

NEW POSSIBILITIES OF CALCULATING THE VOLUMES OF EXTRACTED MASSES IN THE SURFACE MINING OF BROWN COAL

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Abstract

The companies engaged in brown coal mining are looking for ways of managing the mining process as efficiently as possible. The principal mining technology used for brown coal mining in our country, but also in Germany and Poland, are wheel excavators. The evolving GNSS technology has enabled designing and realisation of systems for determining the spatial position of the excavator wheel. The visualisation of the wheel's spatial position and tracking of its real-time motion is performed in the Czech Republic by the program Mine Model developed by the company KVASoftware. One of the most important tasks of mine surveyors is the calculation of the volumes of the extracted masses. The described system performs this task in real-time. This article describes an application that is used to automate volume calculations.

Key words: Wheel excavator, Digital terrain model, GNSS, GNSS Mine model, three-dimensional (3D), volume calculation

1 INTRODUCTION

Brown coal mining is in the Czech Republic still an important industrial sector despite the significant decline in mining during the last twenty years. In the year 2016, over 38 million tonnes of brown coal were extracted [1]. Reliable supplies of domestic brown coal are a stabilising element of Czech power engineering. In recent years over 40% of the electricity consumed in the Czech Republic was generated with the use of the brown coal [2]. The role of brown coal in the heating plant industry is significant. The company Severočeské doly Ltd. is the largest producer of brown coal in the Czech Republic in the long run. Brown coal mining takes place at two localities, namely Mines Nástup Tušimice and Mines Bílina.

At present (2017) valid scenarios consider that coal mining at the Mines Nástup Tušimice will continue till 2037-2043 and at the Mines Bílina Dolines till 2050-2055, all depends on the coal sales in individual years. In the surface mining of coal, but also some of other minerals in the Czech Republic, the mining, transporting, depositing, dumping large amounts of masses, both the main mined mineral as such and the necessary volume of overburden, waste rock, sloams, accompanying raw materials and sometimes also the necessary volume of subsoil. For example, in 2016 alone in the company Severočeské doly Ltd. the volumes of the masses presented in Table 1 were extracted, transposed and possibly deposited. One of the main and most regular tasks of mining surveyors on open-cast quarries is, therefore, calculation of the volumes. It is also one of the most complex and responsible tasks that is linked to the control of the fulfilment of the most important tasks of the business plans of the mining companies and the statistical reporting. The real-time calculation of volumes is performed in the environment of the programs developed by the company KVASoftware [3, 4].

At present, brown coal mining in the Czech Republic is concentrated in several huge open-cast quarries in the North Bohemian Coal Basin and in the Sokolov Basin and it runs under increasingly complex mining-geological and economic conditions (Figure 1). The companies engaged in brown coal mining are looking for ways of better monitoring, controlling, planning, and subsequently managing the processes of wheel excavators, and of making the entire mining process more efficient both technically and economically. One of the important ways in this process is tracking the spatial position of the mining wheel of excavation machines (wheel excavators). [5]

In Germany in the Rhine mining district, the GNSS technology on excavators began in the year 1985 on a single excavator at the Frimmersdorf quarry. The relatively promising test results in 1990 on one excavator at the Bergheim quarry ultimately led to the design of a large SATAMA project. At the end of 1995, some components

of this concept were tested in practice. The results of the project are regularly reported to the professional public through the specialized learned journals, e.g. in the year 1996 in the journal "Surface Mining" [6].

In the Czech Republic, the first real steps of using the GNSS technology for determination of the three-dimensional position of the excavator wheel took place in 1997 in the company Severočeské doly Ltd., specifically in the Mines Nástup Tušimice. The purpose of the testing was to verify the usability of the GNSS technology under real operating conditions. Testing took place on 22nd July 1997 between 10.30 and 13.30 of Central European Summer Time (CEST) and on 23rd July 1997 from 9.00 to 12.30 CEST. During observations, the excavator operated continuously with minor outages within 30 minutes at all the horizons of the technological strips. Only the GNSS devices that were borrowed for 2 days were installed on the excavators. Other required measuring instruments were not installed, and therefore a complex system for calculating the centre of the wheel axis could not be created. The results of the GNSS testing of that time are summarised in the literature [7]. Afterwards, further attempts were halted, also due to the then unacceptably expensive used technique, especially the GNSS equipment.

