Comparison of 2.5D Volume Calculation Methods and Software Solutions Using Point Clouds Scanned Before and After Mining

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The development of contactless mass data collection methods such as laser scanning or digital photogrammetry leads to the development of a wide variety of algorithms and calculations that can be applied to such data. The volume calculation of material that was mined away is one of such applications. This paper compares available software solutions capable of calculating volume, namely commercially available programs Atlas DMT, 3D Reshaper, Leica Cyclone and Trimble RealWorks, and an open-source program CloudCompare. All of these are commonly applicable for general point cloud processing, and volume calculation is just one of the functions offered by the programs. Two principal types of algorithms are used by those software solutions – grid-based algorithms and algorithms based on a triangular irregular network created from the point cloud. Some of the tested programs offer both calculation methods. The experimental testing of the accuracy of those programs was performed on real data from a quarry where laser scanning was used in combination with a GNSS method. The individual software solutions were used to calculate the scanned area, volume calculations using various settings and processing demands (expressed as processing time). Besides, the algorithms used in individual programs, their limitations and specific problems are discussed. Grid-based methods turned out to be very effective due to the low processing time and very good provided results even for relatively large grid cells. TIN-based methods, on the other hand, also provide very accurate results, the processing time is, however, substantially higher. In some cases, the quality of the results also depends on the algorithm constructing the triangular network itself.

Keywords: volume, comparison, Atlas DMT, 3D Reshaper, Leica Cyclone, Trimble RealWorks, CloudCompare.

Introduction

The availability and practical utilization of mass data collection technologies such as 3D scanning (terrestrial, airborne) or multi-image intersection photogrammetry from terrestrial or airborne images (acquired, for example, using fixed-wing aircraft or multicopters) processed by SfM (Structure from Motion) grows (Bartos et al., 2019; Blistan et al., 2016; Blistan et al., 2019; Kršák et al., 2016; Pukanská et al., 2014; Rusnák et al., 2018; Blistan et al. 2020). Thus acquired point clouds are subsequently utilized for various purposes, including volume calculations, for example, for heaps of loose material (Tucci et al., 2019; Salagean et al., 2019), determining the volume of material that has been mined away (Stojcsics et al., 2018; Zápalková et al., 2011), of concrete (Martínez-Sánchez et al., 2016), quantification of morphological changes (Medjkane et al., 2018), pinpointing landslides (Tang et al., 2019), determining the amount of transported loose material (He et al., 2019), and many others.

For volume calculations, it is often necessary to combine such dense data with data acquired using geodetic methods such as GNSS or total station. Such methods provide significantly lower data density but are irreplaceable where, for example, dense vegetation or other obstacles to laser scanning are present.

Multiple algorithms of determining volume from the above-described data have been developed. For practical usage, it is, however, necessary to know the degree to which a selection of an algorithm or settings affects the results.

Many of the above mentioned (and other) papers describe the methods used for determining volume in detail, but the accuracy of the results (and comparison with reality) is not sufficiently discussed, despite the fact that many authors dilute the point clouds massively prior to the volume calculations, which may impact the accuracy. Few studies have compared methods of point cloud-based volume calculations. One of the few was published by Urbancic et al. (2015), where the authors analyse their own calculation methods and methods of interpolation on the resulting volumes. Nevertheless, using own scripts/software is not feasible for everyone and often not for high volume data, and hence, the use of ready-made software solution is in practice usually the preferred method.

In our study, multiple algorithms implemented in various freely or commercially available software solutions have been applied to the same point cloud to quantify the effects of individual algorithms on the

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calculation. Namely, we will apply various methods for volume calculation on data from real 3D scanning that are non-homogenous in density (due to the necessity to manually determine coordinates of some areas by GNSS), and compare their results. Limitations of individual software solutions and settings as well as algorithms used in the individual methods as well as the temporal and economic demands of individual software solutions will be discussed. Both commercially and freely available software solutions utilising triangular network as well as grid-based 2.5D algorithms (which are the most commonly used for groundworks volume calculations) will be tested. Of the commercially available software solutions, Atlas DMT, 3D Reshaper, Leica Cyclone and Trimble RealWorks have been chosen for testing; CloudCompare was used as a representative of freely available software solutions.

