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Shape and size of parcels and transport costs as a mixed integer programming problem in optimization of land consolidation

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ABSTRACT

This article presents a new approach to the problem of optimization of land arrangement. The new element is the use of binary variables in the calculation model using the principles of linear programming. For this reason the optimization model can be classified into the category of mixed integer programming problems (MIP). The proposed optimization model takes into account a number of very important factors in the process of land consolidation, including map of the land diversification or the actual shape of the transportation network. That also implies taking into account the real, not the straight-lined distances between different parts of the model. The solution of the model is an arrangement of plots minimizing the costs associated with the cultivation of these plots, depending on their shapes and distances from homesteads. The value of the land of individual farms before and after the consolidation is preserved. Optimization model has been saved and executed in the environment of the GLPK (GNU Linear Programming Kit) software package.

The presented method has been used to carry out the optimization process on the test object of the area of 587 hectares. The outcome is a new layout of plots in a form which meets all the technical requirements required in the real project process.

1. Introduction

The spatial structure of agricultural land significantly affects the profitability of farms. The existing arrangement of plots is the result of the long-term influence of many factors of historical, social and economic nature and changing legal regulations. They regulate *inter alia* the principles of inheritance and making divisions of land. The result of these processes is the appearance of a phenomenon known as fragmentation of land (McPherson, 1982), which in a very adverse way affects the profitability of agricultural production (Latruffe and Piet, 2014). Fragmentation of land is one of the main causes of the degradation of agricultural areas (Sklenicka, 2016), including the abandonment of agricultural production (Deininger et al., 2012), although this phenomenon has also positive aspects. They include maintenance of high biodiversity (Markuszewska, 2013) and a close relationship with valuable cultural landscapes (Taylor, 2002).

Improvement of the farm land configuration in the short term is possible in practice only through the land consolidation (Sonnenberg, 2002), which in various forms is an activity present in most countries in the world, with a very long history (Lambert, 1963). The land consolidation works are generally carried out in particular in areas with the high fragmentation of land and high population density, mainly in Central and Eastern Europe (Hartvigsen, 2014) and Asia (Niroula and Thapa, 2005).

The procedure of land consolidation is a set of activities of technical, administrative and legal nature, aimed at designing a new layout of plots in the area advantageous from the point of view of agricultural activity. The effects of land consolidation works most often have an economic dimension (Lerman, 2002), but they are seen also in the context of improving the quality of landscape (Gu et al., 2008), protection of the environment (Crecente et al., 2002) and the improvement of the functioning conditions of the local community.

The duration of the full process of land consolidation depends on the applicable national legal requirements, area and the number of plots and the concerned participants. It usually lasts up to several years. Designing a proper configuration of plots is widely regarded as a basic and essential element of the whole consolidation process (Cay and Iscan, 2011; Uyan et al., 2013). It should meet a number of criteria, in order to be accepted without protest by the owners of the land. For this reason, the tools and algorithms

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supporting the process of creating a consolidation project are constantly being developed, including mathematical optimization processes implemented using computer techniques (Lemmen et al., 2012).

The purpose of the research was to propose solutions for optimizing the layout of plots, which would correspond to the requirements of the real process of land consolidation as much as possible. In known methods there is no solution, which assumes the minimization of agriculture costs in areas separated as a result of the land consolidation, taking into account their size, shape and actual distance from the centers of individual farms.

The proposed new approach to optimization uses linear programming with binary variables (Schrijver, 1998), which can be classified as a mixed integer programming class (Wolsey, 2008). This approach, in the case of the construction and resolution of large models, belongs to the Non-deterministic Polynomial-time (NP) class (Genova, 2011). Therefore, the whole method can be classified as a heuristic solution.

2. Optimization in land consolidation

Methods of mathematical optimization of the plots configuration have a long history (Stelmach et al., 1975; Kik, 1980) and are constantly being developed, which is related to the timeliness problems of fragmentation of land in rural areas, development of computational techniques and the increase in computing performance.

