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OPTIMAL PLACEMENT OF LOADING CROSSCUTS IN MINING AND TUNNELLING

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Abstract:
An application of dynamic programming in searching for a cost-effective solution how to placement of loading crosscuts facilities in mining or tunneling is presented. Purpose of the work was to provide a decision-making support for placement of such facilities at minimum costs. The task is to find optimal distance between loading crosscuts within excavation of two parallel drifts as horizontal or subhorizontal development openings in mine. Analogically, the problem can occur at excavation of two parallel tunnel tubes in railway or road infrastructure development. The case supposes linked two-stage haulage of excavated material in a defined perspective of transport using load-haulage-dump vehicle and train with trip. Formulation of exact solution by dynamic programming, testing in concrete conditions in mine development as well as comparisons with results of enumeration are presented.

Key words:
cost-effective optimization, dynamic programming, location problem, two face parallel drifting, loading crosscut, load-haulage-dump.

INTRODUCTION

The dynamic programming was introduced by R. Bellman [1, 2] and so far it has been successfully used in resolving many control problems [3, 4]. An abundance of inspiring references on the application of dynamic programming by various purposes is possible to find in global networks. In this case, the generally taken model of dynamic programming has been applied to solving so-called location problems [5, 6] and [7] or in its dynamic form [8]. Many applications to location problem can be found in surface mining, e.g. [9, 10] or [11]. However, with regards to very special conditions in underground mining and tunnelling there is predominantly used empirical approach and design [12, 13]. In the given case, as subjects of location are considered loading crosscuts at the two faces parallel drifting during mine or tunnel development (*Fig. 1*). After their set up they function as certain linking nodes within a two-stage haulage process with usually technologically different sections of transport in a given perspective. The problem is disputed location of such loading crosscuts bridging two drifts or tunnel tubes during their excavation, to be optimal and cost-effective. In progressing of parallel drifting ahead, the borders of such defined haulage sections are determined always by setting up a new loading crosscut with transloading place between such workings. Then the first phase of haulage by load-haulage-dump vehicle is convenient to start there and the second phase of haulage by train with the trip is convenient to stop there for loading. At the same time, a new stage of transport starts with a newly constituted haulage regime. The task is to find the optimal distance between in such way set up loading crosscuts. i.e. at minimum total costs, resulting also in optimal spacing such facilities along drifts or tunnel tubes in some given underground conditions.

1 TASK FORMULATION (*Fig. 1*)

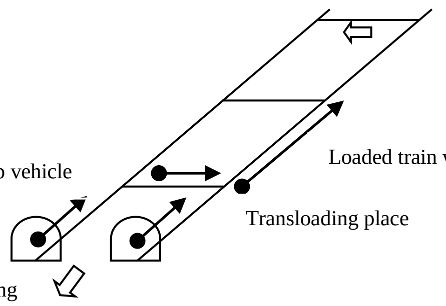

Fig.1 *The scheme of the drifting and the haulage situation.*
Source: author

a) Assume existence of a set of segments, as a set of rounds within drifting to drill and blast, $i = 1,2,...,$ up to a total number of segments m, which step by step approximate a situation in a direct perspective of haulage of such segments: $i = m$, m - 1,...,1. Each of the segments is described by:
- an identification number, given by index i,
- a number of cycles $n_{1,i}$, needed for haulage operations in the first phase to a transloading place, according to a vehicle chosen for this phase,
- a number of cycles $n_{2,i}$, needed for haulage operations in the second phase from a transloading place to the first segment in perspective and then on up to a destination, according to a transport equipment selected for this phase,
- a directional equidistant length Δ (the same for each segment), which is measured from a beginning of segment (always a place of possible realization of transloading place) to an end of segment, with the direct orientation as transport in both phases is performed; so that it represents an elementary step in the approximation of the perspective situation as well as a unit of measurement for routes of transport defined along the segments. The first segment in the perspective is supposed to be already rigged by a transloading place at its beginning.

b) The haulage in the first phase by a given chosen transport equipment, is characterized by a cost $c_{1,j}$ accrued by performing the one whole cycle of transport there, where distance to a transloading place for i segment is measured by a value $j\Delta$, i.e. by the number of segments, which a selected vehicle has to drive and where $j \in \{0,1,...,m - i\}$. Likewise, the haulage within the second phase by a given transport equipment is characterized by a cost $c_{2,j}$ for the one whole cycle of transport there, where distance from a place of transloading place to the first segment has for i segment a value of $(m - i - j)\Delta$, according to a distance j within the first phase. The distance with zero number of segments ($j = 0$) is considered when i segment has a transloading place at its beginning.

