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Section: Sustainable Urban Development

Simulator of Sustainable Urban Development – a tool for selecting the optimal use of land

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Abstract

The most commonly known definition of an optimum land use, is the one according to which, it is such a use, which from legal and physically possible forms of use that are „coherent with its purpose", generates the highest land value (Kinzy, 1992). Sustainable urban development is the optimal way to use the area, which is one in which an area is reasonably used due to the favourable and unfavourable natural and economic. Optimal use of land then is one that offers balance between the evaluation criteria. The author developed a decision algorithm that combines elements of the basic principles of optimizing the environmental, social and economic factors. Environmental (natural) and social (anthropogenic) value optimization was obtained by applying the modified method using the matrix of characteristics that cause optimal land use. Economic optimization is calculated as income optimization – maximizing income from the transformation of land use, taking into account the costs of transition. Land value for all forms of use is determined by a positive and negative influence of natural and anthropogenic characteristics. The author developed the optimizer (simulator) of sustainable urban development in order to choose the rational (optimal) area allocation. It considers three aspects to determine the optimum state of use: first, the natural and anthropogenic characteristics, second, the economic characteristics and third, the conservation of the economic – environmental balance. The developed tool for choosing the optimal use will be extremely useful in the process of elaborating the space use plans. It will select the most advantageous solution for the area and help develop solutions to address issues of not only economic nature, but also concerning environmental and human needs. The concept of the optimal spatial information system will be applied to choose the function. The main simulator application is minimizing uncertainty in the spatial planning process.

Keywords: Sustainable Urban Development; land use; optimization; algorithm for decision-making.

Nomenclature

$T_1T_2 \ldots T_n$ – land function,
$x_1, x_2 \ldots x_n$ – individual land components,
$b_1b_2 \ldots b_n$ – weight of characteristics for the given use. The matrix of natural and anthropogenous characteristics resulting in optimal land use,
$C_1C_2 \ldots C_m$ – value of function for the current use.
W_k , W_{b11x1} – weight of the economic and environmentally-anthropogenous value
O_T – profitability of use transformation
W_T – value of land after transformation
K_T – transformation costs
C_{T1} and C_{T2} – transaction prices;
p_1, p_2 – probability of transaction price occurrence
W_k – price indicator
C_w – start price
J – unit of progression
W_A – value of land for the current use
W_P – value of land for the average use
w_S – game result
p_s –probability of occurrence

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1. Introduction

According to Wheaton [1], since the 19th c., the monocentric city model developed by Ricard has dominated. That model is based on the transport access costs, which conditions accomplishment of the so-called gradients, i.e. profits. The distance between the city centre and peripheries represents the most important characteristic of that model. The potential profits from the optimal land use, according to the author, are generated when the goods and services transport costs are minimised. On the other hand, Rossi-Hansberg [2] points out at the costs of commuting to work. Balance and optimal space use according to the author mean appropriate location of workplaces by determination of existence and uniqueness of the optimal allocation of workplaces [3]. Hence, location models present the city as economic models or as models of the city potential (gravitation).

During the 20th c., the optimal land use resulted from application of economic models. Beckmann [4] introduced the economic notion of the two dimensional continuous space used for area optimisation. Next, the configuration of urban space in two dimensional continuous space was developed with the focus on the flows of goods [5]. The optimal city development was presented by means of numerous computer simulations [6]. That theory has been accepted as a modern economic model based on transformation of the spatial field vector into a continuous plane [7].

Another approach to introduction of the sustainable development was offered by using spatial data presented in the form of layers (overlays) for environmental resources management. That method was called the "Design with Nature" [8]. Land use according to that method is understood as permanent or cyclic intervention of men aimed at satisfying the humane, material and spiritual needs [9]. The projects of eco-towns develop and become increasingly common. In different regions of the world they are referred to as the "new" urban environments focused on accomplishment of sustainable urban life supporting at the same time the environmental focus and transformation to low emission technology [10]. Urban environmental security [11] and focus on climate changes and achievement of low carbon dioxide emissions [12] become the priority components of studies while "creative towns" become an alternative [13].

