Method of Optimal Machine Selection for Construction Processes from the Point of its Energy Consumption Minimizing with Software Support

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Abstract

Energy saving is one of the most important environmental factor during the process of building realization. During this process building planner has to analyse several factors influencing the final effective decision concerning this problem. There are several factors and criteria for effective selection of building machines. In our contribution, the proposed optimizing method is presented and the ability of machines to realize designed building process with minimizing of energy consumption (environmental aspect) is analysed. This method are implemented into two different construction processes: optimal selection of machine groups for soil excavations and optimal selection of the building elevators for vertical transport of building materials during the construction finished processes. Selected scientific methods and theories of problem solution can be divided into these groups: theory of system (creation of building machine selection method), optimizing method (analysis of mechanized building process from the point of minimum energy consumption), queuing theory (application during the mathematical modelling of mechanized soil processes), method of scientific analysis (analysis of factors influencing final decisions), method of scientific synthesis (creation of optimizing method implemented into building processes and possible application in construction sector). The effectiveness of implementation of these methods is increased by software support for both model examples. Results of our research work are shown, that with using automated system we can find optimal machine group for defined process very quickly and by this way during the process of building planning to increase the effectiveness of building machines selection especially form the point of energy minimization.

Keywords –
Construction mechanized process, Energy Consumption Minimizing, Optimal Method

1 Introduction

The optimal selection of machine or machine group for building processes is a very important role of building planner during the process of building planning. During this process building planner has to analyze several factors influencing the final effective decision concerning this problem.

During the process of building planning planner has to analyze suitable selection of building machines and its group for effective proposal of mechanized building processes.

There are several criteria for selection of building machines. In our contribution there are analyzed: the ability of machines to realize designed building process (quality aspect) and minimizing of energy consumption (cost and environmental aspect).

In our research work were implemented several theories and methods. The most important were the theory of systems [1] and principles of optimizing method [2], method of scientific analysis and synthesis. These methods were implemented into optimal selection of machine groups for earthwork excavations and optimal selection of building elevators from the point of minimal energy consumption with software support.

Applications of these methods and software will increase effectiveness of building machines selection from the point of its energy consumption minimizing. There are several authors who analyzed similar problems [3,4,5,6,8,9] concerning the optimal machine selection methods and their environmental impact to construction company effectiveness.

2 Energy Machine Selection Optimizing (EMSO) Method

EMSO Method is based on the theory of systems [1] and optimization theory of the process [2].
The "EMSO Method" consists of the three phases (Figure 1) – Entry phase, Decision phase and Optimization phase. An analysis of all these phases except entry is examined by Figure 1 [7]:

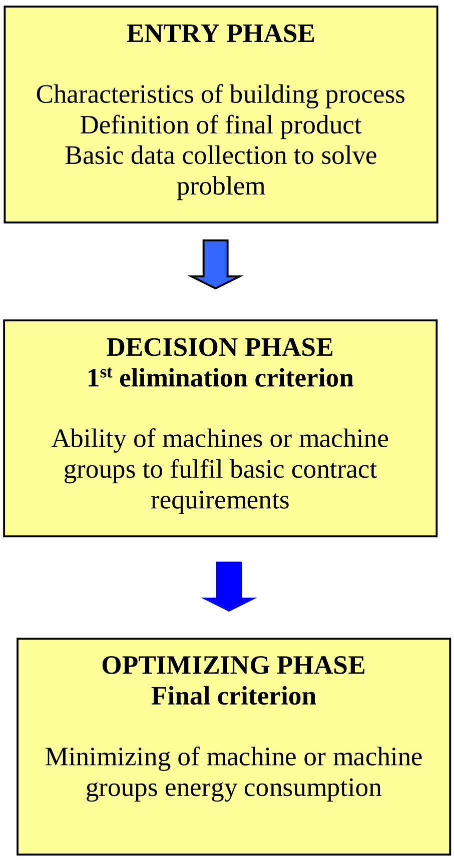


Figure 1. EMSO method phases and criteria

-*the input universe of the system:* that is the set of the machines submitted for analysis in the given phase,
-*the criterion*, according to it is the input universe of the system of given phase analyzed,
-*the procedural steps* being necessary to realize the appreciation of the input universe of the system according to the criterion of the given phase,
- *the output universe of the system*: that is the set of the transport means fulfilling the criterion of the given phase.
The entry phase contains delimitation of problem and objectives necessary to be reached by evaluating, for example the type of building works, characterization of the final product of the mechanized building process, input information necessary for solving of the problem and so on.
The preparatory phase characteristics*:*
The input universe of the system is the set of the transport means being suitable for a given type of the building works.
The criterion (1st eliminating) – production rate aspect (time required for the realization of the final product or quantity of production in determined time)
The procedural steps:
- the construction of the verbal – graphic model of the real system,
- the choice of the variants of building machines for realization of the final building product,
- the selection and the choice of the model variables, their definition, symbol, dimension, quantification with the source of the quantification,
- the formulation of the particular mathematical relations of the model,
- the construction of the mathematical model for appreciation of variants of machines to the 1st eliminated criterion,
- the verification, quantification, numerical solution using software, interpretation and implementation of the created mathematical model.
The output universe of the system – the set of the machines performing the requirements for realization of the final product.
The optimizing phase characteristics:
The input universe of the system is the output universe of the decision phase.
The optimization criterion - the minimizing of the machines energy consumption for realization of the final product of the building process.
The proceeding steps:
- the selection and choice of the decision variables, their definition, symbol, dimension, quantification with giving of the source of the quantification,
- the construction of the mathematical model of the criterion of the optimization,
- the verification quantification, numerical solution using software, interpretation and implementation of the mathematical model of the criterion for optimization.
The output universe of the system – the machine with the minimal energy consumption for realization of the final product of the building process.

In our contribution, the optimizing phase of EMSO method in two different model examples is analyzed: optimal selection of machine groups for earthwork excavations and optimal selection of building elevators from the point of minimal energy consumption with software support.

3 Model Example N.1: Excavation and the Removal of the Soil at the given distance

Basic input data:
Final product of building process – building pit: width (50 m), length (90 m), depth (3,5 m), soil type and class – sandy soil, the 2nd class of cohesion (according to Slovak National Standard STN 733050), required work capacity V_p = 15 750 m ^{3}, transport distance L= 4 km, required time of duration of works T= 14 400 min. (30 shifts), season of year of realization of works – April, May, kind of road surface – mastic asphalt, plane on the whole length.
Comment: presupposition of approximate identical operation of machines during shifts, time for lunch and inspection of machines at the beginning and the end of shift have not being included in time of shift duration.

The input universe of the system of the decision phase is being created by 3 types of depth shovel excavators: DH 411, DH 621, Cat 225 and 3 types of folding transport means: T 148 S1, T 815 S3, S 706 MTSP 24. The same transport means were applied to every type of the excavator. There are 9 variants of the excavator machine group together with the transport means and in every variant we used from 1 to 13 pieces (pcs) transport means. For the evaluation of the machine groups in the optimization phase the concept of queuing theory is being applied. In our contribution are shown final mathematical models (1) of optimizing phase. All data necessary for equations 1 and 2 can be found in Gasparik (2013) – see references.

The mathematical model of the optimizing criterion is in form as follows:

$$MS=T_{sk}.T_{ps}^{-1}.V_p^{-1}.[T_{mr_i}.S_{mr_i}+T_{pr_i}\ S_{pr_i}+(T_{ca_j}\ S_{ca_j}+$$

$$+L_{na_j}.S_{na_j}+L_{pa_j}.S_{pa_j}).N_{a_j}]\ \ (1.m^{-3}) \qquad (1)$$

for i=1, 2, 3; j = 1, 2, 3; N_a =1,2, … , 13,

where
MS - specific F.C. of machine group, excavator + transport means by the required volume of the works (l.m^{-3}),
T_{sk} - duration of work of machine group by earthworks of required volume (min.),

T_{ps} - duration of operation of machines during a shift (min.shift^{-1}),
T_{mr} - time of excavator manoeuvre (min.shift^{-1}),
S_{mr} - fuel consumption of excavator at manoeuvring (l.min^{-1}),
T_{pr} - duration of work regime of excavator except time of manoeuvring (min.shift^{-1}),
S_{pr} - fuel consumption of excavator in operating regime (l.min^{-1}),
T_{ca} - duration of waiting regime of transport mean during running engine (min.shift^{-1}),
S_{ca} - fuel consumption by waiting regime of transport mean (1.min^{-1}),
L_{na} - length of road covering by transport mean with a load, from place of loading to place of unloading (km.shift^{-1}),
L_{pa} - length of road covering by transport mean without of load, from place of unloading to place of loading (km.shift^{-1})
S_{na} - fuel consumption of transport mean by driving with a load (1.km^{-1}),
S_{pa} - fuel consumption of transport mean by driving without a load (1.km^{-1}).