c) Setting up a transloading facility is characterized by a cost c_3 and for each of the possible position at the beginning of segments, the costs are supposed to be the same.

d) The task is whether to place the transloading facilities $p_i \in \{0,1\}$, meaning {yes, no} in segment i, and at the same time how to space them and to make partitioning of the perspective of segments $i = 1,2,...,m$ along their directional length into particular haulage stages in order to get minimum total costs c. All that taking into account: given (or investigated) transport vehicles and their costs under consideration (the values in n_1, n_2, c_1, c_2) and given (or investigated) type of the transloading facility (the value in c_3).

e) The optimum logical values in $p_i \in \{0,1\}=\{\text{true, false}\}$, assigned to each segment i, represents optimal spacing the transloading facilities along drifts or tunnel tubes as well as partitioning thus the set of segments into the different sections of haulage. They represent then a recommended decision that can be interpreted as { "to set up" or " not to set up"} the transloading facility, or { "to start" or " not to start"} a new haulage stage with a new first phase of haulage at the location (beginning) of segment i.

Hence:

$$c = \min\{\sum_i c_i(p_i);\, p_i \in \{0;1\};\, i = m, m-1, \ldots, 1\} \tag{1}$$

where

$$c_i(p_i) = \{ \begin{array}{ll} n_{1,i}\, c_{1,0} + n_{2,i}\, c_{2,m-i} + c_3, & \text{if } p_i = 0,\ j = 0 \\ n_{1,i}\, c_{1,0} + n_{2,i}\, c_{2,m-i-j}, & \text{if } p_i = 1,\ j = \min\limits_{p_{i+j}=0} \{0,1,\ldots,m-i\} \end{array}$$

2 APPLICATION OF DYNAMIC PROGRAMMING

Dynamic programming is a technique for finding optimal sequences of decision for problems that can be described as sequential decision processes. Such a decision, to be optimized, must be divisible into a sequence of partial decision or stages for each of which an optimal solution can be found.

Then

$$\min\{c(x_m, x_{m-1}, \ldots, x_1) = \min \sum_i c_i(x_i);\, i = m, m-1, \ldots, 1\} \tag{2}$$

The principle optimality is usually expressed by a functional f_i in the recursive relationship that defines the optimal solution at each stage.

For the given case:

$$f_i(j\Delta) = \min_{x_i \in \{0; j\Delta\}} \{c_i(x_i) + f_{i-1}(x_i + \Delta)\}, \quad i = 2,3,\ldots,m \tag{3}$$

$$f_1(j\Delta) = \min_{x_i \in \{0; j\Delta\}} \{c_1(x_1)\}, \quad i = 1$$

where j = 0,1,2,…,(m-i) and $f_i(j\Delta)$ expresses the minimum costs of haulage from the perspective segments $i = i,i$-1,…,1 when the backward distance from the transloading place is $j\Delta$. Such values of $f_i(j\Delta)$ are then recorded into array ($f_{i\,j}$) and the respective minimizing values of $x_i \in \{0;j\Delta\}$ being interpreted as { „ to set up" or „ not to set up" } the transloading facility, i.e. { „ to start" or „ not to start" } a new stage with new first phase of haulage, are recorded through the sign of $f_{i\,j}$ where for $sign(f_{i\,j}) \in \{-1;1\}$, respectively.

The value of overall minimum costs c is always in $f_m(0)$, i.e. in $f_{m\ 0}$ within the array, meaning "not to set up" because of the mentioned assumption that the starting segment in perspective is already furnished by a transloading facility. Then there is a running cycle $i = m,\ldots,1$ for a backward searching and decoding values of $f_{i\,j}$ for the final interpretation of $p_i \in \{0;1\}$ for each segment i , where j is set as follows:

$$j = \begin{cases} 0; & if\ sign(f_{i\,j}) = -1,\ p_i = 0 \\ j+1; & else \end{cases} \tag{4}$$

3 EXAMPLE OF APPLICATION

A mining plant makes a decision how to open and to develop a new part of deposit by two faces parallel drifting with two drifts with a supposed length of 500 meters and with their cross-sectional area around 16 to 20 square meters. Electric LHD vehicle with an operational shovel capacity of 1 cubic meter and electric train with a trip of 20 cubic meters are supposed for haulage and short loading crosscuts between the two drifts should be set up with the length of 11 meters. The considered length of drifts can be approximated by a set of 20 segments with the same length of 25 meters (see *Fig. 1*).