Polish literature on the subject of optimal land use is not very extensive. In most cases it is devoted to optimisation of urbanised and suburban areas location or spatial location of economic entities. The optimisation method, which has its genesis in Warsaw optimisation method, also referred to as the land valorisation method is the basic method applied [14]. On the other hand, Bajerowski [15] elaborated the methodology for selection of the optimal land use. The space value diagnose based on the method applying the matrix of characteristics causing optimal use developed by Bajerowski was incomplete and insufficient for taking decisions based on it. As a consequence of absence of the model comparative units for all the states of land use the author of the study [16] complemented the matrix method by anthropogenous characteristics and added the method for determination of comparative units for the economic model after transformation.

This paper presents the algorithm for taking decisions on land allocation. The main objective of the study was accomplished by gathering, organising and processing the set of characteristics describing the optimal state of land use as the criterion for space evaluation forming the base for land use transformation. Additionally, active thematic overlays to the existing spatial information system were developed. As the result a simple and transparent pattern allowing conducting the land use transformation process and choice of the optimal area allocation.

2. Sustainable Urban Development

Spatial planning of a town as a result of which the specified land use method takes place is, or rather should be based on the postulates of widely understood sustainable development that is, according to Ogryzek [16], postulates of rationality of the resultant of the social and economic needs and environmental conditions. Determination of the appropriate direction of development results in the need of using newer and newer models that would support the decision-taking processes concerning space function transformation as legal regulations and management methods require continual improvement of planning methods by combining new scientific disciplines aiming at regulation of development processes. The main objective of that work is to organise in a systematic way the set of characteristics describing the optimal state of land use as the space evaluation criterion representing the base for land use transformation.

According to Cymerman [17], sustainable development of space is of global character and that is why, in construction of its model, it is necessary to:

- combine agricultural and forest land resources management into one system and subject it to uniform rules,
- introduce such forms of natural resources management that would assure maintaining their renewability
- apply modern solutions and technologies protecting resources while retaining their high quality
- consider social conditions related to maintaining the cultural traditions
- consider economic conditions related to the costs of sustainable economy implementation.

Bajerowski [15], claims that identification of components defining the optimal and rational land use is the main problem. He divided them into two groups of conditions: those of natural and those of anthropogenous nature. Conditions of the natural environment change slowly and in the way allowing objective evaluation in the aspect of their functioning. On the other hand, the anthropogenous type conditions are the exponent of the living standards in the given area and they may change rapidly. Defining the character and intensity of the function in a way preventing causing degrading or destroying the natural values that were or are the base for its development represents the main problem related to the natural environment use.

Space, by communicating its characteristics in a specific location, attracts certain events and allows interpretation of them. The attributed set of objective characteristics has no value; only the man gives those characteristics the value depending on the specific plans. The specific collection of geoinformation (space characteristics) in the given place creates the potential that may be measured by the probability of occurrence of events (optimal land use) that those space characteristics are supportive to. Land allocation optimisation, particularly in urban areas, requires solving numerous tasks formulated at the stage of studies and analyses that minimise the possibility of spatial conflicts development. Optimal use of the area is the state where the sum of natural and anthropogenous values for the given function is higher than the natural and anthropogenous value of the current function and where the economic value after transformation is the highest as compared to the other functions of the area.

2.1. Land Use Optimisation Procedure

The core or optimisation is that every fragment of space at a given moment has the possibility of accomplishing the optimal state of use. However, presence of appropriate characteristics in the given area does not "force" the space to assume the correct use status. It should only be concluded that the probability of transformation of the current use state towards the optimal state is the highest (maximal). The accident will cause that the given state would actually be achieved [18]. According to Bajerowski, every land use state is at the same time the function of the demand for the given space use. The demand causes that either areas possessing characteristics appropriate for the given state are chosen of the necessity occurs to transform those characteristics for the purpose of obtaining the optimal use situation. That is why the name "area function" can be used as alternative for "land use state". The Earth surface use state may be characterised according to indicators such as the current way of use, the best suitability of the area for its use as concerns its internal characteristics, the best suitability of the area according to its allocation [18]. Area allocation optimisation, particularly in urban areas requires solving numerous tasks formulated at the stage of studies and analyses to minimise the possibility of spatial conflicts development.