Considering the issue of the plots configuration optimization, the elements, which in the model, in the theoretical approach, should be taken into account, need to be mentioned. The first one is the consideration of the area and shape of plots generated in the optimization process. Because these parameters have the decisive influence on the economic aspects of the farms activity, changing of these parameters, together with the change of their arrangement in space, is the essence of the process of land consolidation. The second element is the consideration of the actual shape of the transport roads network in the area of land consolidation. Distance to the cultivated plots (in the form of costs incurred in connection with transport) is of great importance to the owners of consolidated land, and their minimization should be one of the results of the optimization process. The third element is the need to take into account the elements that restrict the freedom of new frontiers designing: the boundaries of built-up areas, the course of fences, high escarpments, borders of dense forest and water complexes. These elements, together with existing and planned road network and system of rivers create a division of the object on compact complexes, where the plots can be freely designed.

In the view of the optimization process, it is important to mention the issue of the land value maps. Disregarding this factor reduces the process of reallocation of land to a much-simplified version, assuming equal area approach to the separation of land. The need to develop methods of mass valuation of land as an element supporting the process of land consolidation and optimization observes *inter alia* Demetriou (2016).

The final aspect is the integration of optimization algorithms with the whole package of technical solutions used in the process of consolidation (and sometimes in its planning and evaluation), striving towards the building of integrated systems supporting this process. Most of such systems rely on GIS techniques (Demetriou et al., 2012; Tourino et al., 2003), a lot fewer on CAD platform (Janus and Zygmunt, 2016).

Existing optimization models use a number of different approaches and algorithms to obtain the final solution. One of the suggested ways is the use of heuristic methods, proposed by Tourino et al. (2003). In this approach, simulated annealing method (Kirkpatrick et al., 1983) was proposed for searching and narrowing the set of feasible solutions. Another group of heuristic solutions are the methods based on genetic algorithms (Goldberg, 1989), which are an effective tool for solving difficult computational optimizing processes in the field of land consolidation (van Dijk et al., 2002; Akkus et al., 2012; Demetriou et al., 2013).

A further approach to the problem of land reallotment is the use of fuzzy logic methods (Zadeh, 1988), proposed by (Cay and Iscan, 2011). Results obtained on the example of the village Agalar were largely in line with the 'interview-based land reallocation model', what indicates the possibility of using this method in the actual consolidation work.

Another group constitutes methods based on linear programming (Dantzig, 2002), which have long traditions in the process of resolving issues related to the optimization of land use structure (Arthur and Nalle, 1997), in solving multi-site land-use allocation (MLUA) problems (Aerts et al., 2003) and optimization of the plots configuration in heavily urbanized areas (Kucukmehmetoglu and Geymen, 2016). The first attempts to use methods based on linear programming in the process of land consolidation were made in the eighties and nineties of the last century (Stelmach et al., 1975; Kik, 1980; Avci, 1990). Due to the low speed of computers, for a long time, the use of these methods resulted only in the optimal allocation of the land of individual owners in objects, which have been divided into a small number of blocks (complexes) of land.

One of the modern approaches to the use of these methods is the one proposed by Cay and Iscan (2006), optimizing the layout of plots through their exchange within the defined blocks, into which the optimized area was divided. Other assumptions were adopted in the reallotment model based on block priority (Musa, 1999), which is an algorithm that is characterized by a very large reduction in the number of plots on farms. This model does not take into account the distance matrix, its minimization, and wishes of landowners.

Another model suggested by Ayranci (2007) uses a simplified cost approach. It takes into account to some extent the preferences of landowners and the time of travel based on the straight line distances between the individual elements of the proposed simple, theoretical configuration of the land. A limitation of the model is the lack of taking into account maps of land value and the straight line way of measuring the distances.

A model using the principles of linear programming to minimize the average real distance of land in a given area, rather than a straight line, was presented by Gniadek et al. (2013). The proposed solution did not include, however, the diversity of land value and optimizing the shape of the plots, and the resulting allocation of land has equal area approach character.

Among other approaches to optimization is based on the split of the consolidation area in blocks, and the blocks in the virtual strips separated in the direction of designing of plots (Harasimowicz and Janus, 2010). The above approach provides a solution for large and complex tasks. To support the process of reallocation of land, algorithms based on multi-criteria analysis were also proposed, including the Analytic Hierarchy Process (AHP) method (Cay and Uyan, 2013), which in the present case supports the process of obtaining the optimized land configuration due to the preferences of the landowners.

Still, other optimization methods are used in the case of of land consolidation models different from the classical ones. This group includes the Minimum k-Star Clustering method (that belongs to a group of integer binary programming methods) used to solve the model of land consolidation assuming the change of the landowners while maintaining the existing arrangement of plots (Borgwardt et al., 2011). Another method is to use quadratic