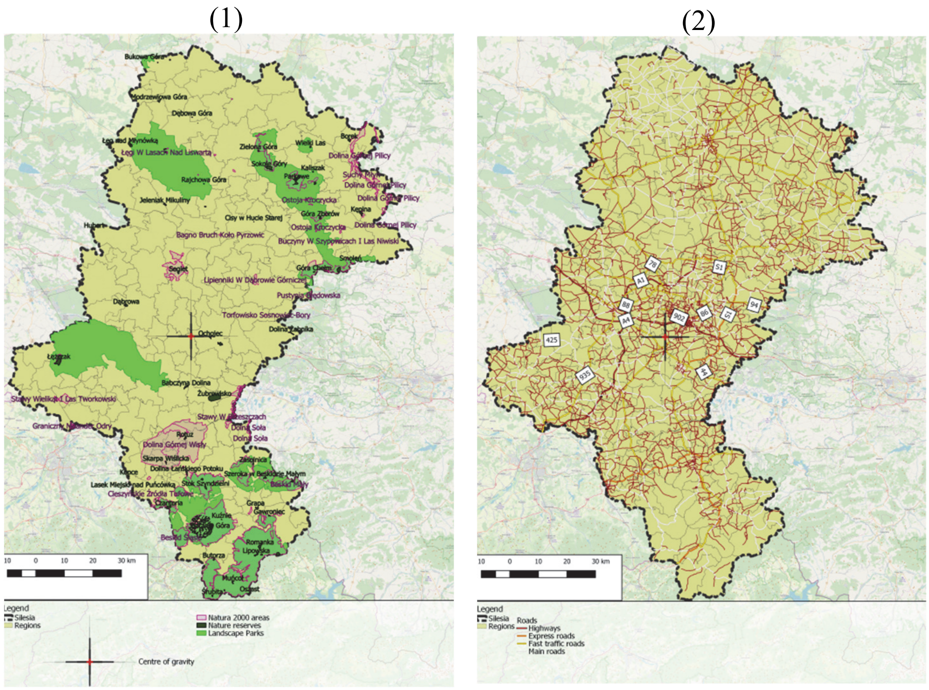


Fig. 3a. (1) Protected areas, (2) Road network
Source: Own elaboration

(3) (4)

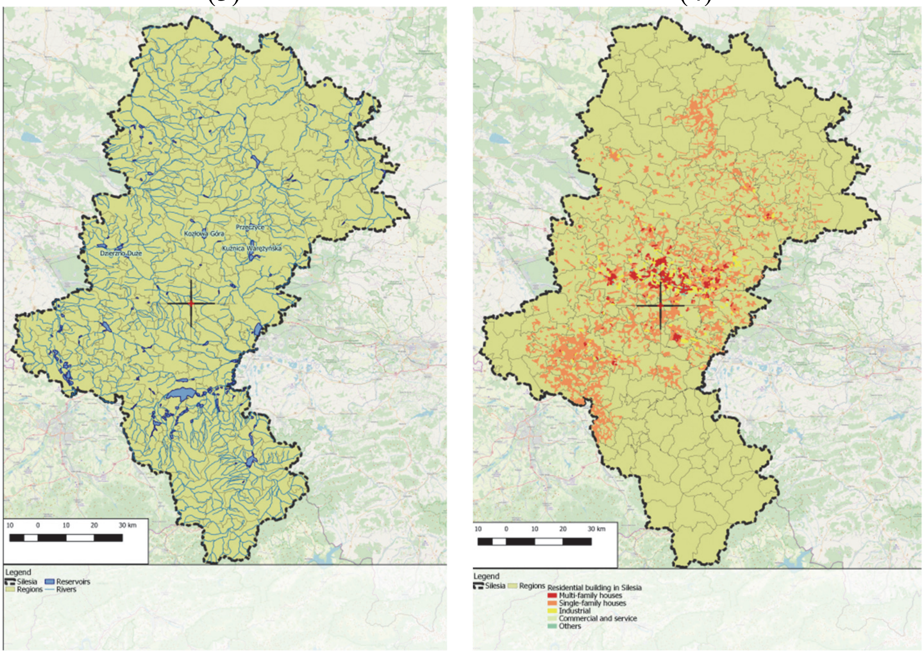


Fig. 3b. (3) Hydrographic network, (4) Residential building in Silesia
Source: Own elaboration

In terms of the spatial data analysed, the designated centre of gravity is characterized by the following geographical features:

1. The owner of the waste (supplier)
   - The owner of the waste (supplier) nearest to the place is Zakład Inżynierii Miejskiej Sp. z o.o. in Mikołów (6.3 km from the designated point). Importantly, the designated point is located between the largest producers of sewage sludge − Katowickie Wodociągi S.A. producing over 27 thousand Mg of sediment (about 19 km from the point), Regionalne Centrum Gospodarki Wodno-Ściekowej S.A. in Tychy, which produces over 22 thousand Mg of sediment (about 16 km from the point) and Przedsiębiorstwo Wodociągów i Kanalizacji in Gliwice, generating annually over 28 thousand Mg sediments (about 28 km from the point).
2. Agricultural holdings (recipient)
   - the centre of gravity is located in the Mikołów region, where the percentage of farms is 30-40%.