Urban space area allocation optimisation aims at control of the current use with the potential for function change into one that will be consistent with the land allocation. In the studied urban area the function matching the natural, anthropogenous and economic characteristics the best should be left while functions that are not optimal should be excluded. The aim of the work is to show that land use transformation is one of the major elements in planning space optimisation.

The studies were conducted in a number of stages listed below. During stage one, the analysis of current solutions as concerns the systems and procedures for taking strategic decisions related to spatial planning and land use optimisation was conducted. The methods and tools of rational planning space management were organised in a systematic way and the existing methods and tools used for evaluation and valorisation of land development status were adapted. Stage two involved development of decision-taking algorithms (so-called decision-taking models) for selection of the optimal area use employing the simulator of sustainable development of towns using the updated matrix of characteristics causing optimal states of use developed for that purpose. Stage three involved development of active thematic overlays (layers) to the existing spatial information systems for the purpose of presenting the process results, the results that support highly diversified spatial undertakings, including the spatial management process:

- thematic overlay (layer) of spatial attributes – defining the positioning, size and geometric shape of objects and their spatial (topologic) relations
- thematic overlay (layer) of descriptive attributes – defining non-spatial characteristics and relations of objects
- thematic overlay (layer) of natural value attributes
- thematic overlay (layer) of anthropogenous value attributes
- thematic overlay (layer) of economic value
- thematic overlay (layer) of social needs
- thematic overlay (layer) of environmental contents

Stage 1 – Lack of the concept for development of spatial information systems containing data, characteristics or methods useful in rational planning space management is one of the most important problems of large towns. Bajerowski claims that identification of components defining the optimal and rational land use is the major problem. He divided them into two groups of conditions – the natural ones and the anthropogenous ones. Conditions of the natural environment change slowly allowing their objective evaluation from the perspective of their functionality. On the other hand, conditions of anthropogenous type are the exponents of the living standards in the given area and may change their value rapidly. Determination of the character and intensity of the function in the way causing no degrading or destructing the natural values that were or are the base for its development is the main problem related to the natural environment use. The process of land use changes is a permanent process. This is caused by the population increase and socioeconomic development worldwide. The needs of people increase while the natural potential are being exhausted. Optimal land use must consider human needs and the needs of the nature and hence the environment balance. Environmental impact evaluation is one of the basic tools management during the development processes meeting the requirements of the sustainable development principle. The environment is understood here not only as the natural environment but also as the social environment.

The most frequently encountered definition of optimal land use is the one according to which, it is such a use, which from legal and physically possible forms of use that are „coherent with its purpose", generates the highest land value [19]. The optimal land use state then can be understood as the function of the needs of the nature and of the men (as the sum of natural and anthropogenous characteristics values that results in the highest value of the land). Consequently, the conflict exists between the necessity of satisfying human needs and the necessity of changing the land use with the changes in the environment conditions and natural possibilities.

Stage 2 – In line with the definition by Kinzy [19], based on the analysis of the rational decisions theory, it is possible to determine the postulates of rationality of the optimal area use, that is:

Postulate of rationality – meaning that the given area can be transformed to the optimal function if it satisfies two conditions of optimal decision rationality (conditions of terrain function optimality) simultaneously:

- the natural or anthropogenous values for the given function are equal or higher than the natural or anthropogenic values of the current function,
- the sum of the economic value after transformation and the natural and anthropogenic value is the highest compared to the other functions of the area.

