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Article

Enhancing Precision Beekeeping by the Macro-Level Environmental Analysis of Crowdsourced Spatial Data

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Abstract: Precision beekeeping focuses on ICT approaches to collect data through various IoT solutions and systems, providing detailed information about individual bee colonies and apiaries at a local scale. Since the flight radius of honeybees is equal to several kilometers, it is essential to explore the specific conditions of the selected area. To address this, the aim of this study was to explore the potential of using crowdsourced data combined with geographic information system (GIS) solutions to support beekeepers' decision-making on a larger scale. This study investigated possible methods for processing open geospatial data from the OpenStreetMap (OSM) database for the environmental analysis and assessment of the suitability of selected areas. The research included developing methods for obtaining, classifying, and analyzing OSM data. As a result, the structure of OSM data and data retrieval methods were studied. Subsequently, an experimental spatial data classifier was developed and applied to evaluate the suitability of territories for beekeeping. For demonstration purposes, an experimental prototype of a web-based GIS application was developed to showcase the results and illustrate the general concept of this solution. In conclusion, the main goals for further research development were identified, along with potential scenarios for applying this approach in real-world conditions.

Keywords: precision beekeeping; GIS; open data; OpenStreetMap; environmental analysis

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1. Introduction

In recent years, beekeeping activities have gained increasing recognition for their importance in biodiversity, ecosystems, agriculture, and human health [1]. Besides being a productive branch of agriculture focused on breeding and maintaining bees for the harvest of various bee products [2], which have well-documented human health benefits [3], beekeeping plays a vital role in broader ecological and agricultural contexts [4]. The pollination services provided by bees help maintain ecosystem balance and are essential for the productivity of agricultural crops [5]. Pollination is essential for the production of many fruits, vegetables, and field crops, including oilseed production [6,7]. The presence of managed beehives in agricultural landscapes can increase pollination rates, improve crop quality and yield, and contribute to the overall productivity and profitability of agricultural systems [8], as well as to the development of rural areas [9]. Considering the decline of insects on both local and global scales, the EU has committed to reversing the decline in pollinators, as outlined in the EU Biodiversity Strategy for 2030 [10]. One possible short-term strategy to safeguard biodiversity and food security worldwide is to increase the number of farmed pollinators, particularly honeybees, relying on beekeepers' ability to preserve them [11].

The effectiveness of beekeeping largely depends on the competence of the beekeepers, who perform various activities based on decision-making processes [12]. Beekeeping activities involve a wide range of tasks and responsibilities aimed at maintaining healthy and productive bee colonies [13,14]. These activities primarily include bee colony monitoring, hive inspections, feeding and nutrition management, as well as pest and disease control [15,16]. Beyond these core tasks, a beekeeper's responsibilities also involve assessing local conditions to ensure optimal apiary placement, such as evaluating the availability of sufficient food resources [17]. Beekeeping also intersects with economic considerations, particularly in commercial operations [18,19]. In such cases, foresight in apiary development, strategic planning, and productivity forecasting are essential. All these responsibilities and tasks undoubtedly demand significant effort and resources from the beekeeper [20,21].

Modern beekeeping has evolved significantly with advancements in technology, science, and sustainable practices, transforming it into precision beekeeping [22]. By using modern technologies and data-driven approaches, precision beekeeping enables beekeepers to monitor beehive health, track environmental variables, and optimize management practices with unprecedented precision and efficiency [23]. Precision beekeeping has emerged as a response to the need for optimal bee colony management, integrating technology and statistical methods to manage apiaries efficiently and minimize the risk of bee population losses [2,24].

The term 'Precision Beekeeping' or 'Precision Apiculture' was first defined in the study 'Application of Information Technologies in Precision Apiculture' [25], where the authors, as computer science engineers, highlighted the potential for applying modern approaches from precision agriculture to beekeeping. Similar to precision agriculture, precision beekeeping is based on a three-phase cycle consisting of data collection, data analysis, and application [26]. While these phases involve a certain level of automation, they still require the beekeeper's involvement, particularly in decision-making and the application process. Precision beekeeping, in its original sense, is described as an apiary management strategy focused on monitoring individual bee colonies to minimize resource consumption and maximize bee productivity [25]. Thus, it can be stated that precision beekeeping, in its original concept, primarily targets the local scale, focusing on individual hives (bee colonies), and is confined to the territory of the apiary and its immediate surroundings. This statement is further supported by the most commonly used solutions in precision beekeeping, which are based on the use of various sensors and Internet of Things devices that focus on the detailed monitoring of individual colonies and apiary parameters [27]. The most common monitoring data include hive parameters such as temperature, hive weight, humidity levels, sounds, gases, and bee activity. Particular attention is also given to external factors affecting the apiary, such as weather conditions, which have a significant impact on the health of the bee colony [11]. Thus, it is possible to track bee activity, colony health and local conditions of apiaries in real-time [28]. However, given that the flight radius of a bee around the hive is approximately 3 km [29], it is very important to take into account the conditions of the surrounding environment on a larger scale. This statement is supported by the fact that, in addition to precision beekeeping's emphasis on the local scale of the apiary, the authors of the concept of precision beekeeping also mention the regional level as a specific geographic area encompassing neighboring bee farms as one of the levels of data collection and exchange [30]. Subsequent studies have expanded on this direction, with one of the key approaches involving the use of spatial data and geographic information systems (GISs) [27,31,32].

There are various environmental factors that can have a negative impact on bees that were also mentioned in several studies related to beekeeping [33–35]. These bring various challenges for beekeepers that threaten the health and productivity of bee colonies worldwide. Urbanization, pollution, and agricultural expansion reduce the availability of suitable areas for beekeeping, as they impact foraging and the persistence of bee colonies [36]. One of the most serious concerns is caused by intensive farming and the resulting presence of pesticides on farmland, as they can be toxic to bees [35]. This may be especially important in the case of migratory beekeepers who change the location of their apiaries. In fact, due to their high sensitivity to chemical and phytosanitary products, as well as their ability to collect samples from the air, vegetation, water, and soil, honeybees serve as bioindicators of disturbances in ecosystems and the environment [5,37,38].