Each of the segments is described by:

- number of cycles needed for hauling of excavated rock material from a segment by an electric LHD (Load-Haulage-Dump) vehicle within the first phase of haulage, i.e. via the two drifts to the nearest loading crosscut with transloading place, where ($n_{1,1}$, $n_{1,2}$,...,$n_{1,20}$) = (1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000), which corresponds with above mentioned parameters with simplification and taking practical aspects such operations, i.e. as if 1 meter of segment fitted roughly 20 cycles of LHD,
- analogically, number of cycles needed for hauling of excavated rock material from the given segment by an electric train trip within the second phase of haulage , i.e. via its haulage drift to its destination, where ($n_{2,1}$, $n_{2,2}$,..., $n_{2,20}$) = (50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50). So, as mentioned above, a train trip keeps capacity about the 20 cubic meters loaded in full by the 20 cycles of LHD.

The costs of the one representative cycle of hauling for the particular phases are always calculated according to a number of via-driven segments during the cycle and are expressed in natural form as consumption of electric power for performing the cycle. Logically, this consumption is increased by increasing the distance measured by the number of via-driven segments, starting from a zero distance that corresponds to a power consumption respectively as follows:

- for hauling within the first phase, if a loading crosscut is located in the pertinent segment, that is about 0,17 kWh,
- for hauling within the second phase, if is driven distance from the train destination to the nearest segments of the drifts, that is about 16,80 kWh.

Then the assessment of electric power consumption being spent by the activity of the LHD vehicle within the first phase $c_{1,j}$ as well as by the train within the second phase $c_{2,j}$ can be formulated simply by:

$$\begin{aligned} c_{1,j} &= 0.165\,j + 0.17 \\ c_{2,j} &= 0.210\,j + 16.80 \end{aligned} \tag{5}$$

where the 0.165 and 0.210 express the uniform increase of the consumption in kWh by every 25meters and $j \in \{0, 1, 2, \ldots, 20\}$ express the number of via-driven segments.

It is assumed that the first segment in perspective, i.e. the last one in the order, is already equipped by a loading crosscut with transloading place and locating others is the subject of investigation. Each of such crosscut is also equipped in order to secure loading of excavated rock material without any break up to the parallel haulage drift,where the next phase of hauling is carried out by the train. The costs for set up such crosscut with the installation of loading place are then expressed in a comparable and countable form, i.e. with always a possible translation of such costs into electric power consumption, including respective works and installations according to given rock environment and used equipment, that is estimated to be about 3000 kWh.

In this way, the task has got character of a trade-off the energy consumption due to increasing the distance of haulage, when by setting up a loading crosscut in a segment causes breaking certain increase of power consumption within the first phase of haulage on account of certain increment of power consumption within the second phase of haulage. The character of the task is not changed even though a real drifting can run otherwise. The economic balance, as well as the recommended location of the crosscuts, remain valid.

In the given case, math solution, with the application of the formulas (3), gives for $f_{m,0}$, which represents the total minimum costs, a result of $f_{20,0}$ = 83 879 kWh. Then for i = 20, 19, … ,1 with the successive setting i according to the equation (4), the encoded solution p_i can be obtain, as follows (p_1, p_2,…, p_{20})= (1, 0, 1, 1, 0, 1, 1, 0, 1, 1, 0, 1, 1, 0, 1, 1, 0, 1, 1, 0). From the course of the solution, it is possible to deduce that the most advantageous interval between the crosscuts for the given situation of two face parallel drifting with a length of 500 meters is the 75 meters (3 times 25 meters of a segment). Whereby, the last crosscut in perspective, the first in order, has got just 50 meters ahead (2 times 25 meters of a segment) since there is finish of the drifts with a designed total length of 500 meters. As seen, the solution recommends inserting the crosscut in each third approximating segment (p_i =0). Placement of the crosscuts according to this strategy and at the same time to start a new haulage stage with the new first phase of haulage after every 75 meters gives the minimum total electric power consumption that is 83 879 kWh at given assumptions.