Using linear programming, the mathematical notation of terrain function optimality is proposed. Analysing a given problem for the purposes of space management, the solution of the system of inequalities represents the optimal solution:

The system of inequalities must satisfy the condition 1 (1).

$$\begin{aligned} b_{11}x_1+b_{12}x_2+ \dots + b_{1n}x_n &\geq C_1 \\ b_{21}x_1+b_{22}x_2+ \dots + b_{2n}x_n &\geq C_2 \\ &\dots\dots \\ b_{m1}x_1+b_{m2}x_2+ \dots + b_{mn}x_n &\geq C_m \end{aligned} \tag{1}$$

If the value of a function other than the current function of the area satisfies condition 1 (1), then from the perspective of rationality it should be accepted. However, satisfying just one of the above postulates is insufficient as the postulate of maximisation of the purpose function according to which the area must satisfy the condition 2 (2) remains to be satisfied. Let us assume that $k_1k_2 \dots k_n$ are the market price indicator W_k.

$$\begin{aligned} U &= k_1 + (b_{11}x_1+b_{12}x_2+ \dots + b_{1n}x_n) = \max \\ U &= k_2 + (b_{21}x_1+b_{22}x_2+ \dots + b_{2n}x_n) = \max \\ &\dots\dots \\ U &= k_n + (b_{m1}x_1+b_{m2}x_2+ \dots + b_{mn}x_n) = \max \end{aligned} \tag{2}$$

Every fragment of space has, at the given moment, the possibility of accomplishing the state of optimal use. However, initiation of every change in the use of that area into the optimal one should be preceded by determination of the transformation profitability as it may happen that the value of the difference between the value of the area under the future optimal use and the current value of the land will be lower than the transformation costs (e.g. costs of elaborating the new local spatial development plan, construction of the technical infrastructure devices, improvement of the status of the roads). In such a case the change of the current land use will not be profitable. The profitability of transformation is the difference of the land value for the given area function and the costs of transformation to that function (3–4) [21].

$$O_T = W_T - K_T \tag{3}$$

For the transformation to make sense, the future value of the state of use must satisfy the condition of the following formula:

$$O_T \geq W_A > W_P \tag{4}$$

The transaction price indicator (area value) obtained from the computer simulation of real property sale by tender is proposed to be applied for determination of the comparative unit for different states of land use. This is a modification of the formula (5) for the expected value of the game [22].

$$\begin{gathered} W_k = (C_{T1}, C_{T2}, p_1, p_2) = p_1 C_{T1} + p_2 C_{T2} \\ C_T = J + C_w \\ J = (1\% \ C_w) * \text{number of occurrences} \end{gathered} \tag{5}$$

The game variations should be computed to obtain a more precise risk measures. The larger the deviation from the results is the more risky the game is source [22]. The software choses the price indicator the risk of which obtained from the modification of the formula (6) for game variations is the lowest [22].

$$WG = \sum_{s=1}^{n} p_s (w_s - W_k)^2 \tag{6}$$

The value of the area for all the functions is determined as the most probable sale price for the real property obtained through tender. Comparison of the indicators for all functions of the area allows determination of the potential profits from disposal of the real property through tender for every method of use. In this way determination of expected model comparative units for all area functions is possible.

Next, the use optimality parameters should be standardised to allow the possibility of comparing them (7):

$$\begin{gathered} W_{k\,1} + W_{(b11x1+b12x2+\ldots+b1nxn)} = \max \\ W_{k2} + W_{(b21x\ 1+b22x2+\ldots+b2nxn)} = \max \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ W_{kn} + W_{(\ bm1x1+bm2x2+\ldots+bmnxn)} = \max \end{gathered} \tag{7}$$

The author developed the simulator of sustainable urban development for determination of comparative units for different states of use (Fig. 1). Based on the method of the matrix of characteristics modified by Ogryzek [16], it determines the functions that are suspected to be possible based on the postulate of rationality and indicates the optimal use.

Fig. 1. Sustainable Urban Development

As the output of the tender process simulation, the application determined the required parameters ready for analysis based on the application input data and the random factor. The application also uses the conducted psychological analysis of decision-takers and mathematical devices from the games theory applied in case of auctions, i.e. tenders according to the theory of games. Hence, the Simulator selects the value the occurrence of which is the lowest. The function marked with blue circle satisfies the conditions of optimal area function while the current function is indicated by the red circle. The necessary weights of individual terrain component characteristics for the natural characteristics are obtained from the matrix of natural characteristics by Bajerowski [15] and the matrix of anthropogenic characteristics by Ogryzek [16]. The Simulator, based on the data from the map, determines the natural and anthropogenic values applying linear programming. Using the built in module of sale simulation, it will determine the economic value of the studied land lot.