Addressing these challenges requires a multifaceted approach, combining macro-level environmental data analysis and a suitability assessment of interested areas. A possible solution in this case could be using geographic information in combination with analysis and classification methods to perform the pre-exploration of the territory of interest. When using geographic information for beekeeping needs, much of the research has focused on analyzing a specific territory to perform suitability assessment or obtain important information for decision-making support. In many cases, the outcomes of such studies were static maps based on data from a specific period and relevant at the time of development [31,39–43]. The next stage of development of GIS-based solutions can be considered interactive GIS solutions that allow interaction with spatial data and use mechanisms for updating data over time. One of the clear examples of such solutions is the web-based solution described in [44], called Beescape. It allows one to interactively explore surrounding environment, assessing the quality of the landscapes for supporting bees and other pollinators [45]. The conducted research and proposed solutions demonstrate the relevance of using GIS in beekeeping and also contribute to the development of new ideas and the search for innovative approaches.

In this study, the authors focused on investigating the feasibility of spatial crowdsourcing to explore the potential application of this approach for real-time environmental analysis to support decision-making in the field of beekeeping. The primary objective was to demonstrate the feasibility of using a crowdsourced spatial database in combination with WEB and GIS technologies, highlighting potential scenarios for the technical implementation of the solution. The solution presented in this research paper should be regarded solely as an experimental prototype, demonstrating the concept of the approach from a technical perspective to support further studies in developing similar solutions.

2. Materials and Methods

To conduct this study, an attempt was made to go beyond region-specific data and extend the scope to an international scale. The main goal of this approach was to explore the possibility of developing a universal solution that is not restricted to a specific country or region. For this purpose, the term 'large-scale' data was introduced within the framework of this article. The term 'large-scale' refers to a territorial scope that is significantly larger than an apiary, where most common solutions in precision beekeeping, such as hive or apiary monitoring, are typically applied. Specifically, 'large-scale' encompasses relatively extensive areas, starting from the radius of bees' flight (several kilometers) and extending to the exchange of information at the national or even international level, such as in the case of migratory beekeepers.

Since it is necessary to perform a spatial analysis over areas with a radius of several kilometers at any location worldwide, obtaining data of this scale is challenging due to their variety and volume. Geodatabases from individual countries or regions provide environmental information at various levels of detail. Examples include Field Register Data from the Rural Support Service of Latvia [46] as well as open data provided by The geoPortal of Energy and Geology (Portugal) [47]. However, there are limitations. Solutions developed from such sources are limited to specific countries or regions. At the same time, the use of several databases is complicated by the unification of data. Moreover, it is important to consider data availability and the limitations of their use, including licenses and restrictions.

To overcome these barriers and obtain data on an international scale, open geographic data can be used. One of the crucial approaches for the exchange of open data is data crowdsourcing, which is especially valuable in cases when traditional data collection methods are time-consuming or impractical. There is a large amount of open geographic data sources available worldwide, examples of which are published on Free GIS Data by Robin Wilson [48].

To demonstrate the concept of the approach and the implementation of the solution, the authors of this study used OpenStreetMap (OSM) [49], one of the most well-known open geospatial databases, as a source of spatial data. It is a crowdsourced and open mapping project that includes geographic information about the entire world and relies on contributions from volunteers and stakeholders worldwide who collect, edit, and update spatial data [50,51]. OSM data have gained significant attention for their potential applications in various domains, including navigation, logistics services [52,53], and urban and regional planning [54–56]. They are also widely used to produce land use maps through data reclassification [57–59], which is the primary data processing method employed in this study. Due to its versatility and popularity, the OpenStreetMap database is one of the most widely used spatial data sources for research purposes, offering a valuable alternative to commercial and government datasets.

OSM data represents real-world objects on the ground (buildings, roads, areas, etc.) using tags attached to the corresponding data structures (nodes, ways, and relations), with each tag describing a geographic attribute of the spatial feature. A tag consists of a key and a value. The key is used to define a feature group or type (e.g., highway, building, etc.), while the value provides specific information for the feature belonging to a particular group (key) (e.g., motorway, shop, etc.) [60].

In addition to viewing the map, OSM allows users to obtain spatial data directly from the database. The data from OSM can be obtained in multiple ways, including through the Overpass API (https://wiki.openstreetmap.org/wiki/Overpass_API, accessed on 17 January 2025), which enables the retrieval of OSM spatial data using queries. An example of OSM data obtained using Overpass API query through Overpass turbo (https://overpass-turbo.eu, accessed on 17 January 2025) can be seen in Figure 1.

To better understand the concept and idea of the approach of this research, a high-level architecture was developed (see Figure 2) that illustrates the main components of the solution.

A central component of the approach is an open geographic database (e.g., OpenStreetMap) that allows data to be freely accessed and edited, ensuring that the data are current and rich. The idea is to provide data to the database from interested parties. These data can later be used by beekeepers to analyze the area of interest (by the data processing phase) and obtain valuable information. Such an approach could be beneficial for agriculture in general, as it would also enable the exchange of information between beekeepers and other farmers.