Data

The utilised data have been acquired in the Trebejov quarry in Eastern Slovakia, between Prešov and Košice (Fig. 1). In this quarry, dolomite is being mined in a five-level quarry with the height of individual mining walls between 16 and 25 metres. The top of the quarry is covered by mature beeches and oaks that are being gradually removed in line with the needs of mining progress.

The data was acquired by terrestrial scanning using 3D scanning system Leica C10 in two time epochs; the first scanning was performed in October 2011, the other after rock blasting in February 2012. A geodetic network was permanently stabilized using bolts and used for pinpointing control points. Scanner settings were identical during both scannings, i.e., 20 mm spacing at 50 m.

The data was complemented by a ground survey of the top of the quarry before and after blasting using GNSS RTK in places where scanning would not provide reliable data. As far as the data density is concerned, the data is, therefore, non-homogeneous. The accuracy of the points surveyed using GNSS is lower than that of data measured by laser scanning, with standard deviations of approx. 25mm horizontally and 50mm vertically. This, however, represents no problem for our study as the crucial consideration here is that the data was identical for all methods of calculation. In other words, we needed to compare all algorithms on the same real data; the accuracy of the actual volume calculation is only secondary.
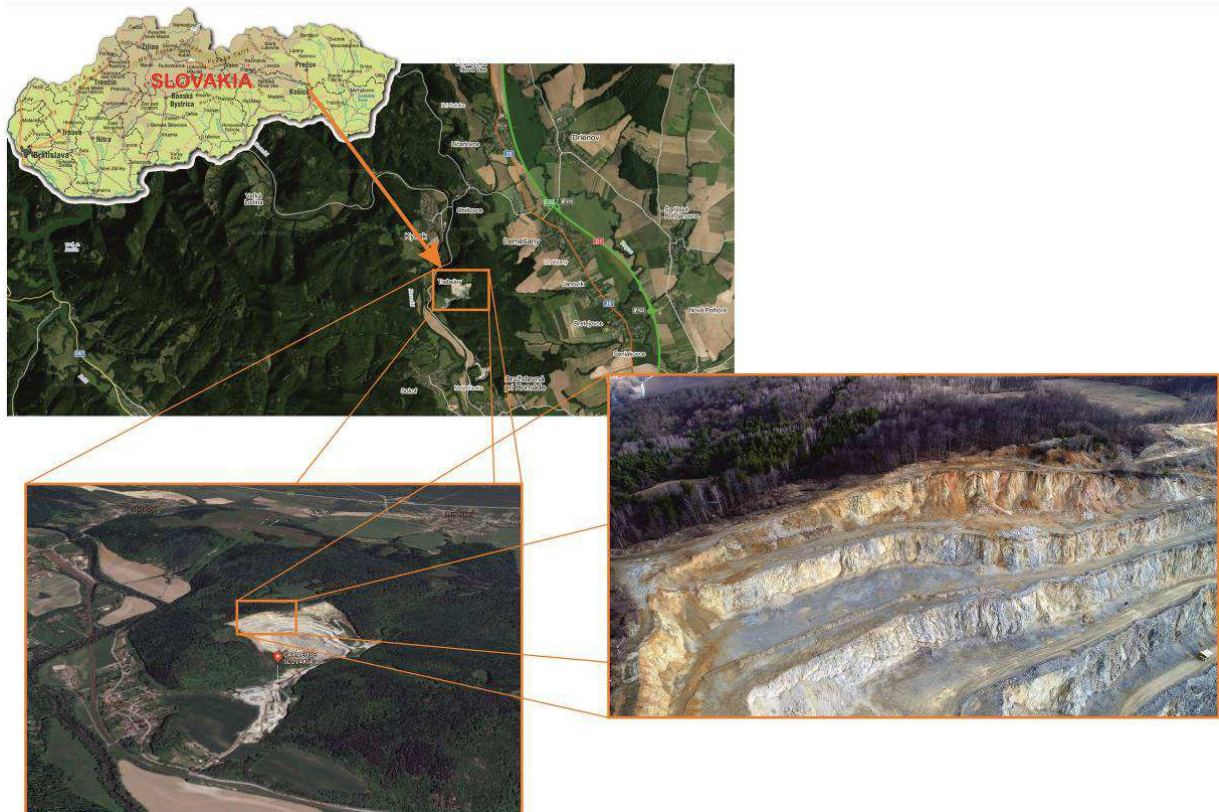
Fig. 1: The Trebejov quarry