Postulate of limited rationality – The given area can be transformed to suboptimal function or may be left in its current function if rational environmental (environmental value) or social needs (social value) for that exist.

According to Penc [23], people aim not so much at optimal solutions but rather at solutions satisfying them. In the majority of cases, in individual or corporate decision taking the aim is to detect and select satisfying solutions and only in exceptional cases the aim is to detect and select the optimal solutions. Instead of searching for the best or ideal decisions, people are satisfied with the decision that satisfies their needs to the satisfying extent only.

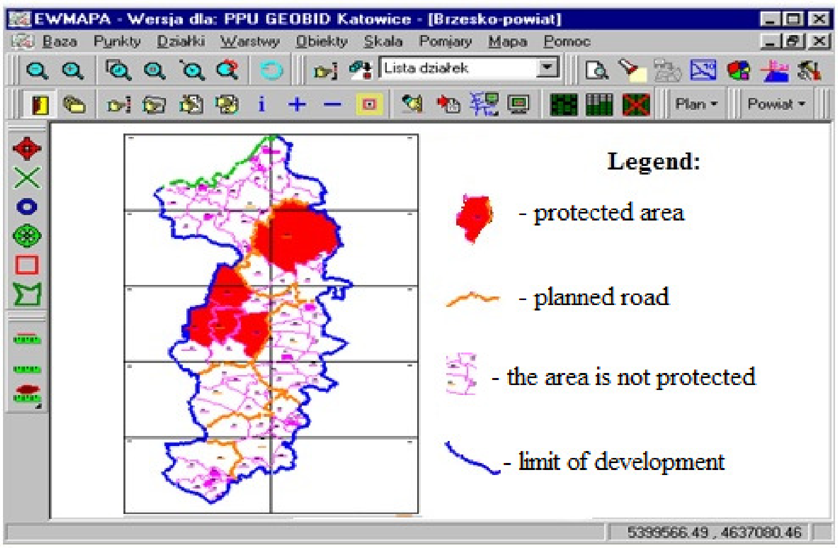

Fig. 2. Proposed variant of motorway course excluding the possibility of crossing Nature 2000 protected areas

Figure 2 presents the environmental impact study concerning a motorway. In the map the filter was applied for visualisation of the areas protected by Nature 2000 programme (red colour) as the reasons for the given variant of the motorway course. Using the arguments in the form of the postulate of limited rationality we apply not to change the current use into optimal in the protected areas. Moreover, the second factor of limited rationality can be noticed, i.e. the social pressure to prevent adaptation of protected areas for construction of road infrastructure.

Stage 3 – The database generated in the simulator of tenders may be used in different ways. First, development of the independent specialist interface named OPTYMALIZACJA [OPTIMISATION] will integrate the GIS software database with the database of the developed simulator of the optimal use of town. Development of the independent interface will allow performance of operations (simulator edit mode) and recording their results on independent layers. Second, (without application edit mode), there is a possibility of recording the results in the form of scanned documents, descriptions of lots or the database of data generated in the process. Third, the enquiry interface or feedback interface it would allow indicating objects that satisfy certain conditions. This can be accomplished in different ways: as patterns, markets or colour change.
As the outcome of conducting the optimisation process for the individual lot, we will obtain thematic layers as the:

- complement to the thematic overlay (layer) of spatial attributes – defining the positioning, size and geometric shape of objects and their spatial (topologic) relations
- complement to the thematic overlay (layer) of descriptive attributes – defining non-spatial characteristics and relations of objects
- thematic overlay (layer) of natural value attributes
- thematic overlay (layer) of anthropogenic value attributes
- layer of economic value attributes of the studied area for each suspected optimal area function.