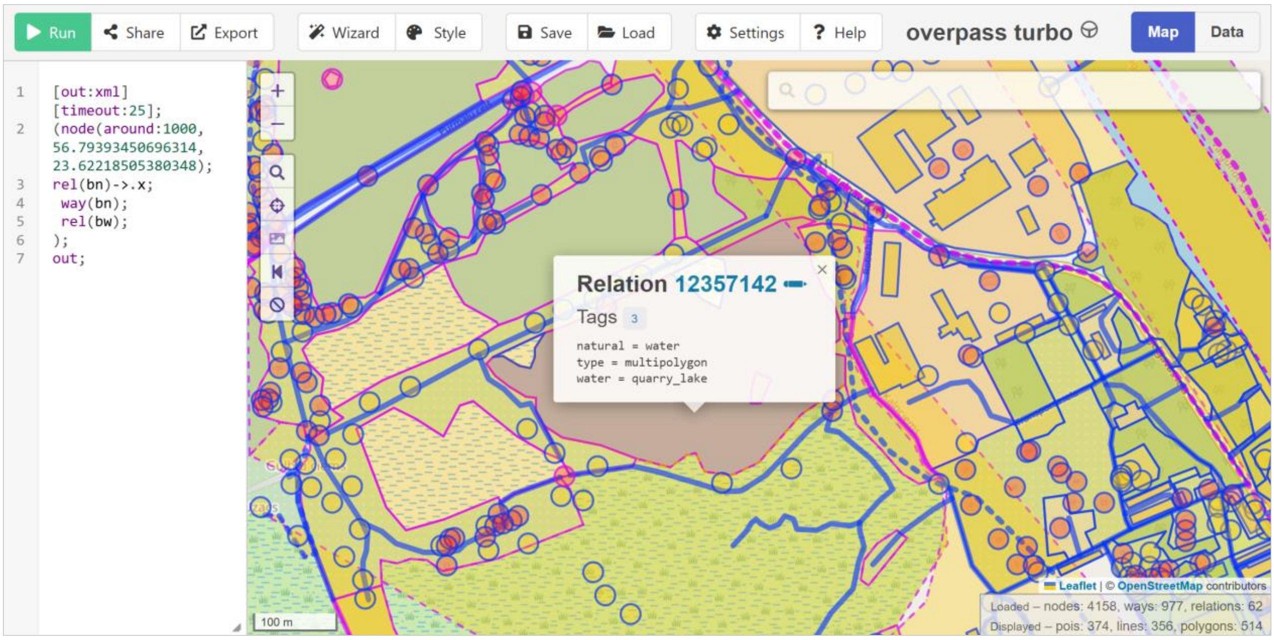


Figure 1. Example of OSM data obtained using the Overpass API query via the Overpass turbo.

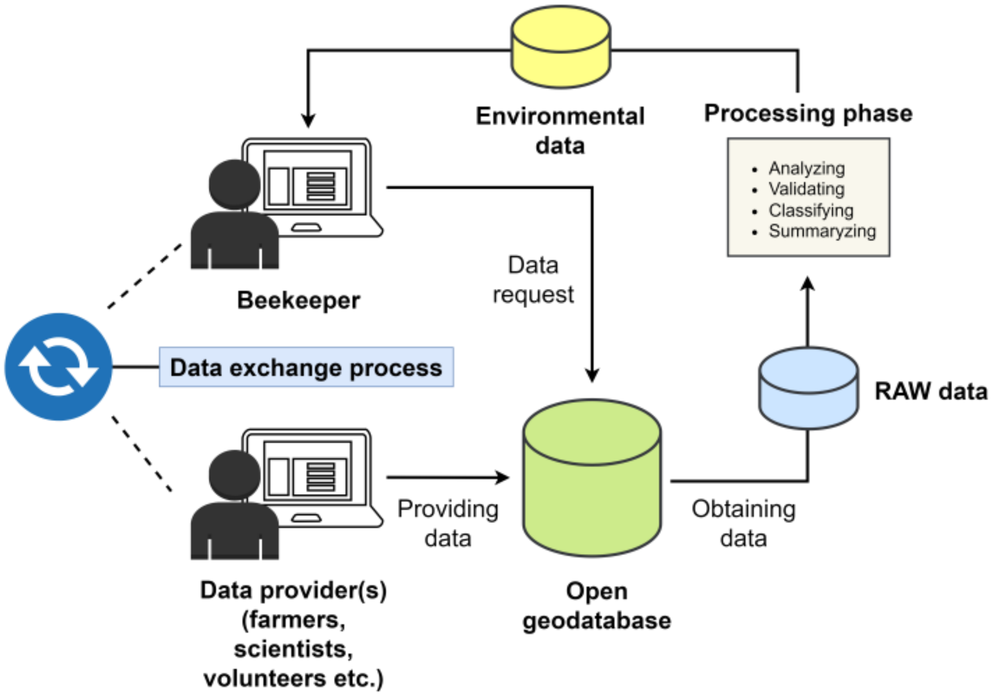


Figure 2. High-level architecture of the proposed approach.

At the core of the solution from a technical perspective is the Data Processing Module (DPM), which includes all the main functionalities related to data analysis, such as data acquisition, processing, and result generalization. The architecture of the DPM is shown in Figure 3.

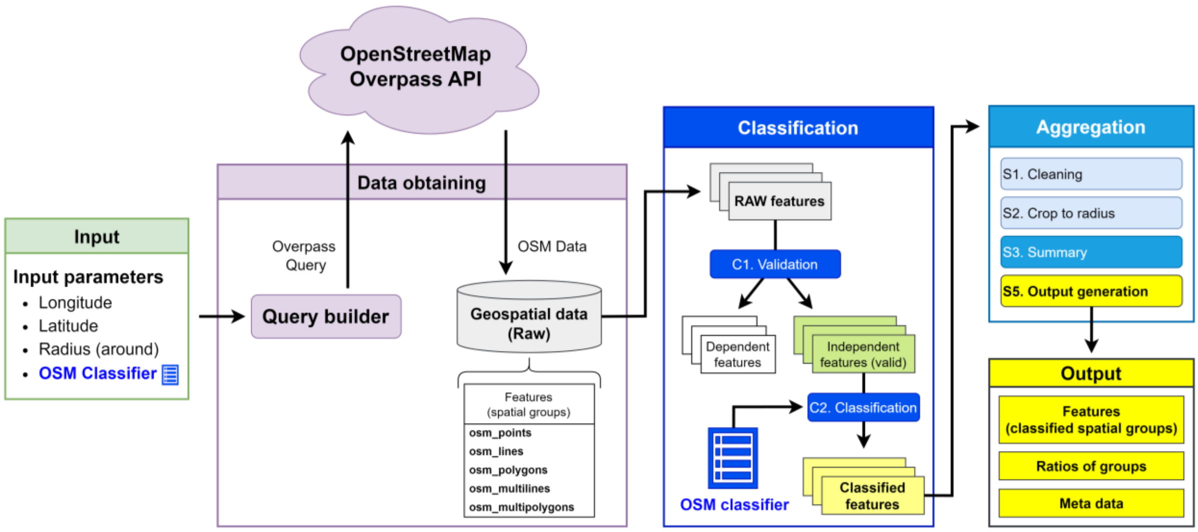


Figure 3. Architecture of the Data Processing Module (DPM).