3. Areas of residential and industrial development
   - the designated point is located approximately 1.6 km from single-family buildings and 1.3 km from industrial areas.
4. Hydrographic network
   - the designated point is located approximately 800 m from the Stragniec water reservoir.
5. Recreation area
   - the designated point is located approximately 800 m from the holiday resort Stragniec.
6. Forms of nature protection
   - the closest reserve − Ochojec, located approximately 6.26 km from the designated point,
   - the nearest landscape park − Cistercian Landscape Compositions Rudy located approximately 13.08 km from the designated point,
   - the nearest protected landscape area − the Bujaków Stream, including the tributaries, located approximately 9.61 km from the designated point,
   - the closest nature and landscape complex − the Jamno Valley, located approximately 0.87 km from the designated point,
   - NATURA 2000 Special Protection Areas − Ponds in Brzeszcze PLB120009 located approximately 23.57 km from the designated point,
   - NATURA 2000 Special Protection Areas − Podziemia Tarnogórsko-Bytomskie PLH240003 located approximately 19.36 km from the designated point,
7. Post-mining areas
   - the designated point is located approximately 1 km from Hałda Panewnicka.

The presented outline of the terrain characteristics allows to define those elements that may affect the exclusion of selected areas, such as the close location of recreation and housing areas and valuable natural areas − the natural and landscape complex of the Jamno Valley.

In order to determine the full balance of the key components of the sludge management system (suppliers − sludge owners, producers/distributors of other substrates and fertilizer users), it is necessary to identify potential location options around the designated centre of gravity. This will allow taking into account relevant transport rates that are important from the point of view of profitability analysis.

The development of a full model of the optimization of the location of installations for processing sewage sludge with the desired level of detail is connected with a detailed analysis of determinants affecting the effectiveness of the implementation of the solution. The following factors can be included:

- **Infrastructural**, including the space for the construction of the facility along with the accessibility of access roads and other infrastructure elements that are related to securing the construction and supply of necessary utilities.
- **Social**, which consists of both the possibilities of providing human resources as well as social acceptance related to the implementation of projects that may significantly affect the environment.
- **Ecological**, which covers all elements related to environmental resources that strongly affect and which may be affected by the construction of the installation.
- **Economic and legal**, which regulate all legal issues and provide indicators of economic effectiveness of investments, which allow to determine whether the investment is justified from the point of view of its profitability.
- **Logistics and technology** – including the spatial characteristics of the installation location and factors limiting the implementation of technologies that can significantly affect the environment, raw material potential of available sewage sludge streams taking into account the quantitative and qualitative characteristics (type and nature of – related to the source of supply, quantity and quality, availability, regularity , diversification of supplies depending on the season), location of other raw materials (fillers) necessary for the production of fertilizers, location of potential collection points for fertilizers. A set of technological indicators covering basic technological parameters, efficiency, recovery level, technological possibility of increasing recycling.

In the process of selecting the location of the installation, the centre of gravity method was used as an element supporting optimal object placement in space (Jąderko and Białecka 2016). The basis for the selection was the raw material potential of sources of supply – understood as the mass of produced sewage sludge. Due to the complexity of the sewage sludge management system and the multidimensionality of the criteria necessary for the analysis, key assumptions of the decision model were developed and presented in the form of an algorithm.

The general description of the structure of the decision model allows to clearly highlight the need for a comprehensive and systematic approach to the problem of selecting the optimal location variant. Based on recognized variables including technological parameters, logistics parameters, geographical coordinates and the raw material potential of sewage sludge, it is possible to network the waste flows and thus to create a comprehensive view of sewage sludge management system with an indication of real demand for the implementation of waste management installations.