Firstly, the original point clouds were adjusted to allow their processing in all tested software solutions. Fig. 2 shows a visualization of the point clouds (top – October 2011, middle – February 2012, bottom – cropped overlay).

The points that were not on the ground (mining equipment, stabilization of control points, etc.) were removed from the cloud. Further, all data were tilted in the same way to remove vertical overlaps, which is necessary for using 2.5D algorithms, and cropped to cover the same area in the XY plane.

The images obviate that our data indeed represent real data, including all common imperfections and problems such as non-homogeneity, holes caused by obstacles, etc. Data 1 (from 2011) contain altogether 6,220,168 points while data from 2012 (Data 2) comprise 3,213,671 points (both including GNSS points). The difference in the number of points is caused by the fact that Data 1 was scanned approximately from half the distance than Data 2, utilising the same scanner settings (the same angle spacing).
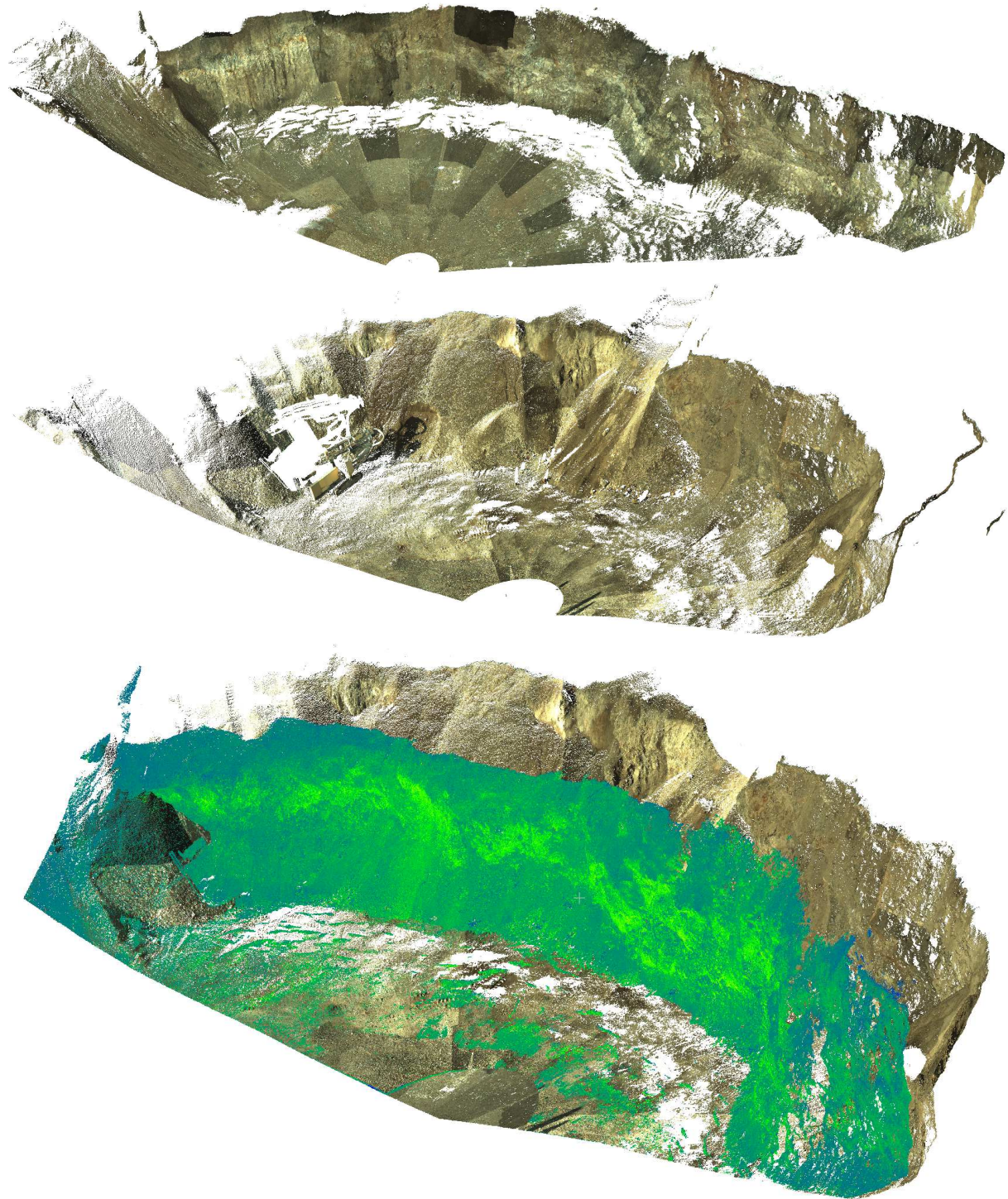

