MULTI-CRITERIA OPTIMIZING METHOD OF EARTHWORK MACHINE GROUP SELECTION IMPLEMENTED INTO SOIL PROCESSES

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ABSTRACT

The optimal selection of machine or machine group for building processes is very important role of building planner during the process of building planning. During this process building planner have to analyze 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 there are analyzed: ability of machines to realize designed building process (quality aspect), duration of mechanized process (time aspect) and minimizing of energy consumption (cost and environmental aspect). Selected scientific methods and theories of problem solution can be divided into these groups: theory of system (creation of building machine selection method), multi-criteria optimizing method (analysis of mechanized building process from the point of more optimal criteria), queuing theory (application during the mathematical modeling 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). Multi-criteria optimizing method were during our research work implemented into soil processes and selected building group machines (excavators and trucks), which are very often used in construction and mining processes. This method can be considered as a multi-level decision making process based on multiple parameters. In our contribution is presented key mathematical models for model example solution and software built in Java, which has been created as a support for method described in this contribution. Application of this method and software will increase the effectiveness of building machine selection from the point of key criteria of optimizing: quality, time and energy consumption.

KEYWORDS

Optimization, multi-criteria, earthwork machine

INTRODUCTION

The optimal selection of machine or machine group for building processes is very important role of building planner during the process of building planning. During this process building planner must analyze several factors influencing the final effective decision concerning this problem. During the process of building planning planner must 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: ability of machines to realize designed building process (quality aspect), duration of mechanized process (time aspect) and minimizing of energy consumption (cost and environmental aspect). From the above mentioned aspects results, that the lowering of the power requirement of the construction process presents an inevitable social-wide problem.

Soil processes are involved in construction and in building process and they can be an important part of a construction project because of powerful heavy equipment. They involve repetitive work cycles, large volume of work, high fuel consumption and they need to be completed within deadline. The scope of these processes varies from a small amount of earth to moving millions of cubic meters of earth. The one thing that all soil processes have in common is that careful planning is the key to success. Traditionally, a project manager uses deterministic methods in analyzing soil processes, although real processes are stochastic.

Considerable efforts have been made in development of efficient techniques and procedures for soil processes and many techniques have been developed so far. Recently, more researches are interested in earthwork operations and most of them use optimization and simulation as the methodologies that can be used for analyzing soil processes. CYCLONE and STROBOSCOPE are the commonly used simulation tools specified for construction (Zhang, 2008). These tools for construction modeling, such as STROBOSCOPE enable accurate and detailed modeling of any complex situation but these tools demand a level of training (Martinez, 1996). In the context of STROBOSCOPE Martinez developed an EarthMover, which is a discrete-event special-purpose simulation modeling tool for earthwork planning. This tool includes STROBOSCOPE as a simulation engine, Visio for the graphical and interactive model definition, Excel for tabular and graphical output and Proof Animation for dynamic output (Martinez, 1998). Halphin developed CYCLONE methodology for modeling and simulating repetitive construction processes (Halphin, 1977). Shi and AbouRizk introduced the resource-based modeling (RBM) methodology in order to automate the modeling process and by using this methodology can the project manager construct a simulation model for a project in a few minutes, but it consisted of only eight basic atomic models and is connected only with earthmoving operations (Shi & AbouRizk, 1998). Marzouk and Moselhi analyzed earthmoving operations by combining genetic algorithm (GA) with CYCLONE and other simulation techniques. Their simulation and optimization considered multi-objectives for selecting near-optimal fleet configuration for earthmoving processes, but could not select any potential combination of various type of equipment which are in the fleet (Marzouk & Moselhi, 2004). The work of Zhang formed a framework of multi-objective simulation-optimization for optimizing equipment-configurations of earthmoving operations and it is proposed by integrating an activity object-oriented simulation, multiple attribute utility theory, a statistical approach like the two-stage ranking and selection procedure and particle swarm optimization algorithm. His procedure is equipped to help compare the alternatives that have random performances and thus reduce unnecessary number of simulation replications. It can speed up the evaluation process, but this integrated framework is still developed (Zhang, 2008).

In this study a computational example is provided to justify our selected scientific methods and theories like theory of systems, multi-objective optimizing method, queuing theory and method of scientific analysis and synthesis. These methods were implemented into soil processes and building machines and its group and will be presented in proposed mathematical model by software which was developed in JAVA. Applications of these methods and software will increase effectiveness of building machines selection from the point of key criteria of optimizing: quality, time and fuel consumption, thus speeding up whole process and avoiding exhaustive calculations and experiments.

