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Izvorni znanstveni članak

Optimization of Land Distribution in Land Consolidation

Rajica MIHAJLOVIĆ, Manojlo MILADINOVIĆ, Mladen ŠOŠKIĆ – Belgrade[1]

ABSTRACT. This paper describes the research on the application of single criterion and multi-criteria optimization of land mass redistribution. The mathematical modeling of the basic requirements for distribution and an example of solving multi-criteria weight models is presented here in the paper.

Keywords: land consolidation, optimization, land mass, mathematical model, redistribution, weight coefficient model.

1. Introduction

Technologically speaking, land mass redistribution consists of dimensioning and positioning land consolidation blocks in the land consolidation area, distribution of values (areas), ordering of new lots in a block and determination of their analytical elements (Mihajlović 2010).

This paper propose the way to select the block to which the land holding will be distributed using mathematical optimization methods. During the process we ought to determine the size, number and shape of the new lots.

In the last thirty years there has been an intensive work on this problem and many papers (Kik 1980, de Vos 1992, Gostović 1979, Grafarend et al. 1979, Kik 1992, Kropff 1977, Lemmen et al. 1986, Pelzer 1972, Hoisl 1984, Wurzl 1984, Miladinović et al. 1994, Mihajlović 1995, Avci 1999, Sonnenberg 1990, Cay et al. 2004, Cay et al. 2006, Cay et al. 2008, Rosman et al. 1998, Mihajlović 2010)

[1] Rajica Mihajlović, PhD, Geod. Eng., Faculty of Civil Engineering, University of Belgrade, Blvd. kralja Aleksandra 73, RS-11000 Belgrade, Serbia, e-mail: rajica@grf.bg.ac.rs,

Prof. Manojlo Miladinović, PhD, Geod. Eng., Faculty of Civil Engineering, University of Belgrade, Blvd. kralja Aleksandra 73, RS-11000 Belgrade, Serbia, e-mail: manem@grf.bg.ac.rs,

Mladen Šoškić, M.Sc., Geod. Eng., Faculty of Civil Engineering, University of Belgrade, Blvd. kralja Aleksandra 73, RS-11000 Belgrade, Serbia, e-mail: mladens@grf.bg.ac.rs.

showed that the help of computers and proven methods of operational research can automate and improve the methodology for developing the proposition (project) of the land mass redistribution and so give significant advantage comparing to the methods applied so far.

The land consolidation model[2] defined in this paper is based on the experiences from already implemented land consolidations and on the regulations in Serbia that are similar to the regulations in most European countries.

2. Defining Land Mass Redistribution as an Optimization Model

The conditions for production on agricultural land depend on fertility, shape, orientation[3], size and distance between a lot and the holder yard, water, paved road or market. Optimal conditions for production can be achieved using optimization methods for ordering and dimensioning the new lots. Taking into account the rules and experience of land mass redistribution (Mihajlović 2010) certain redistribution requirements can be defined and mathematically modeled in the following way:

1. New lots should have the largest possible area (value)

The request for the largest possible areas, i.e. new lots' values, can be defined with the objective function (1), for which the maximum will be demanded.

$$\max F = \sum_{i=1}^{n} \sum_{j=1}^{m} w_{ij} x_{ij} \tag{1}$$

where:

w_{ij} – is distribution coefficient (criteria) for j-th participant in i-th block

x_{ij} – is unknown lot value of j-th participant in i-th block,

w_{ij} coefficient can represent the value of the old land consolidation participants in newly designed blocks, the distance between blocks and holder yards, the minimal differences of soil quality in the old and the new situation or wishes of the participants.

2. Distance between new lots and holder yards should be minimal

The request to minimize distance between new lots and holder yards and maximize the value of new lots can be defined with the objective function (2) for which the maximum will be demanded in the optimization model.

$$\max F = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{x_{ij}}{d_{ij}}, \tag{2}$$

[2] Land mass includes all the land consolidation area.

[3] Position of the longer side of the lot according to the optimal planting zone.

where d_{ij} represents the distance between barycenter of i-th block and j-th holder's yard and can be determined using the designed road network.