Fig. 2. Used data: top – Data 1 (2011); middle – Data 2 (2012); bottom – cropped overlay

Used software and calculation algorithms

Below, the individual software solutions used for testing and their volume calculation algorithms will be described. All used software solutions utilize 2.5D algorithms, which means that for the correct calculation, no vertical overlaps of the data in the individual models are allowed. The results of the computation in individual programs usually produce summation of values with a positive sign (i.e., volume increase, added material), of those with a negative sign (volume decrease, material mined away) and the total summation providing the overall balance.

Atlas DMT ver. 19.08.1

The primary purpose of the commercially available software Atlas DMT (Atlas, spol. s.r.o., Czech Republic) is processing elevation data (both individually surveyed points or point clouds) and transforming them into digital terrain models that can be subsequently further analysed or used for generating graphical outputs.

The term Digital Terrain Model (DTM) means a model of a surface area covering the surveyed terrain. The model is constructed as a 3D combination of points, lines and faces from the input data. Where such data is missing, estimation of the additional surface is calculated to estimate the real surface. The calculation between the points is not based on linear interpolation but uses terrain smoothing. The version used for analysis in this study allows work with up to 666 mils. points and costs, including the volume calculation module, approx. 3850 Eur (http://www.atlasltd.cz/atlas-dmt.html).

The input point cloud and, if applicable, predefined compulsory lines are used to generate an irregular triangular network (TIN), which is used for all Atlas DMT applications and computations. When generating the model, the data are first sorted according to the positions of the points, named and checked for duplicities. Where there are two points too close to each other, one of them is excluded from the following steps. In the presented case, the default settings considering points within 1mm of space as duplicates were kept. In the next step, the triangular network is created and optimized in the projection into the XY plane. A convex model envelope is created as well, which however may lead to creating triangles with acute angles and to generating connecting lines between points that are not associated in the terrain. This is prevented setting up criteria which, when met, mark the triangle as an envelope and is not used further for the actual calculation. In standard settings, the criteria for envelope triangles are an angle opposite the envelope edge greater than 140º or a ratio of the envelope edge and the neighbouring side greater than 2.5. Here, the settings were amended to consider only the condition of an angle greater than 170º. Envelope triangles were manually edited after generalization to achieve a maximum area of the model. This setting was selected to make the model comparable with models from other software solutions, although we are aware that this is not correct from the perspective of land surveying.

ATLAS DMT offers two methods for calculating the volumes of the triangular terrain model against a comparison plane or against another triangular network.

The first one is a regular grid method. The volume is calculated only over the area of model overlap. A regular square grid with a set resolution (step) covering the entire area of interest is created, and the elevation value from the centre of each square (bottom square – one model, top square – the other one) is taken for calculation of the volume of the individual prisms (base area x elevation difference). The elevations are determined from smoothed out triangular models.