Input data concerning the consumption of fuel were given by producers of excavator and transport means. The best energy saving machine groups of each kind are being compared in Figure 2. The most advantageous solution for the realization of output and removal of earth at given distance from the point of view of minimizing of fuel consumption is at analysed model example a choice of the machine group Cat 225 + 6 pcs of T 148 S1.

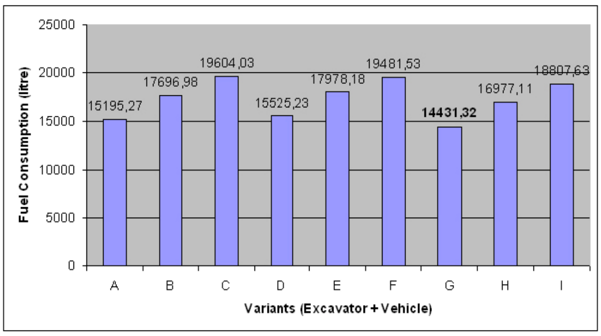
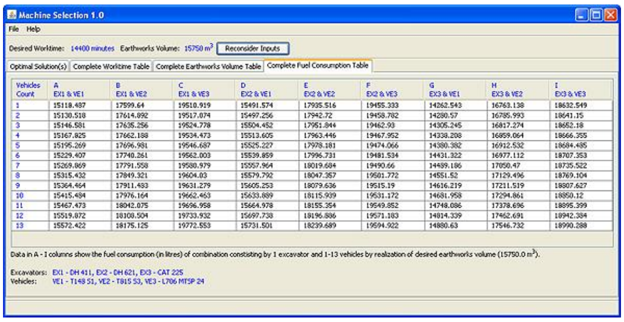


Figure 2. Machine group (excavator-trucks) variants evaluation from the point of minimum consumption of fuel for variants A – I : see Figure 6

The Machine Selection software was created by co-author M.Gašparík as a software support for method described in this contribution. Machine Selection is a desktop application, built in Java.
“Complete Fuel Consumption Table” shows fuel consumption in litres of combination consisting by 1 excavator and 1 to 13 vehicles by realization of desired earthworks volume. This part of result screen is displayed on Figure 3.



Vehicles Count	A EX1 & VE1	B EX1 & VE2	C EX1 & VE3	D EX2 & VE1	E EX2 & VE2	F EX2 & VE3	G EX3 & VE1	H EX3 & VE2	I EX3 & VE3
1	15118.487	17599.64	19510.919	15491.574	17935.516	19455.333	14262.543	16763.138	18632.549
2	15130.518	17614.892	19517.074	15497.256	17942.72	19458.782	14280.57	16785.993	18641.15
3	15146.581	17635.256	19524.778	15504.452	17951.844	19462.93	14305.245	16817.274	18652.18
4	15167.825	17662.188	19534.473	15513.605	17963.446	19467.952	14338.208	16859.064	18666.355
5	15195.269	17696.981	19546.687	15525.227	17978.181	19474.066	14380.382	16912.532	18684.485
6	15229.407	17740.261	19562.003	15539.859	17996.731	19481.534	14431.322	16977.112	18707.353
7	15269.869	17791.558	19580.979	15557.964	18019.684	19490.66	14489.186	17050.47	18735.522
8	15315.432	17849.321	19604.03	15579.792	18047.357	19501.772	14551.52	17129.496	18769.104
9	15364.464	17911.483	19631.279	15605.253	18079.636	19515.19	14616.219	17211.519	18807.627
10	15415.484	17976.164	19662.463	15633.889	18115.939	19531.172	14681.958	17294.861	18850.12
11	15467.473	18042.075	19696.958	15664.978	18155.354	19549.852	14748.086	17378.696	18895.399
12	15519.872	18108.504	19733.932	15697.738	18196.886	19571.183	14814.339	17462.691	18942.384
13	15572.422	18175.125	19772.553	15731.501	18239.689	19594.922	14880.63	17546.732	18990.288

Figure 3. Result screen, Complete Fuel Consumption Table section

4 Model Example N.2: Building elevator selection

This “EMSO method” was applied into building elevator selection for vertical transport of building materials during the finished processes in term of minimum consumption of electrical energy.