The research was restored at the company Severočeské doly Ltd., Chomutov in 2006 and the wheel positioning system was developed for routine continuous operation. At present, it is deployed on all overburden excavators and coal excavators of the company Severočeské doly Ltd. - a total of 22 wheel excavators. The research is described in detail in [8].

Tab. 1 Excavation of overburden and coal at the company Severočeské doly Ltd. in 2016.

	Mines Nástup Tušimice	Mines Bílina	Severočeské doly Ltd.
Excavation of overburden (m ³)	20 282 238	58 590 058	78 872 296
Gross coal excavation (t)	11 957 645	9 486 131	21 443 776



Fig. 1 Aerial shot of a quarry Libouš – view from the South – 2016

2 SYSTEM BASIC COMPONENTS

For enabling a real-time calculation of space coordinates of the excavators wheel, it is necessary to create a set of measuring instruments, the measurements of which will lead to the acquisition of the data necessary for the calculation. Selection of measuring instruments is primarily influenced by the following needs:

- Measurement of the X, Y and Z coordinates of at least two points on the excavator as often as possible,
- Measurement of the entire excavator inclination with respect to the horizontal plane,
- Measurement of the wheel boom inclination with respect to the horizontal plane,
- Measurement of the wheel boom extension (for retractable excavators).

For the measurement of the absolute position of two points on moving excavators, it is most advantageous to use the GNSS technology [13]. Measurement of inclination of parts of the excavator structure is assured by the inclinometers and the wheel boom extension is measured by an incremental rpm sensor - the boom extension is calculated by conversion of rpm of the cogwheel axis, which transmits the electric drive

Algorithms for calculation of coordinates XK, YK and ZK [10]:

$$Y_K = Y_{GPS1} + \sin \sigma_{GPS1, GPS2} \cdot \left[\left(7,557 + IRC \frac{12,03}{40423} \right) \cdot \cos(19,648 - SKL2_X) \pm 35,966 \cdot \cos \beta \right] \quad (1)$$

$$X_K = X_{GPS1} + \cos \sigma_{GPS1, GPS2} \cdot \left[\left(7,557 + IRC \frac{12,03}{40423} \right) \cdot \cos(19,648 - SKL2_X) \pm 35,966 \cdot \cos \beta \right] \quad (2)$$

$$Z_K = Z_{GPS1} - \left\{ \left[1,77 + \sin(19,648 - SKL2_X) \cdot \left(7,557 + IRC \frac{12,03}{40423} \right) \right] \pm 35,966 \cdot \sin \beta \right\} \quad (3)$$

3 PROCEDURE FOR REAL-TIME VOLUME CALCULATION

3.1 Defining areas in the digital model

The principle of volume calculation using the GNNS software 'Mining model' is derived from the principle of defining the area in the digital quarry terrain model using the "GNSS Mining Model" program developed by the company KVASoftware [11]. All source data (objects) entering the surface description must be vectors (even singular). The program generates a general triangular network (Figure 4), in which each of the measured points must be a triangle vertex.