MACHINE SELECTION OPTIMIZING METHOD

By suggesting the “Machine Selection Optimizing Method” (MSO Method) we have developed the present state of knowledge of the purpose of the machines and machine groups for building processes (Gasparik, 2007) and also of the information which has been obtained by study of the theory of systems (Štach, 1983) and optimization theory of the process (Niederliňski, 1983). The “MSO Method” consists of the three phases (figure 1) – entry, decision and optimization.

An analysis of all these phases except introductory is examined:

- 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 machines fulfilling the criterion of the given phase.

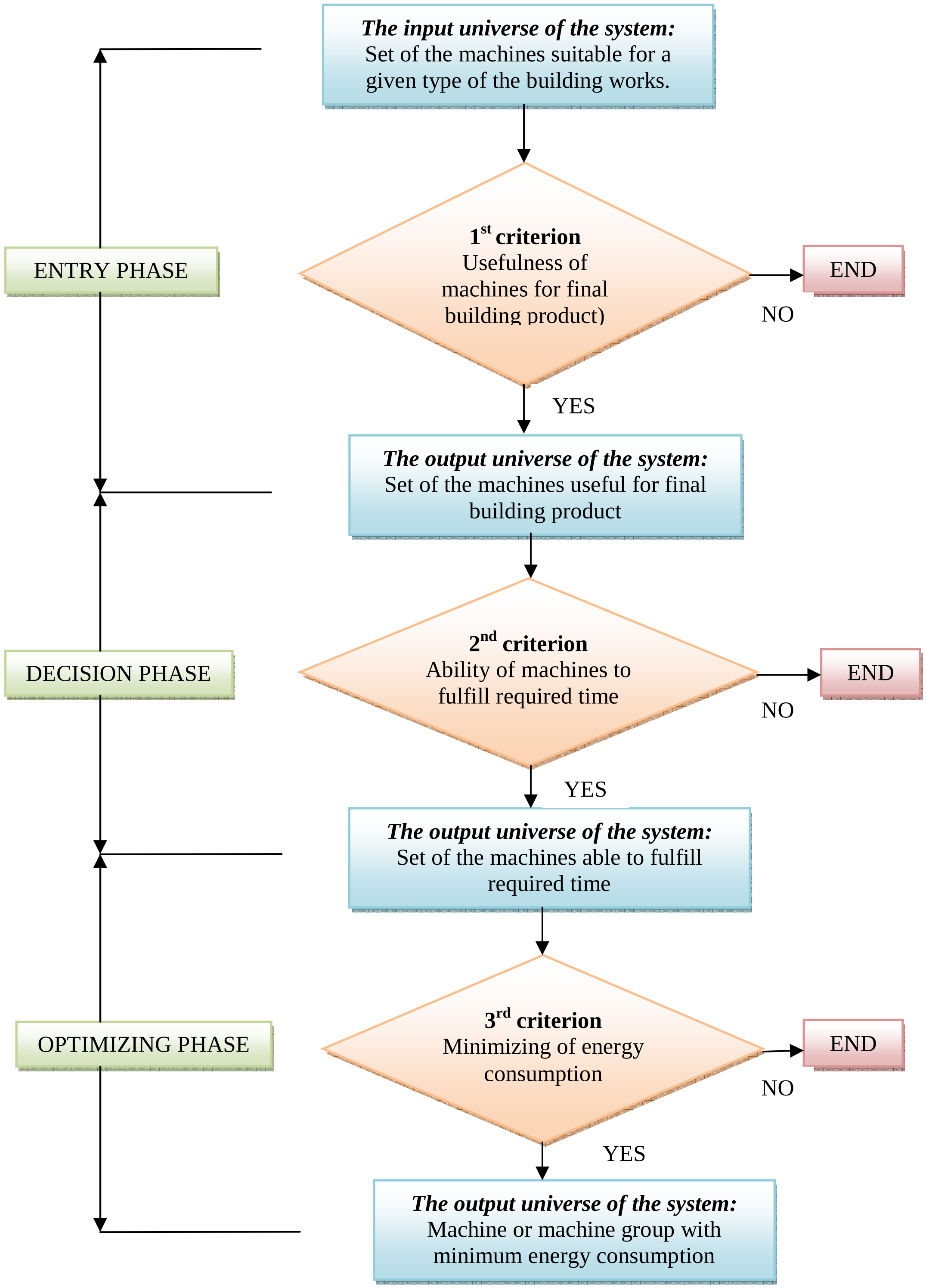

Figure 1 – Phases and criteria of building machine selection optimizing method

The introductory phase contains definition 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.