The other method uses the blending of the triangular networks in the overlap area (envelope triangles are excluded from the calculation). As the original triangles of the two DTMs are not identical in their positions and angles, they are broken into smaller (secondary) triangles with matching base areas. The heights of individual vertices of the triangular prisms are determined as the elevation difference of the individual vertices, which in turn are calculated from the original unsmoothed triangles. The total volume is calculated as a sum of volumes of all individual secondary triangular prisms.

CloudCompare ver. 2.9.1

A freely available open-source software for working with point clouds and triangular meshes can be downloaded from www.cloudcompare.org (Version 2.9.1 was used in this study). This software allows a wide range of operations, including point cloud transformations, their filtering, classification, mutual comparison, etc. It also allows volume calculations both against a comparison plane and against another point cloud. The first step is rasterization of the point cloud, splitting it with a set step into square cells in the XY plane (although XZ or YZ planes are also possible). Subsequently, an average elevation value from all points in the square is calculated. Where there are no points in the cell, the elevation value can be determined as a minimum value from the whole grid, average value from the whole grid, user-defined value, or interpolation from the surrounding cells (only within the convex envelope). The volume calculation itself is then elementary – an elevation difference of

surfaces in individual cells is multiplied by the cell base area to acquire the volume differences of individual prisms.

Leica Cyclone ver. 9.4.2

The commercially available software by Leica (https://leica-geosystems.com/products/laser-scanners/software/leica-cyclone), originally developed for processing data acquired using their 3D scanners, costs 13850 Eur. Leica Cyclone uses the method of prisms for calculation. The two TINs are blended and based on the combination of the triangles from both networks, new (secondary) triangular bases are formed, similar to the second method used in Atlas DMT. This huge number of formed triangles also, of course, increases the number of prisms and the necessary processing time and memory demands. Before the TINs are blended, a normal for the new network can be set in either of the X, Y, Z axes. Should a normal in another direction be needed, the full data must be tilted prior to combining models. When creating a TIN network, it is possible to set the number of points for generating the network. The standard setting shows 500,000 points; the maximum recommended number is 2 mil. points. It is possible to generate an even greater network, however considering its further use for calculating differences and processing demands associated with such network, it cannot be recommended as even high-performing computers often end up with memory overflow or, best case scenario, is taking many hours to perform this task. Once both networks with secondary triangles are created, the original and secondary (new condition, in our case after blasting) TINs are selected by the user, and the calculation is performed (algorithm not made public by the software producer).

3D Reshaper ver. 18.0.7.28912

This software, originally costing approx. 11,500 Eur, is by now sold under the new brand Leica Cyclone 3DR (10,000 Eur). This software only allows volume computation between two networks. The manufacturer's description of the algorithm is as follows: „For the computation of the volume of two surfaces, the software uses a direction for the calculation of the cubature. This direction will be used to calculate projections that will generate elementary objects (tetrahedrons) from which we can calculate an overall volume. The direction must be the direction according to which you see the best the mesh with the minimum of hidden parts (usually according to Z). We create a tetrahedron by a triangle, taking as the vertex the centre of gravity of the mesh, and we add each volume to have the total volume. In the example of a sphere, it seems trivial. But in the case of more complex shapes, this calculation may seem to be false; but some tetrahedrons are found with a negative volume (depending on the orientation of the triangle of the base) which compensates the whole result and makes the calculation accurate no matter the shape of the model." (Acquired by personal communication from representatives of 3D Reshaper).

Trimble RealWorks ver. 11.1.1.442

The commercial RealWorks software (approx. 6900 Eur) serves for processing and analyses of point clouds acquired from 3D laser scanning (https://geospatial.trimble.com/products-and-solutions/trimble-realworks). This software uses 2.5D algorithms (a) calculating the volume directly from the point clouds or (b) a hybrid algorithm calculating the change of volume using a grid overlaying a triangular network. In the first case, the calculation utilizes a regular square grid of customizable size (step/grid size and direction of the calculation can be set). After the calculation, the software creates a graphical representation of individual cuboids. If the point clouds are not homogenous, the volume difference in the grid cells containing points from one point cloud only is not approximated – the software does not perform any automatic interpolation between the points. It is, therefore, necessary to edit such calculation to make the software calculate the differences in these areas as well. Such "holes" must be manually delimited and filled using the tool "Fill holes". The results detail the added (+) and mined away (-) volumes as well as the size of the areas where any volume was added or removed.