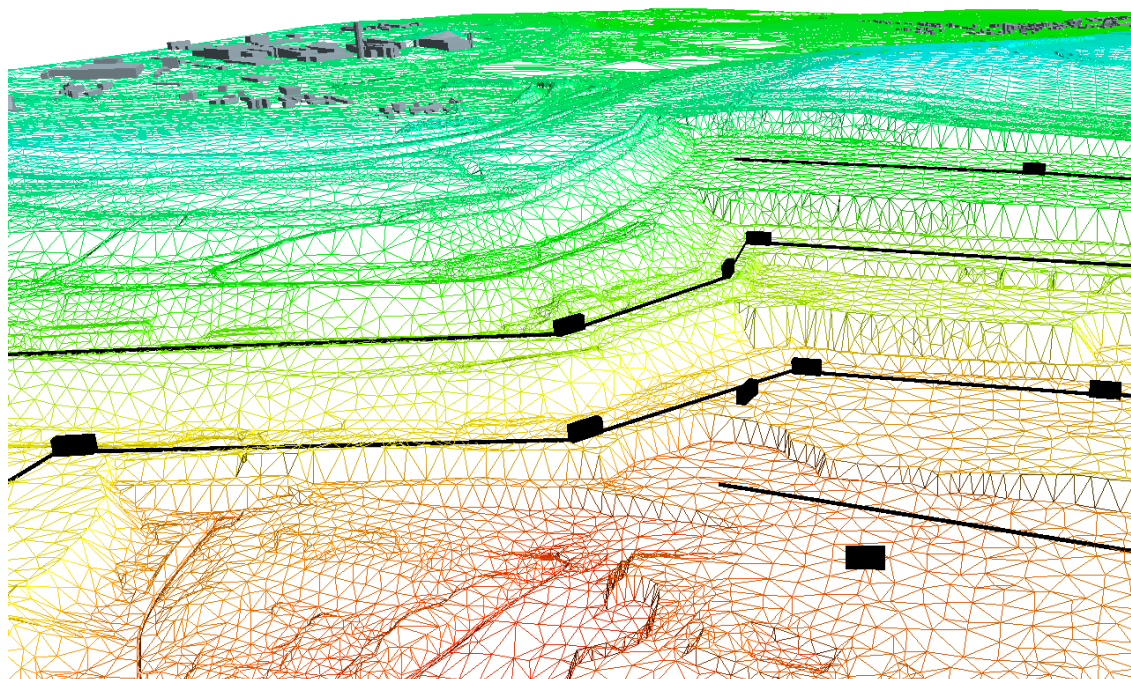


Fig. 4 Generated triangle network of the terrain digital model

Each triangle in the triangular model network represents the elemental plane surface (Figure 5) defined in space by three points (triangle vertices) X_A, Y_A, Z_A and X_B, Y_B, Z_B and X_C, Y_C, Z_C . One of the basic tasks of the program that is necessary for optimising the digital model and various applications, including volume calculations, is the calculation of an unknown Z_N coordinate for the specified general N-point with known coordinates X_N, Y_N . A triangle is found, in the elementary area of which this point will lie. It is then possible to calculate a missing the Z-coordinate for the point on lying on the known area. The desired coordinate Z of the point N is calculated using the determinants from the equation of the area determined by the three triangle vertices A, B, C.

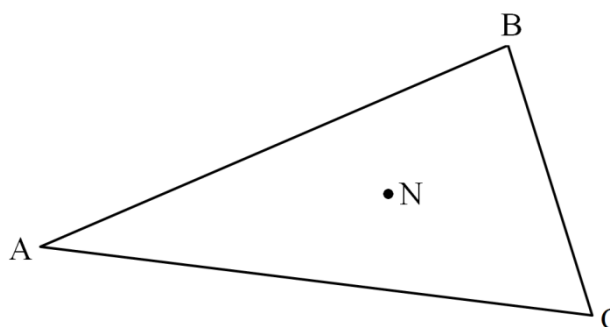


Fig. 5 Elementary triangle of the digital terrain model

3.2 Principle of volume calculations

The principle of all volume calculations and derived calculations (mass, qualitative parameters of the raw material, etc.) depends on the existence of two known 3D surfaces, the geometry of which is determined by the triangular networks of the digital model. The volume calculation takes place between two surfaces, i.e. between two models. This is for example, the volume between the MASTER model (the measured initial state of the quarry) and the REFERENCE MODEL (model of changes after excavation of part of the quarry).

The basic element of the calculation is always the perpendicular triangular vertical prism with general planar bases (Figure 6). The calculation parameter is an integer value indicating the maximum allowed area of the elementary triangle of the base in $[m^2]$.

The program as a first step of calculation performs the recursive reconfiguration of the base triangular network until each triangle has an area less than or equal to the specified value of the parameter [15].

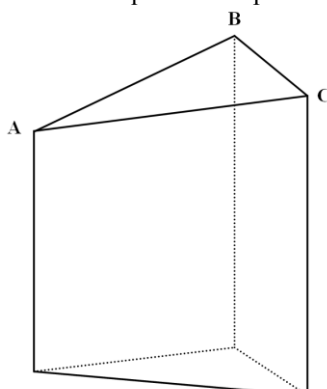


Fig. 6 Triangular prism - the basic element of the volume calculation

Elementary volume:

- Positive value – area of the MASTER model is „above“ the REFERENCE model area,
- Negative value – area of the MASTER model is „below“ the REFERENCE model area.

The total calculated volume is then given by the iterative sum of the elementary volumes over all elements of the triangular network. The values of positive volumes are iterated separately (they are mostly interpreted as the volume of "poured" material) and the values of negative volumes (mostly interpreted as the volume of "extracted" material) are also iterated separately.