Machine selection optimizing (MSO) method characteristics

MSO method consists of 3 phases. The 1st (entry phase) characteristics:

The input universe of the system is the set of the machines suitable for a given type of the building works. The criterion (1st eliminating) is the usefulness of the machines for the realization of the final product of the building process

The procedural step consists of:

- a study of the resulting product of the building process,
- the analysis of problems of the proposal on the machine for a given type of the building process,
- the collation of all the information including the performance data of the machines for their incorporation into a model of the mechanized building process.

The output universe of the system is the set of the machines suitable for realization of the final product of the building process.

The 2nd (decision phase) characteristics:

The input universe of the system is the output universe of the entry phase.

The criterion (2nd 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 the machines, let us say of the machine groups 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 the machines according to the 3rd 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 3rd (optimizing phase) characteristics:

The input universe of the system is the output universe of the decision phase.

The optimization criterion - the minimizing of the energy consumption machines, let us say machines groups 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, let us say the machine group with the minimal energy consumption for realization of the final product of the building process.

MSO method application

This “MSO method” was applied into the selection of machine group for the excavation and the removal of the earth at the given distance from the above mentioned criteria (figure 2).

Figure 2 - Building machine group: excavator + transport means (model example)

With regard to the great number of the model variables and the extent of the work this paper is considering the decision and optimizing phases.

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 decision and optimization phase the concept of queuing theory is being applied. In our contribution are shown final mathematical models (1,2) of decision and optimizing phases. All data necessary for equations 1 and 2 can be found in Gasparik (2007) – see references.

The mathematical model of the 3rd eliminating criterion of the decision phase is in the form:

$$T_{sk} = V_p .\ t_{caj}\ (V_{naj}\, k_{caj}\, k_{kaj}\, .k_{daj}.k_o\, .N_{aj})^{-1}\ \ \text{(min)} \qquad (1)$$

for j=1, 2, 3; N_a = 1, 2, …, 13,

where,

T_{sk} - duration of work of machine group by earthworks of required volume (min.),
V_p - required volume of earthworks (m^3),
t_{ca} - duration of duty cycle of transport mean (min.),
V_{na} - volume of earth removed by transport mean in loosened state (m^3),
k_{ca} - plant factor of transport mean (-),
k_{ka} - coefficient of influence of operation of transport mean at its capacity (-),
k_{da} - coefficient of influence of transport distance at capacity of transport mean (-),
k_o - coefficient of calculation of soil in loosened state at volume of soil in natural state (-),
N_a - number of transport means in machine group (pcs).

The output universe of the system of the decision phase follows from graphical interpretation in figure 3, where suitable variants of machine groups are placed under line representing required time of duration of works T_p. The suitable variants of the machine group of the decision phase are being evaluated in the optimizing phase from the point of view of the minimal F.C. (Diesel oil).

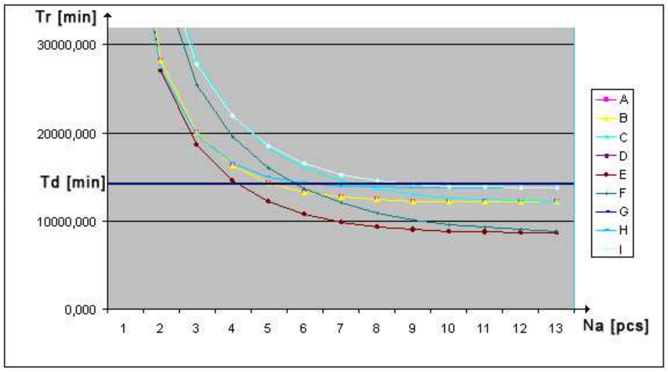

Figure 3 – Dependence of actual duration of earthwork T_r (min) on number of vehicles (pcs) of machine group variants (excavator + vehicles) by required volume of earthworks V_r = 15 750 m^3. T_d = 14 400 min. (required time) for variants A – I : see figure 6

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

$$MS = T_{sk}.T_{ps}^{-1}.V_p^{-1}.[T_{mr\,i}.S_{mr\,i} + T_{pr\,i}.S_{pr\,i} + (T_{ca\,j}.S_{ca\,j} + L_{na\,j}.S_{na\,j} + L_{pa\,j}.S_{pa\,j}).N_{a\,j}] \quad (1.m^{-3}) \qquad (2)$$

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_{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 ($1.km^{-1}$).