In the next step it was contemplated to investigate and compare this result with outcomes of enumeration method to take into consideration and to calculate laboriously the most likely cases of spacing such crosscuts, e.g. 25, 50, 75, 100, 125, 150, 175, 200 meters, at the same given assumptions. So the one cycle of LHD vehicle corresponds approximately with hauling one cubic meter of rock material. The 20 cycles of the LHD vehicle can load one trip of the train completely. The approximation of 500 meters long drifts by a set of 20 segments with a length of Δ = 25 meters remained. A course of the defined costs by the distances is summarized in the *Tab. 1*. It also verifies the exact solution of given case formulated and computed by dynamic programming, i.e. as read there the 75 meters with minimum total costs of 83 879 kWh.

Tab. 1 *Outcomes of enumeration with costs in kWh for the likely spacing cases in meters.*

Spacing	costsLHD	costsTrain	costsCrosscuts	costsTotal
25	12730	37590	60000	110320
50	20000	37380	30000	87380
75	25940	36939	21000	83879
100	33200	36960	15000	85160
125	39800	36750	12000	88550
150	43760	36624	12000	92384
175	51020	38199	9000	98219
200	54320	36288	9000	99608

Source: author

CONCLUSIONS

The purpose of the work was to provide decision-making support for the placement of loading crosscuts with transloading places. They service as certain transport nodes as well as places to start a new excavation stage with new haulage regime within two faces parallel drifting at mine opening or at two faces excavation of tunnel tubes. The pertinent optimization routine is based on the application of dynamic programming and was tested on a case of deposit development as well as on some the most likely cases of the spacing such crosscuts to make verification. However, generally, we must be careful as for the fidelity of applied approximations,for both the space situation and also the costs functions. The more they approach reality, the more a piece of research is successful. In spite of very rough approximations in the given study, the results show that there will always exist mathematically a local minimum of total cost function worthy to search for.

References

[1] Bellman, R., 2003, "Dynamic Programming. Reprint edition," Princeton University Press, NJ, pp. 384.
[2] Bellman, R., and Dreyfus, S. E., 2015, "Applied Dynamic Programming," Princeton University Press, NJ, pp. 390.
[3] Speyer, J. L., Jacobson, D. H., 2010, "Primer on Optimal Control Theory," Society for Industrial and Applied Mathematics, PA, pp. 303.
[4] Bertsakas, D. P., 2017, "Dynamic Programming and Optimal Control," Athena Scientific, Belmont, MA, pp. 576.
[5] Laporte, G., Nickel, S., Saldanha da Gama, F., 2015, "Location Science," Springer International Publishing, NY, pp. 644.
[6] Castro, J., Nasini, S., Saldanha da Gama, F., 2017, "A cutting-plane approach for large-scale capacitated multi-period facility location using a specialized interior-point method," Mathematical Programming, Springer International Publishing, NY, 163(1), pp. 411–444.
[7] Gimadi, E. KH., Kurochkin, A. A., 2013, "An effective algorithm for the two-stage location problem on a tree-like network,“ Journal of Applied and Industrial Mathematics, 7(2), pp. 1–11.
[8] Arabani, A.B., Farahani, R.Z., 2012, "Facility location dynamics: An overview of classifications and applications,“ Computers & Industrial Engineering, 62(1), pp. 408-420.
[9] Roumpos, C., et al., 2014, "The optimal location of the distribution point of the belt conveyor system in continuous surface mining operations,“ Simulation Modeling Practice and Theory, 47, pp. 19–27.
[10] Rahmanpour, M., Osanloo, M., Adibee, N., Akbarpourshirazi, M., 2014, "An approach to determine the location of an in-pit crusher in open pit mines,“ International Journal of Engineering (IJE) Transactions C, 27(9), pp. 1475 – 1484.
[11] Paricheh, M., Osanloo, M., Rahmanpour, M., 2017, "In-pit crusher location as a dynamic location problem,“ Journal of the Southern African Institute of Mining and Metallurgy, 117(6), pp. 599-607.
[12] Darling, P., 2011, "SME Mining Engineering Handbook (3rd. edition*)*," Society for Mining, Metallurgy, and Exploration, Inc. Library of Congress, WA, D.C., pp. 1984.
[13] Bauer, V., 2014, "Mining Technologies," Technical University of Košice, pp. 180.