The other method uses a hybrid algorithm. The software allows the operator to set a normal for computing a triangular network. It is possible to choose the main axes, ideal point cloud fitting, or other options. The point clouds are transformed into two triangular networks used for volume calculation in the direction of the selected normal. However, for the computation itself, the software uses a grid with an optional cell size again; it is, therefore, a combined calculation method based on a created triangular network representing the surface, but the points for the volume calculation itself are acquired using a grid projected on the triangular network.

Testing methods

The respective methods of volume calculation were applied to the data processed as described above. Where the particular software allowed multiple settings or algorithms, all realistically applicable ones were used.

As each software has a different interface and allows different settings, at least some criteria were adhered to where possible to simplify the evaluation of the results. In principle, we can distinguish between algorithms using grid and TIN. For grid solutions, the raster size represents the principal setting, hence multiple cell sizes have been used, namely: 0.005; 0.010; 0.020; 0.050; 0.100; 0.200; 0.500; 1.000; 2.000; 5.000; and 10.000 m cell size. Besides, the interpolation of empty cells from the surrounding cells was applied. It is, however, not possible to unify the settings of triangular networks in a similar way; therefore, the settings were individual and are detailed in the description of the particular software solutions. Comparing the resulting values can then provide information on the magnitude of error associated with the use of particular software, algorithm and setting, as well as its pros and cons. A question remains, which of the methods (if any) can be considered as the most accurate. Considering the principles of the methods, it appears that the TIN-based method used in Atlas DMT makes no or only minimum simplification and uses practically all points for constructing the triangular mesh (except for the practically duplicate points); hence, the value calculated by this method should be the most accurate.

All computations were made using a laptop with Intel i7, 32 GB RAM and a graphics card with a dedicated memory of 6GB.

Results

Atlas DMT

Table 1 shows the results of the grid computation using Atlas DMT. In our case, a difference model with 27,578,415 points, 80,986,334 edges (connecting lines) and 53,990,888 triangles was constructed. The import of the point clouds, generalization and optimization of the triangular network took approx. 1.5 hour; the volume calculation using the triangular networks 3 hours while only using the raster method, the calculation was completed within a few minutes.

Tab. 1. Atlas DMT – results of grid-based volume calculations

Raster size [m]	Number of cells	Surface [m²]	Volume⁺ [m³]	Volume⁻ [m³]	Volume^{total} [m³]	Difference [%]
0.005	83,840,800	2,096.02	72.94	-4,280.02	-4,207.08	0.00
0.010	20,960,100	2,096.01	72.94	-4,280.02	-4,207.08	0.00
0.020	5,240,050	2,096.02	72.94	-4,280.02	-4,207.08	0.00
0.050	838,416	2,096.04	72.94	-4,280.01	-4,207.07	0.00
0.100	209,614	2,096.14	72.93	-4,280.10	-4,207.17	0.00
0.200	52,394	2,095.76	72.94	-4,280.30	-4,207.36	0.01
0.500	8,384	2,096.00	72.93	-4,279.78	-4,206.84	0.01
1.000	2,097	2,097.00	73.17	-4,282.43	-4,209.27	0.05
2.000	523	2,092.00	73.74	-4,285.93	-4,212.20	0.12
5.000	83	2,075.00	71.58	-4,244.68	-4,173.10	0.81
10.000	21	2,100.00	15.93	-3,622.04	-3,606.11	14.28

The calculation from the triangular method yielded the following results: Area 2096,02 m², volume⁺ 72,94 m³, volume⁻ -4280,02 m³, volume^{total} -4207,08 m³. As mentioned above, this result can be considered as the most accurate due to the use of (almost) all points with minimum simplification.