The other decision variables are being given by the relations 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 4. 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 analyzed model example a choice of the machine group Cat 225 + 6 pcs of T 148 S1.

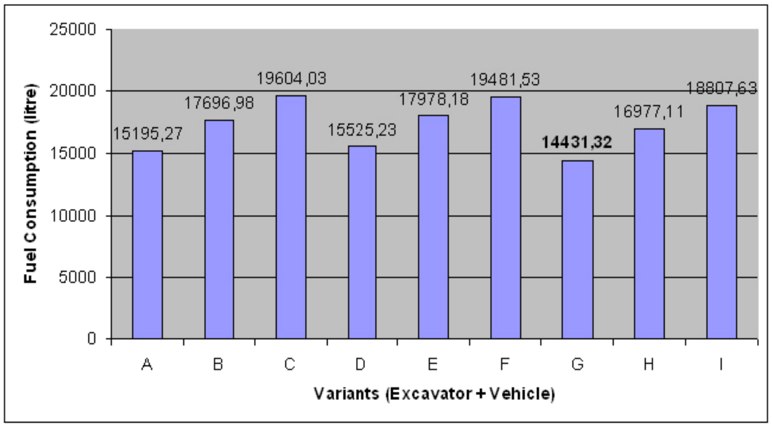

Figure 4 – Machine group (excavator-trucks) variants evaluation from the point of minimum consumption of fuel for variants A – I : see figure 6

MSO METHOD SOFTWARE SUPPORT

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. Therefore it is runnable on all operating systems that support Java Virtual Machine. Introduction screen (figure 5) contains panels to enter input variables. User can choose number of excavator and vehicle types. For both - one as minimum and three as maximum. It is enabled to save inputs into file and load inputs. User can also change excavator and vehicle names. Clicking "Check Inputs" button provides control of input variables values. Wrong values are marked as red, acceptable as green. Button called "Calculate" leads to result screen, which is divided into four sections:

1. Optimal Solutions(s),
2. Complete Work Time Table,
3. Complete Fuel Consumptions Table.

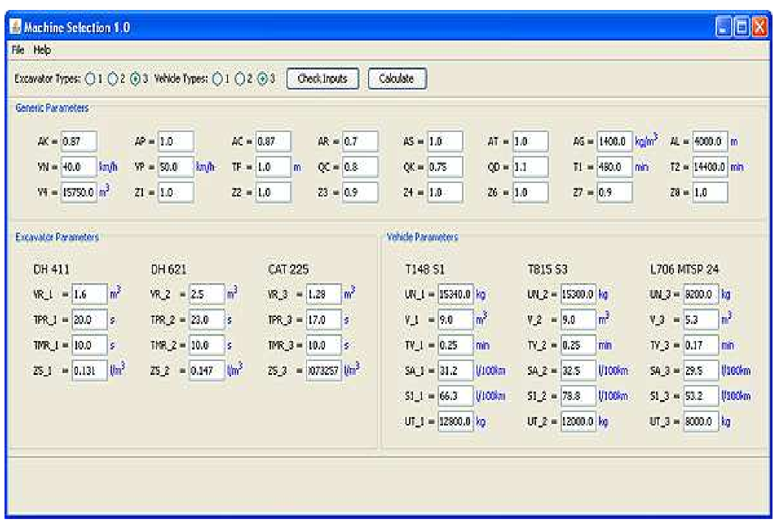

Figure 5 - Input screen of Machine Selection software

"Optimal Solution(s)" contains a list displaying all variants of excavator and vehicle(s) able to solve the task in desired time and volume of work. Best variant is marked as green. It is also possible, that task in desired volume with desired work time is not solvable with maximum number of vehicles 13. In this case, fuel consumption of variant is not calculated and this variant is marked as “out of range” error. This part of result screen is displayed on figure 6