The Data Processing Module consists of five stages:

1. Input stage—defining input data, which include
    a. The coordinates of the point of interest (latitude, longitude),
    b. The radius around the point of interest,
    c. A classifier that represents a dictionary of all OSM objects and their belonging to certain classification groups.
2. Data obtaining stage—creating a query for Overpass API and obtaining data from OSM.
3. Classification stage—performing crucial manipulation operations with OSM data, including the validation and classification of each OSM geospatial feature.
4. Aggregation stage—performing secondary-level manipulation operations with OSM data, including cleaning/cropping, summarizing, and the generation of output dataset.
5. Output stage—returning the output data set, which includes
    a. Classified OSM spatial features (as spatial groups),
    b. A summary, including ratios of classification groups,
    c. Metadata.

The solution was implemented using R 4.3.3, a programming language and environment for statistical computing [61]. Also, various R libraries were used during the implementation. The following are worth noting as the most significant:

- 'osmdata'—a library for downloading and using data from OpenStreetMap (OSM);
- 'dplyr'—a library for data manipulation;
- 'sf'—a library that provides simple features access for R;
- 'leaflet'—an open-source library (based on JavaScript) that is used to develop interactive maps;
- 'plotly'—a graphing library to develop interactive, publication-quality graphs;
- 'shiny'—a free and open-source R library for the development of web applications.

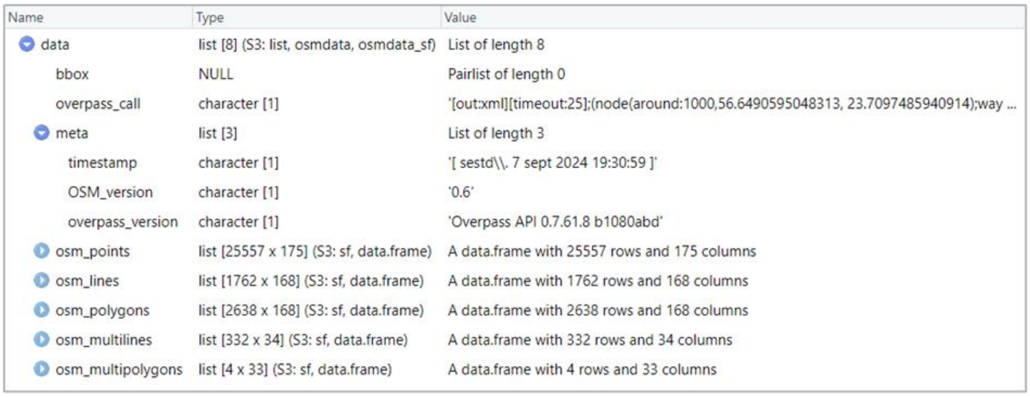
Also, during development, RStudio IDE (an integrated development environment for R) and Microsoft Excel were used.

3. Results and Discussion

OpenStreetMap spatial data were obtained using the coordinates of the point of interest (latitude and longitude) and a radius around it (with a maximum of 3 km set as the general bee flight radius around an apiary or beehive). The OSM data, retrieved using R and the 'osmdata' library, were represented as a List object, consisting primarily of metadata and five OSM spatial groups (as simple feature data frames):

- Points (separate objects, like bus stops, street lamps, etc.),
- Lines and multilines (roads, watercourses, etc.),
- Polygons and multipolygons (areas, fields, etc.).

It is important to note that the OSM data obtained at this point were raw, meaning they required further processing. An example of the data retrieved from OSM can be seen in Figure 4.



Name	Type	Value
data	list [8] (S3: list, osmdata, osmdata_sf)	List of length 8
bbox	NULL	Pairlist of length 0
overpass_call	character [1]	'[out:xml][timeout:25];(node(around:1000,56.6490595048313, 23.7097485940914);way ...
meta	list [3]	List of length 3
timestamp	character [1]	'[sestd\\. 7 sept 2024 19:30:59]'
OSM_version	character [1]	'0.6'
overpass_version	character [1]	'Overpass API 0.7.61.8 b1080abd'
osm_points	list [25557 x 175] (S3: sf, data.frame)	A data.frame with 25557 rows and 175 columns
osm_lines	list [1762 x 168] (S3: sf, data.frame)	A data.frame with 1762 rows and 168 columns
osm_polygons	list [2638 x 168] (S3: sf, data.frame)	A data.frame with 2638 rows and 168 columns
osm_multilines	list [332 x 34] (S3: sf, data.frame)	A data.frame with 332 rows and 34 columns
osm_multipolygons	list [4 x 33] (S3: sf, data.frame)	A data.frame with 4 rows and 33 columns

Figure 4. View of OSM data obtained (screenshot of RStudio IDE).

The next step after obtaining the OSM data was processing. Functionally, the processing stage can be divided into the validation, classification, and aggregation phases.

3.1. Validation

Before classification can be performed, it is important to validate whether each spatial object is suitable for classification. Each OSM spatial object is characterized by tags that include a unique identifier (osm_id), data about the represented object, and geometry. Since the obtained data are raw, they may contain spatial objects that can be considered as dependent objects (parts of other objects). For example, a point may be a geometric component of another object, such as a line segment. In this case, the point does not represent any real object and therefore lacks valuable data. The example below illustrates such a case of a dependent spatial object (see Figure 5).