3. New lots should have the most convenient shape

The request that a lot has the most convenient shape can be defined for the whole land consolidation area as the lower and upper limits for all lots (3), groups of block, individual block or even for each owner in each block.

$$x_{ij} \geq DL_i, \;\; x_{ij} \leq GL_i, \;\; i = 1, 2, \ldots, n, \;\; j = 1, 2, \ldots, m \tag{3}$$

where

DL_i – is the upper limit of new lots values in block i, and

GL_i – is the lower limit of new lots values in block i.

By defining the lower and the upper limits of new parcels and the project fixed table width we are directly determining their shape (a rectangle with the most appropriate aspect ratio).

4. The sum of new lots values should be equal to the sum of the old plots values

The request to give to each participant the value equal to the one they entered the land consolidation process with (decreased for the common area percentage, of course), is defined as the constrain function (4):

$$\sum_{i=1}^{n} x_{ij} = VP_j, \;\; j = 1, 2, \ldots, m. \tag{4}$$

If in (2) would be requested that these values can be with ±10% difference from the value that entered the land consolidation process, then there would be two groups of constraints that would represent the upper and the lower limit of the value assigned to the lot:

$$\sum_{i=1}^{n} x_{ij} = VP_j(0.9 + k)$$

$$\sum_{i=1}^{n} x_{ij} = VP_j(1.1 - k) \tag{5}$$

$$j = 1, 2, \ldots, m$$

where

VP_i – is the value of the j-th participant for redistribution,

n – is the number of land consolidation blocks,

m – is the number of participants whose holding is being distributed, and

k – is the common needs reduction coefficient.

5. Quality of old and new lots should have minimal difference

The request that the difference in the quality of the input land and redistributed lots be minimal can be defined with the following criteria function:

$$\max F = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{1}{|KP_j - KT_i|}x_{ij} \tag{6}$$

where

KP_j – is the ratio of the j-th owner's holding value and area, and

KT_i – is the ratio of the i-th block values and area.

The request set in (2) that the land distributed from redistribution's land mass can differ not more than ±20% from the area inputed to redistribution's land mass could be roughly defined by two sets of constraints:

$$\begin{aligned} &\sum_{i=1}^{n}\frac{1}{KT_i}x_{ij} \geq \frac{VP_j}{KP_j}(0.8+k),\ \ (j=1,2,\dots,m),\\ &\sum_{i=1}^{n}\frac{1}{KT_i}x_{ij} \leq \frac{VP_j}{KP_j}(1.2-k),\ \ (j=1,2,\dots,m), \end{aligned} \tag{7}$$

where k is the common needs reduction coefficient.

6. Same or smaller distance from the old and new lots to the holders yards

One solution to defining this request could be done with the objective function of the form (1) where the coefficient w_{ij} take the sum of the values of the old lots in newly designed blocks c_{ij} and for such objective function maximum is requested in the optimization model.

$$\max F = \sum_{i=1}^{n}\sum_{j=1}^{m}c_{ij}x_{ij} \tag{8}$$

Another possibility for defining the request for equal (or smaller) distances between old and new properties is to define the groups of constraints (9):

$$\sum_{i=1}^{n}PN_{ij}x_{ij} \geq \sum_{l=1}^{p}PS_{lj}v_{lj},\ \ (j=1,2,\dots,m). \tag{9}$$

That is, if we take the reciprocal values of distance from holder's yards to the barycenter of new block and the defined sector of old state for the path parameters (Kik 1980) it will be:

$$\sum_{i=1}^{n}(1/d_{ij})x_{ij} \geq \sum_{l=1}^{p}q(1/f_{lj})v_{lj},\ \ (j=1,2,\dots,m), \tag{10}$$

where

PN_{ij} – is the parameter of the path between j-th owner's yard and i-th block,

PS_{lj} – is the parameter of the path between j-th owner's yard and l-th old state sector,

f_{lj} – is the distance between j-th participant's yard and l-th old state sector,

v_{lj} – is the value of j-th participant's holding from the old state in l-th sector,

p – is the total number of sectors in the old state,

x_{ij} – is the unknown values of j-th participant's lot in i-th block,

d_{ij} – is the distance between j-th participant's yard and i-th block, and

q – is the coefficient of proportionality which defines the functional difference between old and new path network.

7. Respect wishes of the land consolidation participants for the land grouping

Participants' wishes can be taken separately for the location (block) of the future lot and for the size (value) of that lot or for the location and size of a future lot at the same time. Thus, for example, the wish coefficient may take: for the first wish – 100 points, for the second – 80 points, 60 points for third and so on.