Input data: 9 floored building object (see Figure 4), operational project of building object.

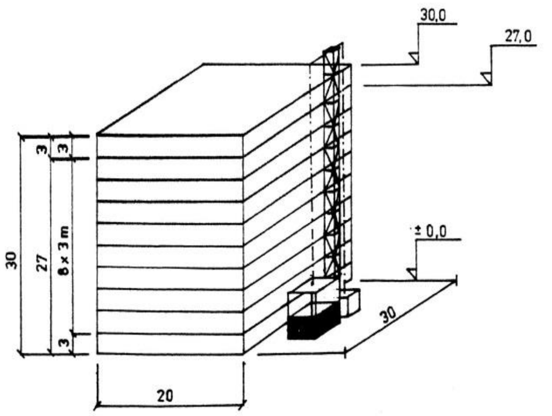


Figure 4. Analysed building object for optimal selection of building elevator

Input universe of system in optimization phase:

- building elevator: WBT 5-600,
- building elevator: VS 5,
- building elevator: VS 6.01,
- building elevator: NOV 500,
- building elevator: NOV 1000 A.

Criterion: optimization – minimization of consumption of electric energy of elevators in a process of vertical transport of materials to building object.

Procedural steps:

1. Experimental method of measuring value of electric current, which is withdrawn by construction elevator´s electromotor during its operational mode.
2. Experimental measuring work was done on specific constructions in Bratislava (Slovakia), in the presence of expert for elevators. The elevator was continually burdened by 50 kg (1 bag of cement) until maximum loading capacity. The values of electric current flowing through phase conductor of three phase line and withdrawn by electromotor of elevator during continual loading in both direction (upwards and downwards) are measured by clip-on ammeter.
3. Results of experimental measuring of electrical current values which were withdrawn by electromotor of elevators during operational mode. Above mentioned measuring work was implemented on all analyzed types of elevators. Results of measurements are recorded in tables and also graphically illustrated.
4. Construction of mathematical model of optimality criterion

   The content of this point is to construct mathematical model of consumption of electrical energy of elevator for tonometer of transported materials.

   The foundation for calculation of measuring consumption of electrical energy of elevator are experimental measured intensities of electric current withdrawn by its electromotor.

   The consumption of electrical energy of elevator for tonometer of transported material could be calculated as follows:

$$E = \frac{\sqrt{3}}{3600} \cdot \frac{U \cdot I}{v \cdot m} \quad [\text{Wh/tm}] \tag{2}$$

where

U – nominal line voltage of three-phase distribution system in volt (380 V),

I – real intensity of electric current withdrawn by electromotor of elevator in ampere,

v – transport velocity of elevator in meter per second,

m - load mass transported by elevator in tonne.

Note:

1. At work there is analyzed case, when elevators are going in upward direction they are loaded, however in downward direction they are not loaded by materials. From measured and calculated variables we can observe different combinations.

2. In case of operational-personal elevators NOV 500 and NOV 1000 A, service is necessary in elevator´s cage, that is why we consider empty (without load) elevator’s mass

100 kg and elevator load capacity is changing in case of NOV 500 to 400 kg and in case of NOV 1000 A to 900 kg.

The overall consumption of electrical energy of elevators for transport of material to 1 m elevation (tonometer) and its return to initial position we can calculate as follows:

$$E_c = E_h + E_{pd} \text{ [Wh/tm]} \quad (3)$$

where

E_h - the consumption of electrical energy of elevator for tonometer of transported material in upward direction in watt hour per tonne and meter (Wh/tm),

E_{pd} - the consumption of electrical energy of elevator for tonometer of transported material in downward direction not loaded by materials in Wh/tm.

Graphical interpretation of dependence of overall electrical energy consumption to transport material by elevators E_c [Wh/tm] is illustrated on Figure 5 and graphical interpretation of dependence of overall electrical energy consumption of elevators E_c [Wh/tm] on percentage extraction their load capacity is illustrated on Figure 6.

5. The determination of final electrical energy consumption of particular types of elevators after overall work performance E_v [Wh].

For approximate calculation of E_v [Wh] overall mass of materials ABP, which is transported by elevator to particular floors M_i [kg], where i = 1, …,n, is determined.

Based on characteristic of different materials types, average value of percentage extraction of load capacity of elevator x is estimated, subsequently based on this value the E_c [Wh/tm] is defined from figure 6.