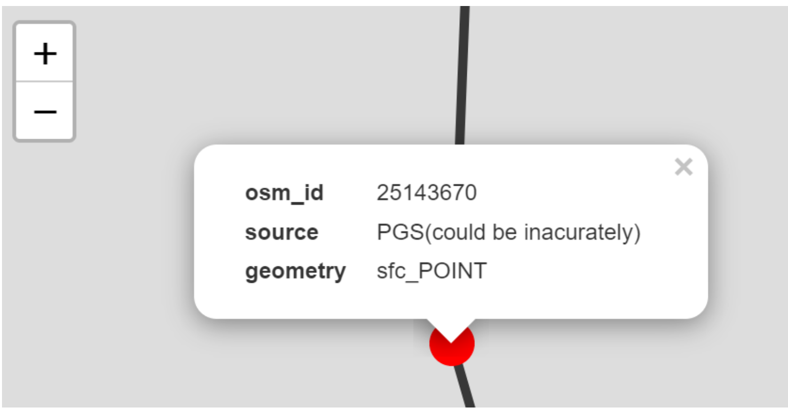


Figure 5. The example of a dependent (invalid) spatial object (point).

In another case, a point may represent a real object, for example, a bus station. In this case, it will have relevant data describing the specific bus station. Therefore, it is crucial to remove dependent objects from the spatial groups and keep independent spatial features that provide valuable information about specific objects. The example below illustrates such a case of an independent (valid) spatial object (see Figure 6).

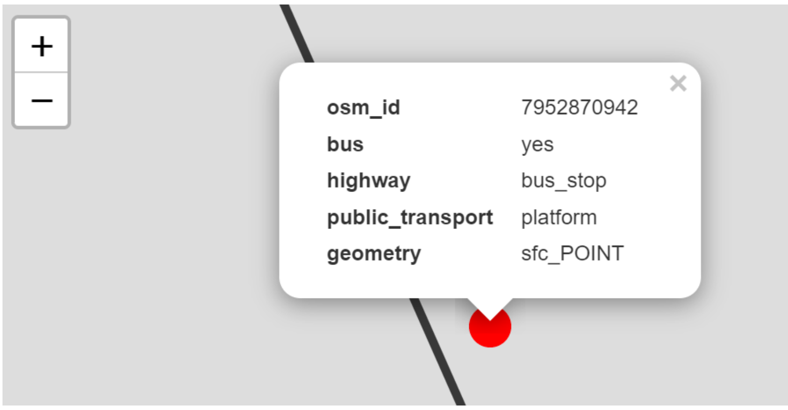


Figure 6. The example of an independent (valid) spatial object (point).

3.2. Classification

The purpose of the classification phase is to assign each spatial object to a specific class. It is crucial to note that the development of the classification stage was based on studying the technical side of the approach. The accuracy of the classification in this case was not verified; therefore, classification results can only be used as an experimental source of information. The classification process is based on using a classifier that serves as a dictionary for all existing OSM spatial features (tags). The idea was to use a list of all existing (known) OSM features and to indicate their belonging to certain classes. At the moment of a development of the classifier (autumn 2023), 1325 unique spatial features of OSM were identified. All of them were analyzed, and, as a result, 1130 unique features were determined as the primary ones, which will be used in the process of spatial object classification.

Classifier has the following classes:

- Zone: Natural/Rural (zNR), Industrial/Urban (zIU), Both (Neutral) (zB);
- Origin: Natural (oN), Anthropogenic (oA), Both (Neutral) (oB);
- Important: true/false (1/0);
- Danger: true/false (1/0).

Classifier itself represents a table, containing existing OSM tags (keys and values) and their classification according to their belonging to certain classes. An example of the OSM classifier table can be seen below (see Table 1).

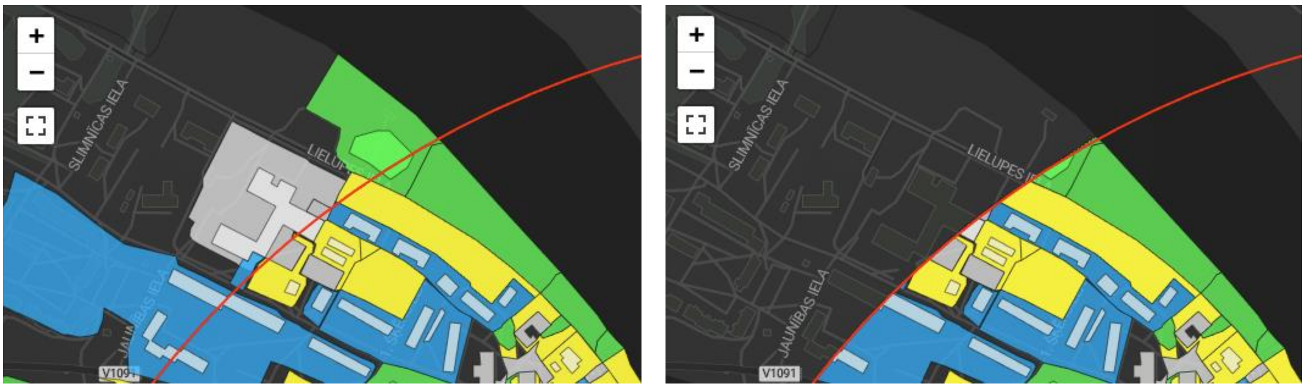
Table 1. An example of the OSM classifier table.