3. Specialist analyses – own studies on Sustainable Urban Development

The Spatial Information System is a system for obtaining, processing and making available the data to the system users and hence it can be extremely useful in supporting the processes of regional development and competitiveness of regions. It is expected that the Spatial Information System will support regional development, investment processes, allow analysing socioeconomic phenomena changing in time and space, building scenarios and forecasts as well as taking decisions by investors and at all public administration levels. Given the above premises, it would be useful to include in the system the module of database generated in the process of planning space optimisation to feed, analyse and use geoinformation and to present the results (thematic layers) for such processes that support highly diversified spatial undertakings, including the spatial management forecast. Expanding the geoinformation systems with the proposed thematic layers would allow spatial analyses and simulation of space use optimisation processes. It may also form an independent tool (plug) in any GIS environment, which would cut down the costs and shorten the time of development of the optimal conditions for function choice and positioning of, e.g. roads, tunnels, bridges, recreation places, schools and kindergartens, etc. Location and spatial distribution of the population are the fundamental tasks of planners, urban planners and the transformation operation, the application of which must be justified is the necessary taking the decisions (spatial management). The methods and tools proposed in the paper should represent the necessary component of every contemporary Spatial Information System. That system supports spatial planning, registration of objects and spatial installations. At the same time, it is the tool for performing operations on spatial data and, first of all, it is a digital collection of maps. Performance of specialist analysis after input of the results from the simulator of optimal allocation of areas requires application of filters and markers as well as marking with special patterns the lots satisfying a specific condition, i.e. the lots with specified current use status.

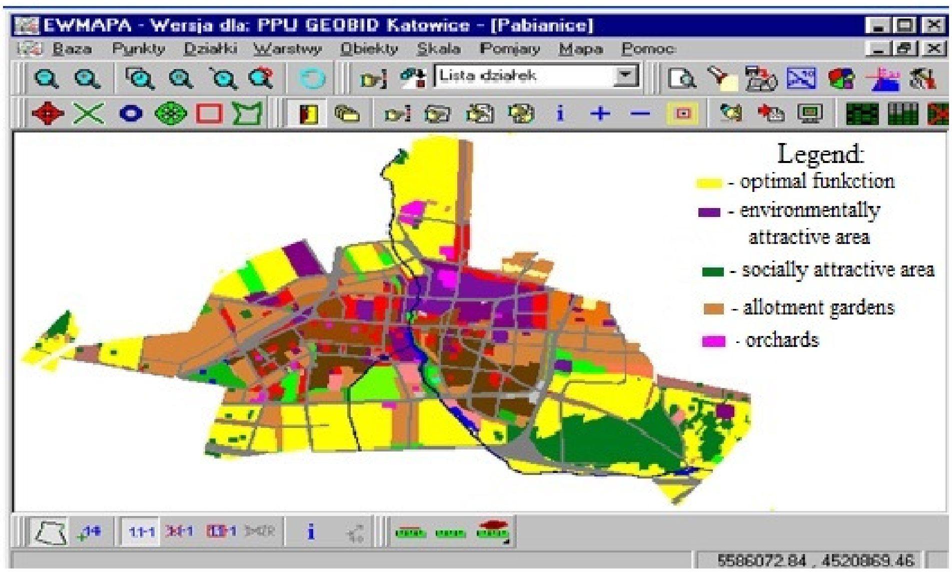

Fig. 3. Inventory of lots in the process of optimisation

In Figure 3 the lost the current use of which satisfies the postulates of rationality were marked in yellow using the GIS software. Lots that satisfy the postulates of limited rationality were marked in green and violet. The other colours were used to mark other suboptimal functions, infrastructure, linear elements, etc. It should be verified whether a legal-administrative possibility of transformation exists for the remaining lots in the studied area according to their allocation to the optimal function. The detailed analysis indicates that as a consequence of the town development, the areas with non-urban function, i.e. arable land, orchards and garden lots were "swallowed".

Analysis conducted in Figure 4, in which only the lots for which allocation of the area for construction of a kindergarten could be the optimal use were marked in green presents another use of the simulator. The area chosen by the town for kindergarten construction should be consistent with its allocation and that is why the marker was used to indicate the register lot that satisfies the additional condition, i.e. generates the highest profits in case of selling it for construction of a private kindergarten.