The resulting electrical energy consumption of elevators E_v [Wh] is calculated as follows:

$$E_v^k = E_c^k \cdot \sum_{i=1}^{n} M_i \cdot h_i \cdot 10^{-3} \quad \text{[Wh]} \quad (5)$$

where

E_c^k - overall electrical energy consumption "k" type of elevator for transport of 1 tonne material to 1 m height [Wh/tm], where k=1,…,p,

M_i – mass of material, which is transported to "i" floor [kg] ,where i = 1, …, n,

h_i - height of "i" floor [m], where i = 1, …, n,

Model example:

M_i = 10 000 kg for i = 1, …,9 (typical floor)

h_1 = 3 m, h_2 = 6 m, h_9 = 27 m (Figure 4)

$\bar{x}$ = 70 % (figure 6), E_c [Wh/tm] (Figure 6)

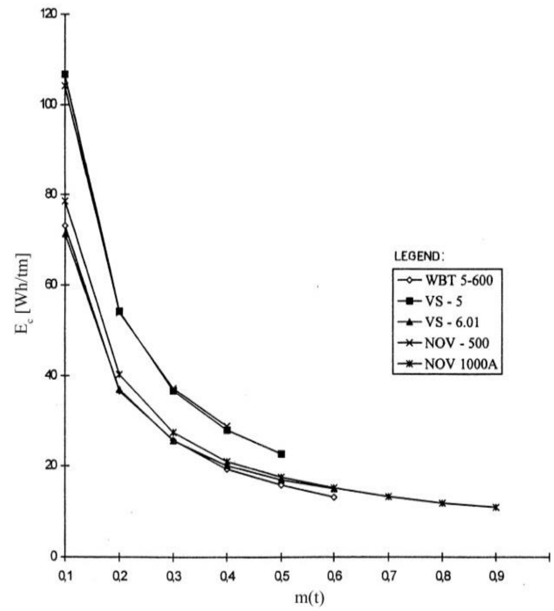


Figure 5. Graphical interpretation of dependence of overall electrical energy consumption to transport material by elevators for tonne and meter E_c [Wh/tm]

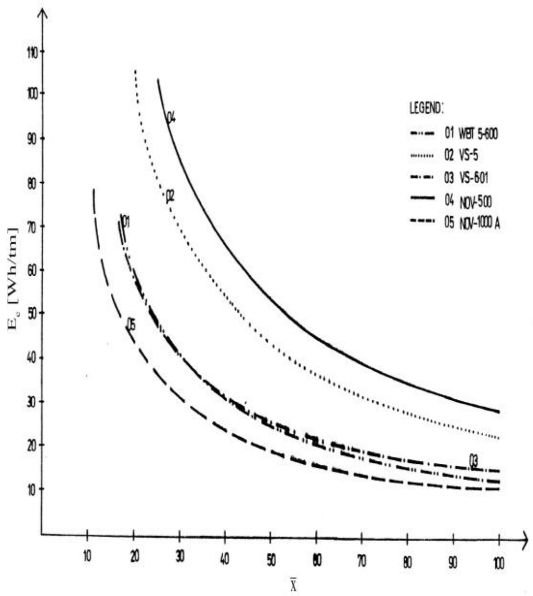


Figure 6. Graphical interpretation of dependence of overall electrical energy consumption of elevators E_c [Wh/tm] on percentage extraction their load capacity.

The solution of model example is shown by Figure 7.

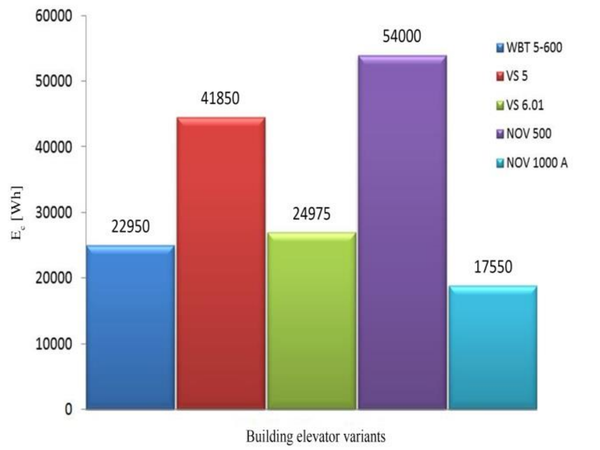


Figure 7. A comparison of elevator variants in term of overall electrical energy consumption during the process of vertical transportation of building materials to analyzed building object.