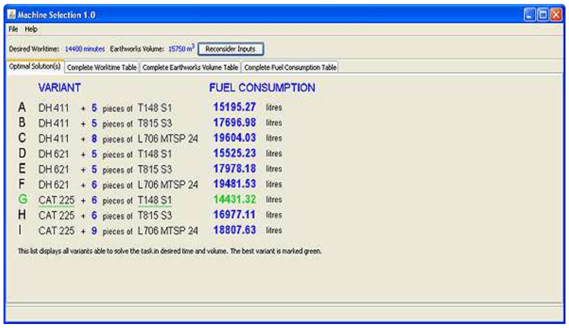

Figure 6 - Result screen, Optimal Solution(s) section

“Complete Work Time Table” is a table created to display data for all combinations of excavator and vehicle types. Data show the time in minutes needed by combinations of 1 excavator and 1 to 13 vehicles to solve the task in desired volume. If a combination of excavator and vehicles is able to complete the task in time set by user, result time data is highlighted green, otherwise red. This part of result screen is displayed on figure 7.

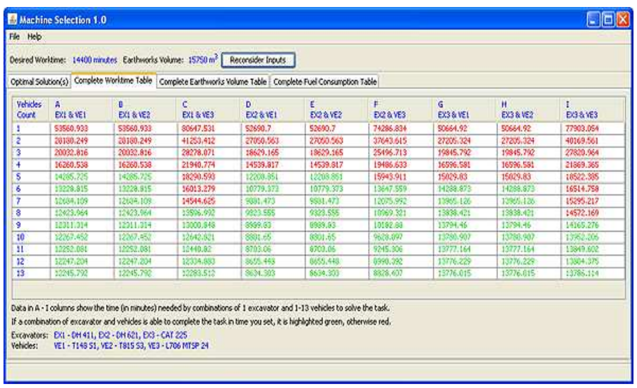

Figure 7 - Result screen, Complete Work Time Table section

“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 8.

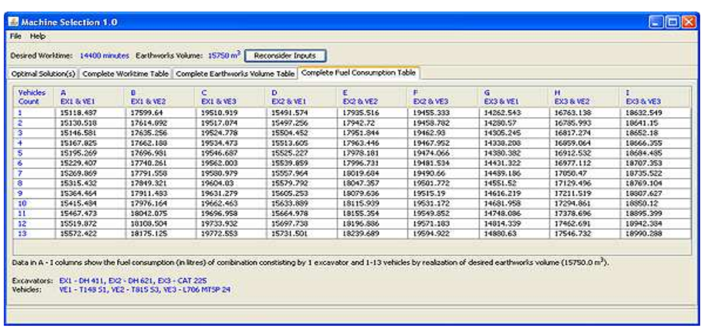

Figure 8 - Result screen, Complete Fuel Consumption Table section

THE ANALYSIS OF SELECTED FACTORS INFLUENCING WORK DURATION AND CONSUMPTION OF FUEL

Using our software we analyzed these selected factors and effects for the optimal machine group from our model example described before:

- effect of required volume of earthworks on the duration of the work and fuel consumption (figure 9 and figure 10)

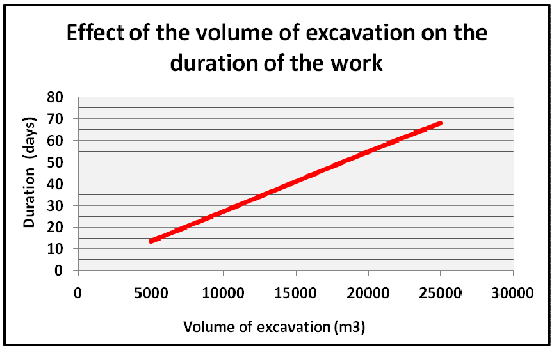

Figure 9 - Effect of required volume of earthworks on the duration of the work

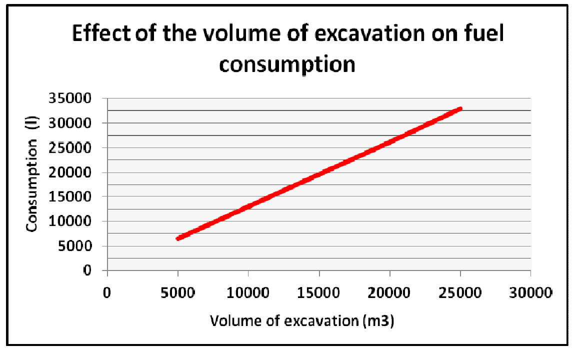

Figure 10 - Effect of required volume of earthworks on consumption of fuel

- effect of transport distance on the duration of the work and fuel consumption (figure 11 and figure 12)