Another solution is that the participant declare in which block he wants to get a lot, to give a number of alternatives and the sizes of the lot and possible variations from the given size (range). Based on the wishes defined this way, we could adopt the following limits:

$$\begin{gathered} x_{ij} \geq DZ_{ij}, \text{ za } DZ_{ij} > 0; \quad x_{ij} \leq GZ_{ij}, \text{ za } GZ > 0, \\ x_{ij} = 0, \text{ za } DZ_{ij} = GZ_{ij} = 0, \ (i = 1, 2, \dots, n; \ j = 1, 2, \dots, m) \end{gathered} \tag{11}$$

where

DZ_{ij} – is the lower limit for j-th participant's wish to get a lot in i-th block, and

GZ_{ij} – is the upper limit for j-th participant's wish to get a lot in i-th block.

The land mass redistribution based on the principle of wishes is given in Hupfeld (1971) and Mihajlović (2010).

8. The sum of new lots values distributed in one block should be equal to the *value of that block*

The criterion that the sum of values distributed to a block should be equal to the value of that block can be represented as a group of constraints whose general formula is:

$$\sum_{j=1}^{m} x_{ij} = VT_i, \ (i = 1, 2, \dots, n). \tag{12}$$

where GZ_i is the value of the reallocation blocks.

Certain deviation of the sum of new lots values from the block value could also be allowed for these requirements (e.g. ±10%). In that case, the constraints (12) would give two sets of constraints:

$$\sum_{j=1}^{m} x_{ij} \geq 0.9 \cdot VT_i,\ (i = 1, 2, \dots, n), \quad \sum_{j=1}^{m} x_{ij} \leq 1.1 \cdot VT_i,\ (i = 1, 2, \dots, n), \qquad (13)$$

9. The maximum and minimum for the number of lots per each owner

The maximum number for the number of lots per each owner can be written as:

$$\sum_{i=1}^{n} k_{ij} \leq MG_j,\ (j = 1, 2, \dots, m) \qquad (14)$$

Similarly, the minimum number of lots of an owner can be defined as:

$$\sum_{i=1}^{n} k_{ij} \geq MD_j,\ (j = 1, 2, \dots, m) \qquad (15)$$

where

k_{lj} – is the binary variable (0 or 1) (i = 1,2,...,n; j = 1,2,...,m),

MG_j – is the maximal number of distributed lots to j-th owner, and

MD_j – is the minimal number of distributed lots to j-th owner.

The defined constraints have to do with the shape of new lots, so when defining number of lots in the block one must keep that in mind. This could be introduced as the restrictions when using binary integer programming or mixed programming. The defined constraints could be used as constraints when applying binary integer programming (BIP) or mixed programming.

10. The maximum and minimum for the number of lots per each block

The maximum for the number of lots per each block can be constrained with equations:

$$\sum_{j=1}^{m} k_{ij} \leq NG_i,\ (i = 1, 2, \dots, n) \qquad (16)$$

While the minimum number of lots per each block is defined with the group of constraints:

$$\sum_{j=1}^{m} k_{ij} \geq ND_i,\ (i = 1, 2, \dots, n) \qquad (17)$$

where

k_{ij} – is binary variable (0 or 1) (i = 1,2,...,n; j = 1,2,...,m),

NG_{ij} – is maximal number of distributed lots in i-th block, and

ND_{ij} – is minimal number of distributed lots in i-th block.

This group of constraints is also only applicable in case of binary or mixed programming, as the previous one.

3. Optimization Models of Land Mass Redistribution

Mathematical models can be defined as single criterion or as multi-criteria optimization models by combining certain mathematically modeled requirements from Chapter 2.

3.1. Single Criterion Optimization Model

Considering the general formulation of linear programming mathematical model (Mihajlović 2010) adapted to solving with simplex method and mathematically modeled requirements for grouping lots and land mass redistribution in Chapter 2, the following mathematical model could be set as:

Objective function

$$\max F = \sum_{i=1}^{n} \sum_{j=1}^{m} w_{ij} x_{ij} \tag{18}$$

with constraints

$$\begin{gathered} \sum_{j=1}^{m} x_{ij} = VT_i, \ \ i = 1, 2, \dots, n, \ \ \sum_{i=1}^{n} x_{ij} = VP_j, \ \ j = 1, 2, \dots, m \\ DL \le x_{ij} \le GL, \ \ i = 1, 2, \dots, n; \ \ j = 1, 2, \dots, m. \end{gathered} \tag{19}$$

Therefore, we seek the maximum value of objective function F which is the product of distribution coefficients w_{ij} and the unknown values of new lots x_{ij}.