Key	Value	Zone	Origin	Primary	Important	Danger
abutters	commercial	zIU	oA	1	0	0
abutters	industrial	zIU	oA	1	0	0
abutters	mixed	zB	oA	1	0	0
abutters	residential	zB	oA	1	0	0
abutters	retail	zIU	oA	1	0	0
access	agricultural	zNR	oB	1	1	0
landuse	allotments	zNR	oA	1	1	0
leisure	fitness_centre	zIU	oA	1	0	0
leisure	fitness_station	zIU	oA	1	0	0

The classification of objects in the classifier was carried out on the basis of their description and information about their most probable position and role in relation to the surrounding geographic area. For example, 'landuse = allotments' in most cases describes allotment gardens, made by humans, used for gardening (growing vegetables, fruits and flowers) that in most cases are not used for permanent residential purposes. Such an object will probably be located outside cities and urban areas, in rural areas (zones). Moreover, this type of object can be noted as important and may be of particular interest as the flowering plants growing there can serve as a good source of food resources for bees. In another case, the object 'leisure = fitness_centre', describing a place with exercise machines and other fitness equipment, most likely will be located in a populated area (urban zone) to ensure the proper attendance of active people. Objects of this type can be useful in determining the level of urbanization of a particular region, which is also important for the exploration of the surrounding environment. Objects that may be potentially dangerous for bees belong to the 'Danger' class and may serve as an important factor for avoiding a specific area, such as waste landfills, which may pollute surrounding areas. It is important to note that bees are highly sensitive to the environment. During the classification process, all obtained and valid OSM spatial objects from all spatial groups were classified according to the classifier and supplemented with the corresponding classes.

3.3. Aggregation

The aggregation phase is aimed to perform secondary-level processing of OSM data in order to clean and summarize classified data as well as generate the output dataset. One of the most important operations of the aggregation stage is 'Crop to radius', the purpose of which is to limit OSM data to the initially selected area of interest (radius). An example of the 'Crop to radius' operation can be seen on Figure 7.



(**a**) (**b**)

Figure 7. 'Crop to radius' operation: (**a**) OSM data before cropping; (**b**) OSM data after cropping.

The operation 'Crop to radius' is crucial as the OSM spatial objects obtained may be located outside the defined area of the query. There are several reasons for this. First, OSM objects may have a geometry, which goes beyond the boundaries of a defined area. Second, OSM objects may have related objects that are located outside the defined area.

Another important operation to highlight is the summary preparation. This operation is necessary to prepare a generalized view of the statistics of the results. First, it generates common metadata about the total count and total area of OSM feature groups (see Table 2). Second, it prepares a summary dataset of performed classification that includes the count and areas of each classification group, as well as the ratios (in percentage) between them (see Table 3). Both these datasets are used in the visualization process of the results.

Table 2. Metadata (as a table) of the performed classification.

Object Group	Meta Parameter
Points	40
Lines	109
Multilines	3
Polygons	33
Multipolygons	3
Objects, total	188
Polygons, area (ha)	164
Multipolygons, area (ha)	2416
Total, area (ha)	2580

Table 3. Summary dataset (as a table) of the performed classification.

Class	Count (Objects)	Count Ratios, %	Area (Polygons), ha	Area Ratios, %
zNR	54	28.72	2364	91.63
zIU	5	2.66	1	0.03
zB	129	68.62	215	8.33
oN	8	4.26	2231	86.47
oA	143	76.06	17	0.65
oB	37	19.68	332	12.88
Important	14	-	122	-
Danger	0	-	0	-

The final operation of the aggregation phase is output generation, which aggregates all resulting data as an output dataset. It contains classified OSM features (five spatial groups), including a summary of each group, as well as general summary and metadata datasets (as previously described). The output dataset itself is a list object, which is further used by a prototype of a web-based GIS application as the main data source.

3.4. Web-Based GIS Application

An experimental prototype of a web-based GIS application named BeeLand Macro uses the Data Processing Module as a core and clearly demonstrates all its functional capabilities. The application was developed with a focus on a user-friendly experience, allowing users to freely explore areas of interest by performing real-time spatial analysis. The main component of the BeeLand Macro is an interactive map that allows selecting a specific area (as a circle) worldwide by clicking on the map or by adjusting the location settings available in the 'Location' tab on the sidebar (see Figure 8).

When the location and radius of the area are selected, the user needs to click on the 'Get data' button to execute the DPM. The user will be informed about the progress of the execution via the 'Please wait' window. When the DPM finishes execution, the application presents the results by providing access to map filters of classified spatial features, as well as providing a classification summary in the form of interactive pie charts and information boxes (see Figure 9).