3.3 Volume calculations in the GNSS system Mining model

The above-mentioned basic principles of mass calculation are used by the system for the calculation of the excavator wheel spatial position also for continuous calculations of the volumes of the excavated masses. The program works with the elements called "GNSS dynamic maps". GNSS Dynamic Map in KVASoftware applications is a system of partial index matrices and a description of active matrix elements by a set of equations enabling dynamic definition and modification of the matrix elements in time. The result is a dynamic

model describing the space affected by "excavation" – i.e. in the program environment by the parametric model of the wheel of a particular excavator tracked by GPS [4].

The used method of areas description of a dynamic GPS map is based on the requirement of fast indexing of the area elements, i.e. rapid calculation of the area modification (updating) using at the same time the smallest possible amount of data (file size) because the data is shared over a network together with a number of other applications.

All the calculations are performed applications running in parallel entitled the "GNSS Mining Model" (one application for each excavator) above the common data space. At present, four applications of the "GNSS Mining Model" can be run in parallel on a quad-core processor (referred to as a GPS server) [12].

The site of interest can be divided into an unlimited number of partial index matrices, ideally one matrix individually for each excavator and for its assumed progress. The matrices may overlap each other for the case that the excavation areas of individual excavators partly share a common space. The application ensures that no data redundancy occurs in the overlapping matrices. The matrices are graphically defined in the basic digital model map, and they can be arbitrarily edited in time (zoomed out/zoomed in, cancelled, and added). Each matrix element represents a 1x1m square of the raster, and after an initiation, the matrix elements are inactive (i.e., they contain no data).

The program simultaneously generates the excavator wheel model as a parameter-defined cylindric model. The parameter is the cylinder diameter (= wheel diameter) and cylinder height (= wheel width). The wheel cylinder model is oriented in the space using the wheel rotation axis.

By passing the wheel cylinder model, the "affected" elements of the dynamic map are activated and an index is assigned to them to fields (files), which then contain 8 elementary areas (triangles, i.e. plane equations) for each active element (Figure 7). The application ensures a mutual relationship between the elementary faces and also with respect to the neighbouring active matrix elements = continuity of planes in the 1st derivative. The active map elements in the model map are in the application rendered in gray.

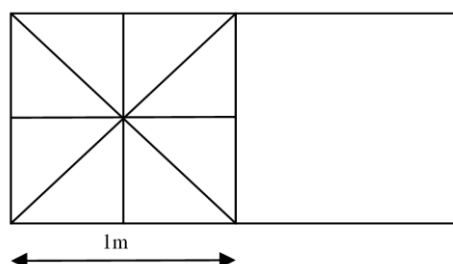


Fig. 7 Active (on the left) and inactive matrix element (on the right) with dimensions 1x1m

The active element is referenced by an index to another 8 elementary areas in order to refine the model and increase the accuracy of the volume calculations [11]. Each of the elementary areas (triangle) is described by the parametric equation of the plane, its parameter consists of the coordinates X, Y, Z of the triangle vertices in the coordinate system. At the same time, an information about the date and time of activation/modification of the matrix element/modified is inserted for each activated and modified matrix element. The initially inactive matrix elements are activated by the "pass" of the excavator wheel model. When activating the matrix element, at first all 8 elementary areas are "laid" on the current terrain model, i.e. they copy the terrain in the 1x1m square.

For these new area elements, their intersection with the wheel area is then calculated. Elements of the area, which receive by this intersection a new lower dimension at any vertex, are modified to a new value. The Z coordinate thus creates in respect to the original values an elementary triangular prism, which is the basic element for the volume calculation.

Figure 8 shows a spatial view of the quarry area for excavator the SchRs1320/110 taken on 21st August 2017. The wire model shows the originally measured terrain of the quarry, the blue colour shows the current digital terrain model, which is created during the excavation of minerals by the wheel in real time.