Coefficient w_{ij} and unknowns x_{ij} in the objective function can represent the following properties:

1) the sum of the old lots of redistribution participants that fall into the newly designed blocks $w_{ij} = c_{ij}$,
2) the reciprocal of distance between land consolidation blocks and holders' yards $w_{ij} = d_{ij}^{-1}$,
3) the reciprocal of the absolute difference between the ratio of lots (holdings) values and area which participants entered the land consolidation process with and ratio of reallocation blocks values and area $w_{ij} = |KP_j - KT_i|^{-1}$, and
4) wishes of land consolidation participants in percents (points) according to priorities ($w_{ij} = z_{ij}$); for instance: z_{ij} could take 100 for the primary desire, 80 for the first alternative, 60 for the second alternative, etc.

The groups of constraint can be defined by combining the equations defined in Section 2. Inequality sign may be used in place of equality sign. Then it can be allowed to distribute lower or higher value of new lots for a defined percentage (e.g.

10%) to a block and to compensate in money. The system of inequality constraints can be extended to new groups of equalities or inequalities. The first group of constraint equalities (19) can be replaced with two new groups of constraints:

$$\sum_{i=1}^{n} x_{ij} \geq VP_j(0.9+k),\ (j=1,2,\dots,m),\ \sum_{i=1}^{n} x_{ij} \geq VP_j(1.1-k),\ (j=1,2,\dots,m), \tag{20}$$

The second group of constraints (19) can also be replaced with two new equalities:

$$\sum_{j=1}^{m} x_{ij} \geq 0.9 \cdot VT_i,\ (i=1,2,\dots,n), \quad \sum_{j=1}^{m} x_{ij} \leq 1.1 \cdot VT_i,\ (i=1,2,\dots,n), \tag{21}$$

3.2. Multi-criteria Optimization Model

Multi-criteria programming allows introducing more objective criteria functions. Considering mathematical modeling of the land mass redistribution that is presented in Chapter 2 it is evident that the multi-criteria programming can include a greater number of defined requirements simultaneously, thus allowing objective optimization of land mass redistribution. For instance, the four objective functions in multi-criteria model taken from Chapter 2 can be defined by:

$$\begin{gathered} \max F_1 = \sum_{i=1}^{n}\sum_{j=1}^{m} c_{ij}x_{ij}, \quad \max F_2 = \sum_{i=1}^{n}\sum_{j=1}^{m} d_{ij}^{-1}x_{ij}, \\ \max F_3 = \sum_{i=1}^{n}\sum_{j=1}^{m} |KP_j - KT_i|^{-1}\, x_{ij}, \quad \max F_4 = \sum_{i=1}^{n}\sum_{j=1}^{m} z_{ij}x_{ij} \end{gathered} \tag{22}$$

The forming of a mathematical model starts from the fact that the distribution coefficients in criteria function (22) ($w_{ij} = c_{ij}$, $w_{ij} = d_{ij}^{-1}$, $w_{ij} = |KP_j - KT_i|^{-1}$ or $w_{ij} = z_{ij}$) are not in the same measurement units and thus must be normalized like in (23) and (24).

$$g_{kij} = \frac{w_{kij}}{\sum_{j=1}^{m} w_{kij}}, \quad i=1,\dots,n, \quad k=1,\dots,p \tag{23}$$

Normalized objective function has the following form:

$$\max F_k = \sum_{i=1}^{n}\sum_{j=1}^{m} g_{kij}x_{ij}, \text{ za } k=1,2,\dots,p=4; \tag{24}$$

The final objective function is reduced to single criterion function:

$$\max G = \sum_{i=1}^{n}\sum_{j=1}^{m} q_k g_{kij}x_{ij}, \text{ za } k=1,2,\dots,4; \tag{25}$$

where q_k is weight coefficient of each function.