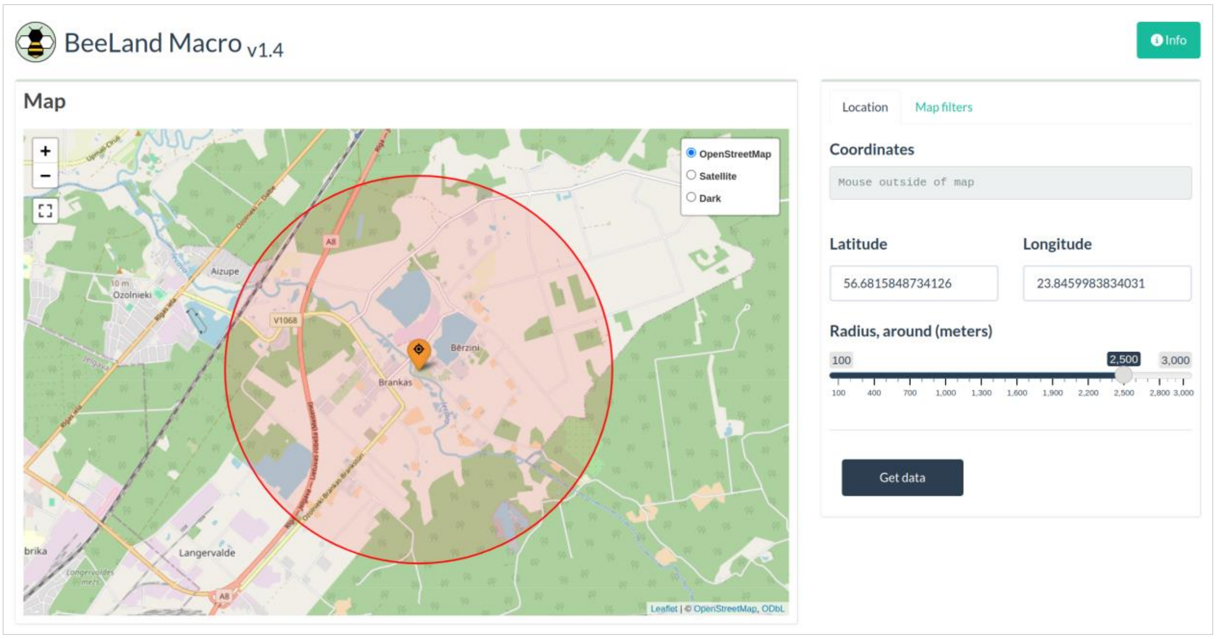


Figure 8. Interactive map of BeeLand Macro application.

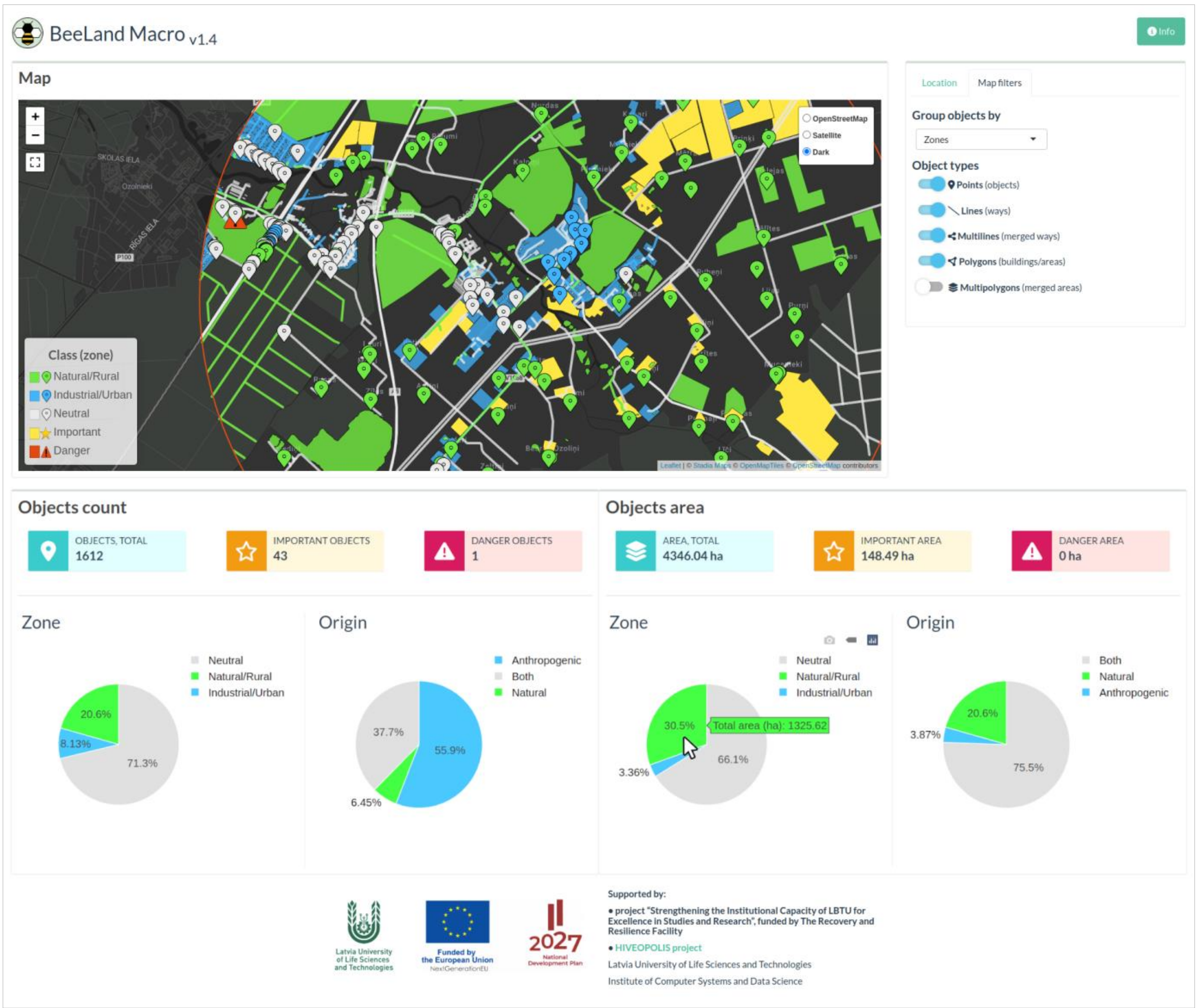


Figure 9. General view of the BeeLand Macro application.

By using map filters, it is possible to manage the visibility of OSM spatial features (as layers), encoded by different colors depending on a class (described on the legend of the map). Each spatial feature can be explored individually and interactively by inspecting its properties, which are displayed in a pop-up window that appears by clicking on the specific feature (see Figure 10).

Figure 10. Properties of spatial features (polygon).

The classification summary represents an interactive visualization of DPM results, developed with an emphasis on the ease of perception. Classification results are grouped by the object count and object area and allow assessing the situation regarding various environmental characteristics, such as the approximate level of urbanization, anthropogenesis, and the greenness of territories. Individual information blocks highlight specific information regarding individual groups of objects that require special attention. These include important and dangerous objects in particular. Using summary pie charts makes it easy to evaluate the percentage ratio of different zones and the structure of the origin of spatial objects. As a result, the user could have a general understanding of the environment in a particular location, which could be helpful in the decision-making process as well as in planning further activities.