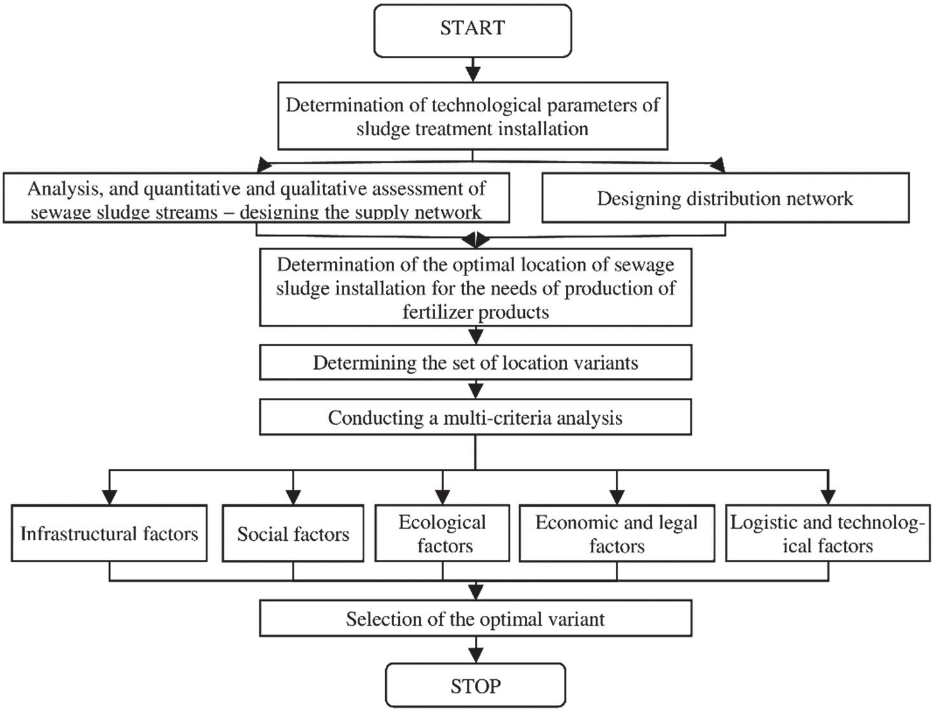


Fig. 4. Algorithm of the decision model
Source: Own elaboration

5. Conclusion

The centre of gravity method is one of the oldest and most frequently used methods to determine the location of objects. Due to the high degree of generalization in economic practice, it finds application primarily in the determination of location variants – predisposed areas. The determination of the base location by means of the said method can be included in the most important stages of the initial analysis, which will indicate the material potential of the designated area taking into account the mass of sewage sludge constituting the key substrate for the production of fertilizers. It should be emphasized, however, that the choice of location depends on a number of factors, hence another important step is to conduct a detailed multi-criteria analysis of the target location options.

Additionally, the decision model should be of a staged and procedural nature, including:

- analysis of areas predisposed for the construction of the installation together with the assessment of the impact on the environment;

- multi-criteria analysis along with its assessment (analysis of costs and benefits, eco-effectiveness, social and economic effects of investments);
- impact on competitiveness, growth and employment.

Spatial data included in the process of determining the optimal location allows for a comprehensive approach to the research problem only when a multi-criteria analysis is carried out including the assessment of factors excluding construction of the location (e.g. close proximity to valuable natural areas and residential areas). An especially important aspect in the perspective shape of the decision model for the selection of the optimal location of sewage sludge installation is to ensure the possibility of simulating the efficiency of the fertilizer sludge production process taking into account the quality properties of sediments supplied from various sources. This approach will enable the development of a universal model that is part of a comprehensive decision support system related to the objectives of the circular economy.

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References

Barla, F., Nikolakopoulosa, A. & Kokossisa, A. (2018). Design of Circular Economy Plants – The Case of Waste Textiles to Chemicals, *Computer Aided Chemical Engineering, 44*, 1153-1158.

Burger, C., Kalverkamp, M., Pehlken A. (2018). Decision making and software solutions with regard to waste management, *Journal of Cleaner Production, 205*, 210-225.

Directive (EU) 2018/851 of The European Parliament and of The Council of 30 May 2018 amending Directive 2008/98/EC on waste.

Dos, Santos, P.H., Neves, S.M., Sant'Anna, D.O., de Oliveira, C.H. & Carvalho, H.D. (2019). The analytic hierarchy process supporting decision making for sustainable development: An overview of applications, *Journal of Cleaner Production, 212*, 119-138. (https://www.sciencedirect.com/science/article/pii/S0959652618336734 (04.12.2018))

Jąderko K., Białecka, B. (2016). *Model technologiczno-logistyczny procesu energetycznego wykorzystania odpadów*. P.A. NOVA, Gliwice 2016.

Jąderko, K. (2018). *Challenges in developing decision systems supporting wastewater management in a context of circular economy*, 18 International Multidisciplinary Scientific GeoConference SGEM 2018. Conference proceedings, 17-24.

Jąderko, K., Białecka, B. (2015). Decision support systems in waste management – a review of selected tools, *Systemy Wspomagania w Inżynierii Produkcji, 1*(10), 32-41.

Krawczyk S. (2001). *Quantitative methods in logistics*. Volume II, C.H. Beck, Warszawa 2001 (in Polish).