Limits, with such defined objective functions, can be made by combining the equations defined in Section 2. For instance, they may be:

$$\sum_{i=1}^{n} x_{ij} = VP_j, \text{ za } i = 1, 2, \ldots, n; \quad \sum_{j=1}^{m} x_{ij} \geq VT_i \cdot P1_i, \text{ za } i = 1, 2, \ldots, n$$

$$\sum_{j=1}^{m} x_{ij} \leq VT_i \cdot P2_i, \text{ za } i = 1, 2, \ldots, n \tag{26}$$

$$x_{ij} \leq GL, \text{ za } i = 1, 2, \ldots, n; \; j = 1, 2, \ldots, m, \; x_{ij} \geq DL, \text{ za } i = 1, 2, \ldots, n; \; j = 1, 2, \ldots, m,$$

where

$VT_i \cdot P1_i$ is the upper limit of the sum of new lots that fall in the block i,

$VT_i \cdot P2_i$ is the lower limit of the sum of new lots that fall in block i.

For the coefficients $P1$ and $P2$ deviations percentage (e.g. 2%) could be taken to the discretion of (the designers) but their value does not exceed ±10%.

Thus a mathematical model can further customized to specificity of the methods defined to solve multi-criteria optimization problems such as interactive methods for solving like the STEM (STEP Method) method, weight coefficients method, the criteria functions space bound methods or the goal programming (Mihajlović 2010).

4. Example of the Application of Optimization Models in the Land Mass Redistribution

A mathematical model from (19) is tested on land consolidation area of 106.9727 ha with 261 lots before land consolidation that were belonging to 16 participants with an average 0.4098 ha.

Figure 1 shows the lots before and after the land consolidation obtained by applying multi-criteria weight coefficients method with four objective functions with the same weight of 0.25.

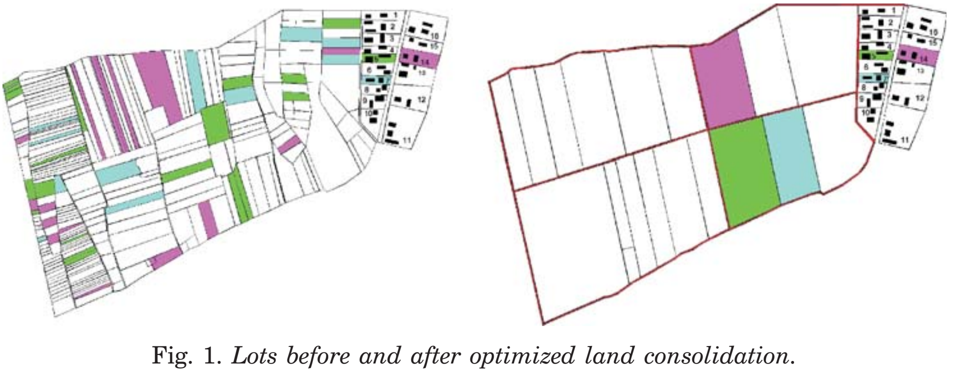

Fig. 1. *Lots before and after optimized land consolidation.*

Table 1. *Data on holdings of the participants in the old state of consolidation.*

Holder	Properties of holdings before land consolidation				
	Number of lots in old state	**Total area of lots (ha)**	**Total value of lots**	**Average value of lots**	**Ratio value over area**
1	17	43069.8	30523.3	1795.5	0.70859
2	19	79095.0	60700.8	3194.8	0.69206
3	11	21051.1	16035.4	1457.0	0.73462
4	15	66331.5	50778.2	3385.2	0.66960
5	19	71010.3	52609.1	2768.9	0.65574
6	21	67658.9	50813.4	2419.7	0.78170
7	13	64811.3	51444.8	3957.3	0.63951
8	19	64906.4	48365.1	2545.5	0.72841
9	21	89291.7	70351.2	3350.1	0.76747
10	16	78213.8	54128.1	3383.0	0.76277
11	16	68124.7	49930.5	3120.7	0.76731
12	12	43407.8	29089.4	2424.1	0.74102
13	10	101876.8	66882.8	6688.3	0.75112
14	19	82061.8	64148.0	3376.2	0.79392
15	18	75006.4	47966.7	2664.8	0.74519
16	15	53809.3	39183.1	2612.2	0.78784
Total	261	1069726.6	7829499	2999.8	0.73192

Table 1 shows the basic data on each participant's holding in the state before, and in Table 2 after, land consolidation as a result of the multi-criteria optimization weight coefficients method with four objective function (22), i.e. (25) with the same weight 0.25.