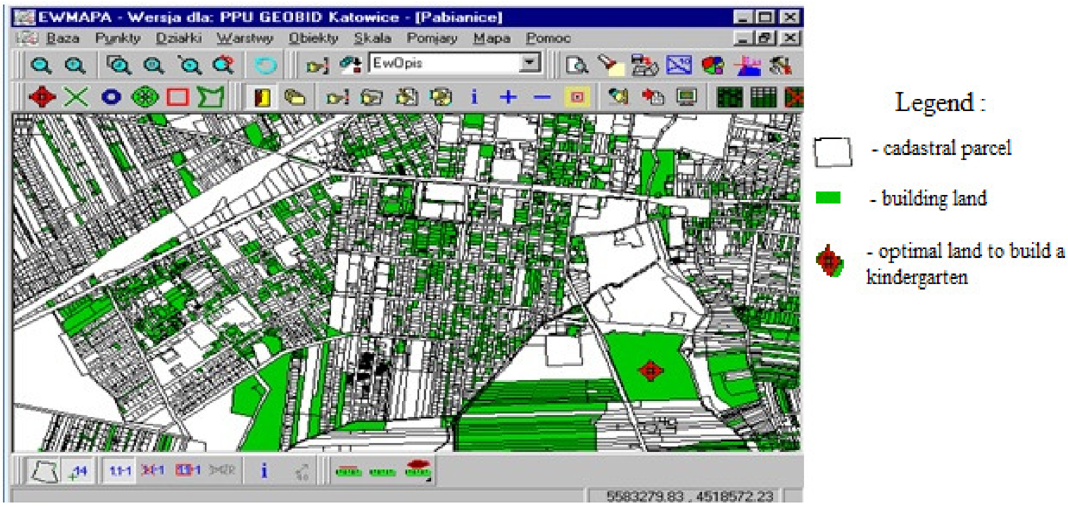

Fig. 4. Search for location for a kindergarten

4. Construction of references

Transformation of land uses is one of the main tools (instruments) of planning space management (spatial management). As the target and outcome, spatial planning must optimize the relations between the natural-economic value and the social-environmental value of space. It cannot be forgotten, however, that the main goal of spatial management is to protect specified values of the space and to give the space rational shape. Protective activities cover the efforts at maintaining balance between the natural elements of the environment and products of human activity. Space development, on the other hand, is the transformation activity related to the new directions of socioeconomic development. Hence, optimal land use results from the balance between the criteria of its evaluation.

The GIS (Global Information System) is the system of obtaining, processing and making data available to the users and hence it is obvious that it will support development, investment processes, allow analysis of socioeconomic phenomena as well as building scenarios and forecasts and taking decisions by investors based on its data. The prospects for system development include activities involving data complementing and updating, extension of teleinformation infrastructure, purchase of necessary equipment and software. Conversion of data, characteristics and methods in the spatial information system is the result of multi-criteria analysis of rational space management process model solutions process. Model solutions consider the trends in spatial process optimisation and trends in global economy. Formulation of model solutions for generating spatial information systems in the aspect of functionality and costs incurred as well as factors influencing operation of rational land function transformation management aims at minimising uncertainty in the spatial planning process. The system presented can be used in different scales and at different fields of application.

As the output of the conducted land use optimisation process, we will obtain the database that may be used as thematic layers of maps in the spatial information systems. The expected results include, among others, consistent, current and reliable spatial and descriptive data as well as information about the data, streamlining of information flow, increase in work efficiency and effectiveness of taking decisions, transparency of public decisions taken, assuring general access to the data and public evaluation of decisions taken as well as improved effectiveness of funds use in the economy.

The developed decision-taking algorithm, thanks to the tools of which it has been composed, allows determination of the optimal land allocation. Use of the developed simulator and the matrix of characteristics determining the optimal states of use for the design purposes will allow determination and control of the projected model comparative units for all area functions as well as determination of the optimal area function conditions. The developed tool for selection of the optimal function may be extremely useful in the process of space use plans development. It will allow choosing the most favourable solutions for the given area; it will help develop solutions considering not only the economic but also the environmental aspects and human needs.

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