3.5. Crowdsourced Data

Since this study focused on exploring the potential of using crowdsourced data, it is important to highlight the key characteristics of such data, namely their quality and completeness. OSM data, often regarded as one of the best examples of crowdsourced data and Volunteered Geographic Information (VGI), have quality and reliability as some of their most widely discussed attributes [62–66]. Various approaches and methods have been proposed to assess and improve the quality of OSM data, including comparisons with reference datasets [67,68], the use of machine learning techniques [69,70], and intrinsic analysis [71,72]. Studies have examined different aspects of OSM data quality, such as completeness, logical and topological consistency, as well as positional and thematic accuracy [66,73,74].

Thus, due to the diverse aspects and characteristics of crowdsourced data, opinions on their quality and applicability vary. Some studies emphasize the positive aspects of crowdsourced data, such as accessibility, relevance, and practicality, while others focus on their quality issues, highlighting potential shortcomings. The authors of this study believe that these differing opinions among researchers are well founded. Crowdsourced data often exhibit significant heterogeneity in their characteristics due to the nature of their origin [75]. One of the most important factors contributing to this heterogeneity is the motivation of participants in the crowdsourcing process, specifically the presence of perceived benefits from their activity. This is reflected in the levels of data completeness and accuracy, which often vary by region. For example, more populated areas tend to achieve higher positioning accuracy and data completeness compared to sparsely populated regions [76]. Such outcomes are to be expected, as urban areas with developed infrastructure are likely to be of greater importance to a larger number of people than remote rural areas [77].

In beekeeping, it is also important to recognize the value of a specific territory for participants and their commitment to fostering symbiosis with other agricultural sectors. For instance, the territory where beekeepers and other farmers operate holds significance for both parties. Their collaboration can provide mutual benefits, as pollination is essential for agriculture [78,79], while also supporting the production of bee products. A crowdsourced data solution could serve as an information exchange platform to facilitate this cooperation. For example, crop farmers could update information about their activities, such as pesticide use, changes in crops and field structures, or the timing of upcoming plant flowering. This information would be highly valuable for beekeepers planning their activities, particularly migratory beekeepers seeking suitable areas to support their apiaries [80].

At the same time, since bees are highly sensitive to environmental factors, it is important for beekeepers to monitor the current situation in a specific region. Timely updates on issues such as pollution, new development projects, or the creation of a blooming garden could provide valuable information about changes in the environment. However, given the experimental nature of this study, the assumptions mentioned above are hypothetical and would require more detailed research if the concept were to be implemented for practical use.

3.6. Accuracy of Results

Although the main objective of this study was to investigate and demonstrate the technical approach, the accuracy of the results remains an important consideration. Since the solution presented in this study is a demonstration prototype, it is not intended to produce reliable data in real-world conditions at its current stage of development. To apply such a solution in real-world scenarios and obtain meaningful results, it must be thoroughly adapted to meet specific needs and scale. This adaptation should include a more detailed development of the data processing phase, particularly the classification and validation of crowdsourced data, in collaboration with relevant experts.

A particularly important step in developing a real product based on the presented prototype is attracting the target audience—potential users such as beekeepers, farmers, and other interested parties. This is a crucial point, as such a solution will primarily serve as an information exchange platform, where the main role will be played by its users and stakeholders.

The accuracy of the results in such a solution is highly dependent on the quality of the input data. Therefore, in the case of OSM and similar crowdsourced databases, the approach described in this study can be applied in real-world settings if interested parties and contributors in specific regions take collective responsibility for providing accurate and complete data for the common good. However, it is important to note that crowdsourcing, as an approach, inherently carries the risk of inaccuracies, which is an inevitable limitation despite the significant resource opportunities it provides.

4. Conclusions

The use of modern technologies in precision beekeeping helps to overcome various types of difficulties, making it sustainable and relevant to the nowadays realities. Research aimed at developing this branch of agriculture has led to the emergence of various effective methods and ICT solutions that provide significant support to beekeepers in their activities. This is especially relevant in the context of the current level of global digitalization. Given the role of beekeeping in agriculture and maintaining ecosystems, it is necessary to continue to explore possible solutions for current problems.

At the local level, the use of various types of IoT devices allows for the remote, highly accurate monitoring of the parameters of individual bee colonies. Numerous solutions exist, including commercial options, which indicate the relative development of this area. However, an analysis of existing studies has shown that one of the major challenges in beekeeping relates to environmental factors on a larger scale, such as the lack of suitable areas, pollution, and intensive agriculture, where the use of IoT devices could be challenging and inefficient. To adapt beekeeping practices to the environmental challenges and ensure suitable conditions for bee colonies, it is crucial to have data on the environment within the approximate flight radius of honeybees.

This study sought to explore the potential of using open geospatial data to support solutions in this problem area. The use of open spatial data is justified by the crowdsourcing approach in the development of such data sources, which is an effective method for providing data on a large scale. Additionally, emphasis was placed on analyzing real-time environmental data, which can be particularly valuable for beekeepers seeking to conduct a quick, general assessment of the environment during the planning stages of their activities.

Within the framework of this study, an experimental demonstration prototype of the solution was developed using the WEB and GIS technologies to explore the possibilities and demonstrate the technical implementation of the proposed approach. In its current stage of development, this solution is not intended for real-world application, as its practical use would require significant adaptation and further research in collaboration with experts and potential users. Nevertheless, this solution can serve as an example and a conceptual foundation for the development of similar solutions.

Overall, the study demonstrated the potential of this approach, which may also prove beneficial for similar research. However, it is important to consider the limitations and drawbacks. Given the scale of the problem and the multitude of environmental factors, obtaining accurate and reliable crowdsourced spatial data is challenging. As a result, assessing the accuracy of analysis outcomes, especially in classification, is difficult. While open data sources can significantly facilitate data collection, they present considerable risks of inaccuracies and incompleteness. Therefore, applying the developed solution in real-world conditions remains limited at this stage and requires further study and refinement. The research in the field of precision beekeeping highlights the importance and necessity of innovation, offering new opportunities and potential for further studies while contributing to the adaptation of agriculture to modern realities.

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