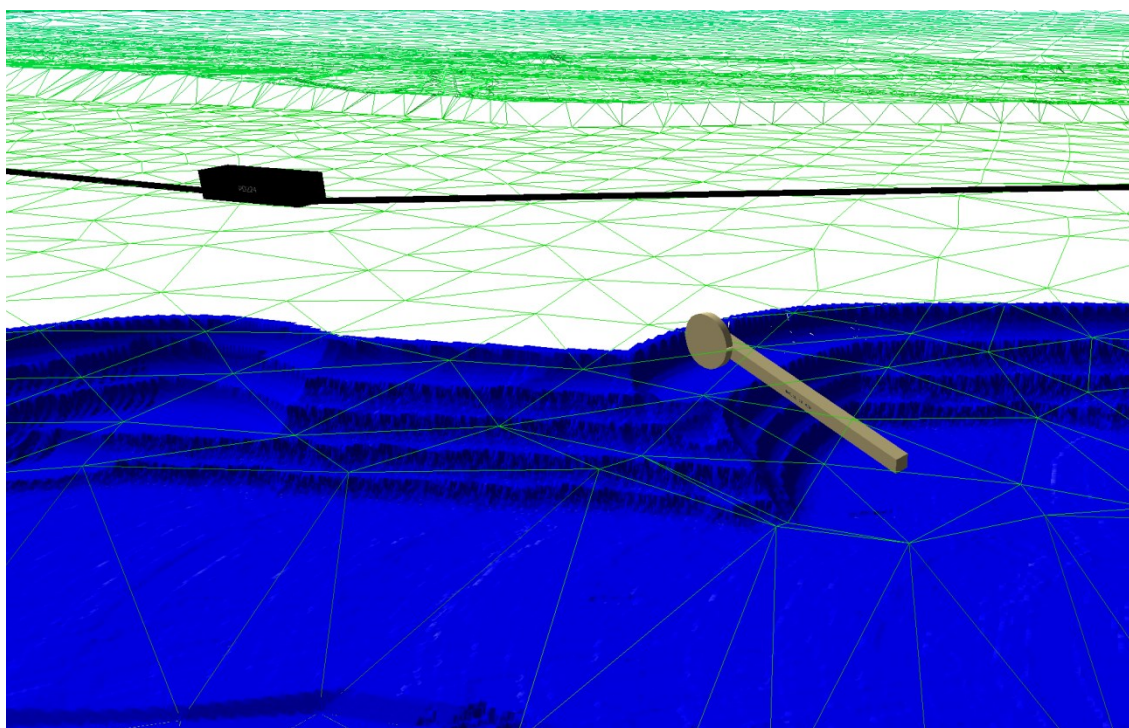


Fig. 8 Spatial view of the area of the quarry for the excavator SchRs1320/110 taken on 21st 8. 2017

Each such elementary vertical triangular prism is then also the basic element for calculation of the intersections with the areas of the geological model and hence also for the calculation of the volume masses, tonnages and qualitative parameters. A similar procedure is used for modification of the matrix elements, i.e. for the repeated pass of the wheel cylinder model. For the already existing elementary areas in the matrix element, the intersection with the wheel area is calculated again, and each lower dimension modifies the original dimension. If a change takes place, the date and time for the given matrix element are updated. Each change in the wheel position (within the interval of 5 seconds for a sampling of the wheel position) is calculated as an intersection with a number of elementary areas of all the affected matrix elements in the entire wheel path. Accumulation of all elementary volumes in the sampling interval represents a basic element for subsequent total volume calculations within a selected time interval.

4 COMPARISON OF VOLUME CALCULATIONS

The company Severočeské doly Ltd. performs a monthly check of the excavated volumes. The method used for measurement of the new state of the quarry is aerial digital photogrammetry (Digital Camera UltraCam Xp). The centres of taken digital images are at the height of approximately 750-800m above average terrain level, and the scale factor is 1: 7,600, resolution (pixel size) is 5.5cm. The evaluated states of sections of the initial and final state then create a spatial computational model and the volume of excavated masses is calculated individually for each excavator. This method of measurement, commonly practiced at the quarry, was used also for comparison of the volume calculations based on the data obtained using the real-time spatial position calculation system of the excavator wheel. The measurement (taking of images) of the state of excavation sections for the excavators SchRs 1320.1/110 and KU800.20/106 based on the data from aerial photography took place on 30.7.2016 at 10:15 and then on 31.8.2016 at 12:29. The volume of the mass excavated by the excavator at this interval was calculated by a standard measurement procedure in a digital quarry model environment using the triangular vertical prism method (Method 1).

The system “GNSS Mining model” generates continuously for each excavator a database of excavated mass. At the moment of each performed calculation of the wheel position (it means every 5 seconds) the date, time of calculation and the values of the calculated volumes and tonnage are recorded in the database. Since the date and time of the measurement of the quarry by the aerial photogrammetry method are known, it is very easy to make a comparison. In the environment of the program “GNSS Mining model” an excavator was chosen and the date and time were entered in the mining tracking module. In the investigated period the system “GNSS Mining Model” calculated the volume of the overburden excavated by the excavator SchRs 1320.1/110 to be 1 115 988 m³ - Figure 9.

the mining tracking

Volume [m ³]	1115987.7	Per the current	1 hour
Clear out [m ³]	1115987.7		
Tonnages [t]	0.0		

During work shift: morning Day: 28.11.2014

For the period

from:	30. 7. 2016	10:15:40
to:	31. 8. 2016	12:29:40

Blue dashed arrow points to the 'from' date/time. Red dashed arrow points to the 'to' date/time.