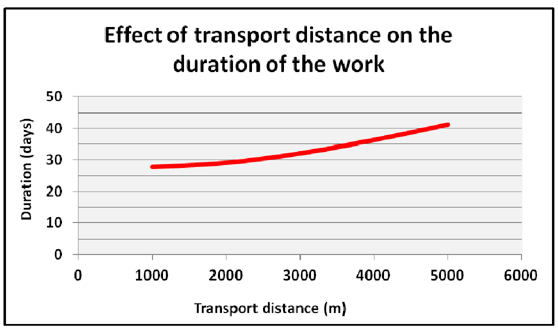

Figure 11 - Effect of transport distance on the duration of the work

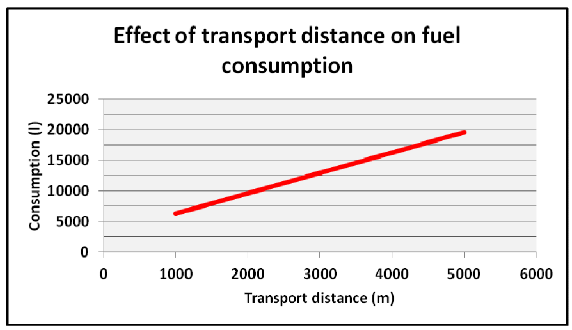

Figure 12 - Effect of transport distance on consumption of fuel

- effect of the terrain and the resultant speed of vehicles on the duration of the work (figure 13 and figure 14)

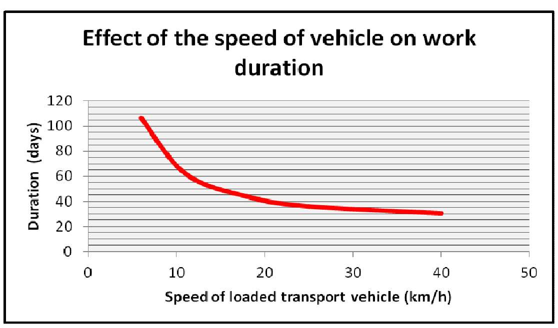

Figure 13 – Effect of the speed of vehicle on work duration

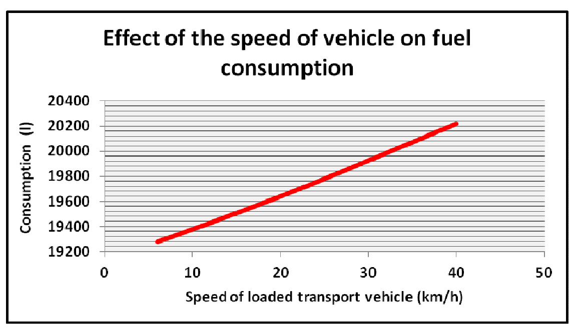

Figure 14 – Effect of the speed of vehicle on fuel consumption

CONCLUSION

Multi-criteria optimizing method was during our research work implemented into soil processes and selected building group machines (excavators and trucks), which are very often used in construction and mining processes. In our contribution was presented key mathematical models for model example solution and software built in Java, which has been created as a support for method described in this contribution. Application of this method and software will increase the effectiveness of building machine selection from the point of key criteria of optimizing: quality, time and energy consumption. The most important factor in our MSO method is that it is able to eliminate energy variants of the machines, during the design and preparation phase of construction. By using software it gives information about energy usage of machines when considering their use in the final product of the building process and gives the possibility to make fast decision for the choice of the optimal machine in a short time.

As you can see in last chapter, all the observed factors are influencing the duration of work and fuel consumption. It is important to note that these factors cannot be ignored and disregarded. The results we have achieved, it is clear that each and every factor significantly affects on fuel consumption and duration of work. The impact of some is larger, with some minor, but in either case, is not negligible.

For a practical application of the proposed MSO method it is necessary to improve the quality of input data, especially energy use information. The volume of savings of the operating expenses possible to be obtained already in the preparation phase of buildings by this method are not negligible, vice versa, it shows the disclosure of reserves that are available in the choice of machines for building processes. This MSO method will find a full application only when these reservations will be removed. This contribution was prepared as a part of scientific research project VEGA N. 1/0184/12.

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