Calculation of the new lots values in land consolidation blocks was done using the MATLAB script named *VKRaspodelaTK* (Nikolić 1994) based on the mathematical model presented in (Vujošević et al. 1996, Martić 1978, Wagner 1975, Opricović 1998). Arrangement of new plots in one land consolidation block is done with script *Nadela* of *OPKOM* script library (Mihajlović 2010).

By analyzing the distribution criteria w_{ij} it can be seen that the (18) criteria 1) ($w_{ij}=c_{ij}$) and 4) ($w_{ij}=z_{ij}$) initially limit the distribution of new lots only to blocks where there are old lots in possession of a participant or where there is a defined desire, while criteria 2) ($w_{ij}=d_{ij}^{-1}$) and 3) ($w_{ij}=|KP_j-KT_i|^{-1}$) include the entire land consolidation area (every block).

Based on the results shown in Table 2, 19 new lots were obtained with an average value of 40817.7 a and enlargement coefficient of 13.7 times.

Table 2. *The distribution of new lots values in blocks using the weight coefficients method with four of the objective function with the same weights 0.25.*

Holder number		**Land consolidation blocks**			
		T1	**T2**	**T3**	**T4**
1	objective func. ceof. *g*	0.66	0.39	0.55	0.66
	value of lot *x*				**30087.7**
2	objective func. ceof. *g*	0.65	0.37	0.74	0.85
	value of lot *x*				**54074.9**
3	objective func. ceof. *g*	0.78	0.51	0.51	0.52
	value of lot *x*	**48665.5**			
4	objective func. ceof. *g*	0.55	0.29	1.05	1.10
	value of lot *x*				**29103.6**
5	objective func. ceof. *g*	0.27	0.35	6.22	1.45
	value of lot *x*			**66795.9**	
6	objective func. ceof. *g*	0.87	0.90	1.23	0.40
	value of lot *x*	**63505.1**			
7	objective func. ceof. *g*	0.30	0.28	12.32	2.76
	value of lot *x*			**48444.4**	
8	objective func. ceof. *g*	0.46	0.46	1.83	0.55
	value of lot *x*			**6725.2**	**31488.6**
9	objective func. ceof. *g*	0.75	1.00	0.00	0.49
	value of lot *x*	**6489.8**	**53582.8**		
10	objective func. ceof. *g*	0.64	0.89	0.00	0.42
	value of lot *x*				**15321.9**
11	objective func. ceof. *g*	0.72	0.95	0.42	0.48
	value of lot *x*	**41467.1**			**6220.6**
12	objective func. ceof. *g*	0.54	0.74	0.54	0.53
	value of lot *x*				**50968.4**
13	objective func. ceof. *g*	1.10	0.92	0.47	0.36
	value of lot *x*	**51048.9**			
14	objective func. ceof. *g*	1.61	2.12	0.00	0.28
	value of lot *x*		**51828.6**		
15	objective func. ceof. *g*	1.13	0.91	0.50	0.37
	value of lot *x*	**48645.9**			
16	objective func. ceof. *g*	1.54	1.95	0.40	0.29
	value of lot *x*		**71015.0**		

5. Concluding Remarks

Solving the land mass redistribution model is in most cases the large-scale problem and requires a professional software without software-hardware limitations. This is achieved to a large extent with software solutions from this work and from (Mihajlović 2010) which led to a solid basis for further works and improvements. According to the performed analysis it can be concluded that the weight coefficients method provides very useful results making it easier for decision maker by providing objective and optimal results.

Based on the research and obtained solutions from this work we can conclude that a real basis is created for further research and improvements of theoretical, technological and practical achievements.

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Optimizacija raspodjele komasacijske mase

SAŽETAK. U radu su prikazana istraživanja vezana za primjenu jednokriterijske i višekriterijske optimizacije kod raspodjele komasacijske mase. Izvedeno je matematičko modeliranje osnovnih zahtjeva raspodjele i prikazan je primjer rješavanja višekriterijskog modela metodom težinskih koeficijenata.

Ključne riječi: *komasacija, optimizacija, komasacijska masa, matematički model, raspodjela, metoda težinskih koeficijenata.*

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