Łupicka, A. (2002). *Logistics networks. Theories. Models. Research*. Akademia Ekonomiczna, Poznań (in Polish).
Makarichi, L., Techato, K. & Jutidamrongphan W. (2018). Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision-making, Resources, *Conservation and Recycling, 139*, 351-365.
Marshal Office of the Silesian Voivodeship. Voivodship reports on waste management 2017 (https://bip.slaskie.pl/dzialalnosc_urzedu/srodowisko/raporty-wojewodztwa-dotyczace-gospodarki-odpadami.html (16.11.2018)) (in Polish).
Merkisz-Guranowska, A. (2012). Optimisation criteria in vehicles recycling network location, *Logistyka, 2*, 549-556 (in Polish).
Resolution No 88 of the Council of Ministers. of 1 July 2016 (item 784). National Waste Management Plan 2022. Warsaw 2016 (in Polish).
Simeone, A., Luo, Y., Woolley, E., Rahimifard, S. & Boer, C. (2016). A decision support system for waste heat recovery in manufacturing, *CIRP Annals, 65*, 1, 21-24.
The Local Data Bank for 2017 (https://bdl.stat.gov.pl/BDL/start (22.11.2018)) (in Polish).
Zhao, X., Bai, S. & Zhang X. (2019). Establishing a decision-support system for eco-design of biological wastewater treatment: A case study of bioaugmented constructed wetland, *Bioresource Technology, 274*, 425-429. (https://www.sciencedirect.com/science/article/pii/S0960852418316602 (08.12.2018)).

Abstract

The objective of this article was to develop a structure of a decision-making model for selection of optimal locations of sewage sludge installation on the example of the Silesian Voivodeship. Selection of locations for waste treatment facilities belongs to complex multicriteria decision-making problems.

Taking into account the problems of modelling the supply network for the effective management of sewage sludge corresponding to the concept of circular economy, the paper presents the application of the centre of gravity method for determining the optimal locations for the sewage sludge treatment plant based on the fertilizer production process.

The research carried out for the purpose of this study included identification of key elements of the sewage sludge management system, analysis and quantitative and qualitative assessment of sewage sludge streams, analysis of criteria excluding the selection of installation locations, gathering spatial data resulting from defined criteria, determination of optimal location for installations (using the method of determining optimal solutions for the location of objects – the centre of gravity method). All spatial data are presented on thematic maps prepared with the use of QGIS software.

The result of the research is a description of the decision-making model structure based on optimization of installation location and including technological and logistic, ecological, infrastructural, economic and legal and social criteria in the process of planning the location of a circular economy plant.

Keywords:
waste logistics, sewage sludge, circular economy, decision support, centre of gravity method

Wyznaczenia optymalnej lokalizacji instalacji zagospodarowania osadów ściekowych na potrzeby produkcji produktów nawozowych

Streszczenie

Celem artykułu było opracowanie struktury modelu decyzyjnego dla wyboru optymalnej lokalizacji instalacji zagospodarowania osadów ściekowych na przykładzie województwa śląskiego. Wybór lokalizacji dla obiektów przetwarzania odpadów należy do złożonych wielokryterialnych problemów decyzyjnych.

Biorąc pod uwagę problematykę modelowania sieci dostaw dla efektywnego zagospodarowania osadów ściekowych odpowiadających koncepcji gospodarki obiegu zamkniętego w artykule przedstawiono zastosowanie metody środka ciężkości dla wyznaczania optymalnej lokalizacji dla zakładu przekształcania osadów ściekowych w nawozy.

Przeprowadzone na potrzeby niniejszej pracy badania obejmowały m.in. identyfikację kluczowych elementów systemu zagospodarowania osadów ściekowych, analizę i ocenę ilościowo-jakościową strumieni osadów ściekowych, analizę kryteriów wykluczających wybór lokalizacji instalacji, zgromadzenie danych przestrzennych wynikających ze zdefiniowanych kryteriów, określenie optymalnej lokalizacji dla instalacji (z wykorzystaniem metody wyznaczania optymalnych rozwiązań dla lokalizacji obiektów – metody środka ciężkości). Wszystkie dane przestrzenne zostały przedstawione na mapach tematycznych opracowanych wykorzystaniem oprogramowania QGIS.

Opracowany na podstawie prac badawczych opis struktury modelu decyzyjnego uwzględniający optymalizację lokalizacji instalacji pozwolił na uwzględnienie kryteriów technologiczno-logistycznych, ekologicznych, infrastrukturalnych, ekonomiczno-prawnych oraz społecznych w ramach procesu planowania lokalizacji zakładu gospodarki cyrkularnej.

Słowa kluczowe:
logistyka odpadów, osady ściekowe, gospoda obiegu zamkniętego,
wspomaganie decyzji, metoda środka ciężkości