Output universe of system - NOV 1000 A (see Figure 7).

4.1 Elevator Selection Optimizing (ESO) method application with software support

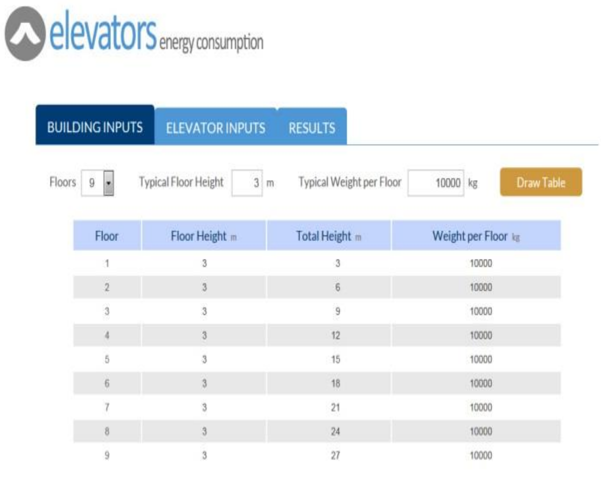
Above analysed model example can be effective solved using Elevators Energy Consumption software as a web solution based on html, php and javascript to compute energy consumption of several elevators and choose the best choice (the one with lowest energy consumption). The main screen is divided into 3 parts: Building Inputs, Elevator Inputs and Results.

4.1.1 Building Inputs

In this section (Figure 8) user enters number of floors of a building, typical floor height and typical height, delivered to the floors. For each floor, user can specify its own height or weight, needed to delivery.

4.1.2 Elevator inputs

This part (Figure 9) serves to specify number of elevators (from 1 to 5), their names and E_c constants, assigned to capacity values, varying from 25 to 100 percentage.



Floor	Floor Height m	Total Height m	Weight per Floor kg
1	3	3	10000
2	3	6	10000
3	3	9	10000
4	3	12	10000
5	3	15	10000
6	3	18	10000
7	3	21	10000
8	3	24	10000
9	3	27	10000

Figure 8. Building inputs

	Elevator1	Elevator2	Elevator3	Elevator4	Elevator5
x (%)	WBT 5 600	VS 5	VS6.01	NOV 500	NOV 1000A
25	48	80	47	103	37
30	40	70	40	86	31
35	34	61	35	73	27
40	31	53	32	66	23
45	27	48	28	58	21
50	24	43	25	53	19
55	22	39	23	48	17
60	20	37	21	44	15
65	18	33	19	42	13
70	17	31	18.5	40	13
75	16	29	18	37	12
80	15	28	17	34	11
85	13.5	25.5	16	32	10.5
90	13	24	15	31	10
95	12	23	14.5	30	9.5
100	11	21.5	14	28	9.4

Figure 9. Elevator inputs - values of E_c [Wh/tm]

4.1.3 Results

In Results section (Figure 10), user is asked to choose capacity for each elevator and after clicking the button Draw Results he gains result values of total energy consumption (E_v). Elevator with the lowest consumption (the winner) is marked green.

Figure 10. Results section

5 Conclusion

The most-important factor in this "EMSO" method is that it is able to eliminate machine variants with high energy consumption during the process of building planning. By using a software it gives information about energy consumption of machines when considering their use in the final product of the building process (earthwork excavation, vertical transport of building materials) and gives the possibility to make fast decision for the choice of the energy optimal machines in a short time. At the same time it is necessary to stress that by this method the machines are being evaluated from one point of view only (energy consumption), which, it is true, is one of the most meaningful views of this time, but it needs not be crucial in every case. Therefore, it is necessary when proposing an elevator to take the point of view to minimize the energy consumption as a part of the multi-optimal proposal. For a practical application of the proposed "ESO" method it is necessary to improve the quality of input data, especially energy information. This data involved in our contribution were obtained by experimental measurement. The producers of building machines and elevators can offer this data shown in our contribution as a basic information concerning their excavators, transport means and elevators and using software building planner can very easy and fast select energy optimal variant of building machines. The volume of savings of the operating expenses possible to be obtained already in the preparation phase of building realization by this "EMSO" method are not negligible, vice versa, it shows the disclosure of reserves that are available in the choice of machines for excavation process and elevators for vertical transport of building materials.

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