Fig. 9 Determination of the mass volume in the environment of the program “GNSS Mining model”

Method 3 is also presented for comparison - which represents the results of the volume determination continuously obtained from the data of the weighing scales by converting the determined mass to volume. This method is thus logically less accurate namely due to the heterogeneity of the composition of the overburden materials, the degree of their bulkage at the moment of weighing, and thus resulting uncertainty in determining the bulk density for the conversion of mass to volume. These data, however, serve to operators in the period between the measurement (approx. 1 month) for daily statistical reporting, which is always corrected by the so-called cubage difference as soon as the correct volume is measured by the measurement method [16].

The results of the volume calculations are compared in Tables 2 and 3. The difference between volumes calculated by Method 1 (standard measurement) and Method 2 (GNSS Mining Model) is minimal. For excavator SchRs 1320.1/110 it makes 0.3% and for KU800.20/106 it makes 2.4%. The difference in the volumes found between the Method 3 and the Methods 1 and 2 is quite considerable (13.9%, 11.4%), the results obtained by conveyor scales must always be afterward corrected.

Tab. 2 Results of volume calculations from 30. 7. 2016 till 31. 8. 2016 – excavator SchRS 1320/110

Method for calculation of volume excavated by excavator	Volume [m ³]	Difference
Method 1 – from photogrammetric evaluation of quarry	1 119 337	
Method 2 – from system GNSS Mining model	1 115 988	-0,3%
Method 3 – conveyor scales	964 000	-13,9%

Tab. 3 Results of volume calculations from 30. 7. 2016 till 31. 8. 2016 – excavator KU800/20

Method for calculation of volume excavated by excavator	Volume [m ³]	Difference
Method 1 – from photogrammetric evaluation of quarry	392 022	
Method 2 – from system GNSS Mining model	401 287	+2,4%
Method 3 – conveyor scales	351 100	-11,4%

5 CONCLUSIONS

The difference between the initial volume obtained by the standard metric calculation from the photogrammetric data (Method 1) and those obtained by the investigated method of the application "GNSS Mining Model" (Method 2) is minimal. Similar differences can be achieved also when comparing the volumes obtained from data by evaluation of the same aerial images taken with two different photogrammetry evaluation. Similar results were obtained also for other excavators. The system is now deployed on all 22 excavators at the Mines Nástup Tušimice and Mines Bílina. It performs the work that could be called with some exaggeration 'measurement without the presence of a measurer'. In the real quarry, the wheel movement removes rocks and soils. The position of the wheel is known at all times. In the digital model 'GNSS Mining Model' the is "copied" in real-time. Model of the wheel shell gradually "penetrates" the digital model of the quarry. The following rule applies: "At the places that were overrun by the wheel there are no minerals anymore". In this way, a new surface is gradually created by excavator mining.

The issue, which has not yet been satisfactorily resolved, is an error-free transfer of data from the excavator to the PC server or transfer of corrections for the GNSS systems to the excavator (GPRS, Radio Modems). Dropouts lasting several minutes or more cause that during that period the wheel movement is not simulated in the system and the actual volumes of the excavated volume are not entered into the database. When

examining the three-dimensional model created by the wheel in the model environment, these dropouts are mostly seen as some "nonsensical" non-excavated sections on the excavator's travel range. However, when this issue of data transmission will be resolved, the standard measurements will not be completely replaced by this system. It is necessary to measure not only the excavation sections but also all other spaces of the quarry where any changes took place.

On the other hand, the fact that mining technicians receive extra data about excavated volumes with considerable accuracy immediately after completion of the monitored period, such as calendar month, i.e. sooner than the results obtained from aerial photography, presents a considerable advantage. Moreover, these results are more accurate than the values obtained from the conveyor scales. Especially the data on the overburden extraction is significant since the volume of the overburden extraction in [m³] per individual overburden profiles is the target tracking data. The minimum differences in the calculated volumes lead us to an opinion that the state of the quarry obtained on individual sections by tracing the terrain model spatially depicted in the system 'GNSS Mining Model' can be considered sufficiently accurate also as an initial state for common mining planning of excavator mining operations.

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