The grid-based calculations reveal that, surprisingly, there is no change in the accuracy of the results up to the 2.0 raster size (results are presented in Tab. 1, where Difference column shows relative (percentage) changes to the most accurate value (first) in this table). For better comprehension, 10m³ represents approx. 0.2 % of the total volume. The results acquired using the TIN and grid method, therefore, correspond very well to each other.

CloudCompare

Volumes were calculated using the above-described method within several minutes. The results are shown in Table 2. Here, we again observe that some grid coarsening (in this case, up to 0.2m) preserves the same result accuracy; from the grid size of 0.5 m, the error slightly grows, but even for a 1.0 m grid, the error represents only approx. 1.4 % of the total volume.

Tab. 2. CloudCompare – results of grid-based volume calculation

Raster size [m]	Number of cells	Surface [m²]	Volume+ [m³]	Volume- [m³]	Volumetotal [m³]	Difference [%]
0.005	84,038,480	2,100.96	73.000	4,280.09	-4,207.09	0.00
0.010	21,010,210	2,101.02	73.13	4,279.88	-4,206.75	0.01
0.020	5,253,430	2,101.37	73.04	4,279.76	-4,206.72	0.01
0.050	841,085	2,102.71	73.45	4,279.87	-4,206.42	0.02
0.100	210,453	2,104.53	72.92	4,287.80	-4,214.88	0.19
0.200	52,815	2,112.60	73.75	4,282.21	-4,208.46	0.03
0.500	8,479	2,119.75	75.22	4,299.95	-4,224.73	0.42
1.000	2,155	2,155.00	73.72	4,338.25	-4,264.54	1.37
2.000	562	2,248.00	71.21	4,402.10	-4,330.88	2.94
5.000	106	2,650.00	107.59	4,595.00	-4,487.41	6.66
10.000	32	3,200.00	216.33	4,853.66	-4,637.34	10.23

Leica Cyclone

Two calculations with different maximum numbers of points for TIN construction were performed, namely with 500,000 and 2mil. points. The processing time for 500,000 points was approx. 5 minutes, for 2 mils. points approx. 4 hours. The results are shown in Table 3; the difference is negligible.

Tab. 3. Results of volume difference calculation in Leica Cyclone

Raster size [m]	Volume+ [m³]	Volume- [m³]	Volume total [m³]	Difference [%]
2000000	*4,280.60*	*72.90*	*-4,207.70*	*0.00*
500000	*4,283.70*	*72.70*	*-4,211.00*	*-0.08*

3D Reshaper

The software only allows the calculation of the difference between two meshes; no customizable settings are available. The results indicate that 4251.47 m³ was mined away, 76.26 m³ added and the total balance is therefore -4175.21 m³. The TIN generation took several minutes and the volume calculation tens of seconds.

Trimble RealWorks

The calculation was performed three times, using various settings. The first calculation used two triangular meshes (Table 4), the second two point clouds with factory settings (without filling holes; Table 5) and the last one for two point clouds with holes filled prior to the computation (Table 6). The computing time was several seconds for grids of 0.02m and more, several minutes for a grid of 0.01 and approx. 15 minutes for a grid of 0.005m. The calculation for generating TIN took several minutes..

Tab. 4. Results of Trimble RealWorks – a direct calculation from two TINs

Raster size [m]	Number of cells	Surface [m²]	Volume+ [m³]	Volume- [m³]	Volumetotal [m³]	Difference [%]
0.005	*83,501,400*	*2,087.54*	*-4,268.96*	*72.16*	*-4,196.80*	*0.00*
0.010	*20,875,360*	*2,087.54*	*-4,268.97*	*72.16*	*-4,196.80*	*0.00*
0.020	*5,218,825*	*2,087.53*	*-4,268.95*	*72.16*	*-4,196.79*	*0.00*
0.050	*835,020*	*2,087.55*	*-4,268.95*	*72.16*	*-4,196.79*	*0.00*
0.100	*208,760*	*2,087.60*	*-4,268.93*	*72.17*	*-4,196.76*	*0.00*
0.200	*52,188*	*2,087.52*	*-4,268.95*	*72.16*	*-4,196.78*	*0.00*
0.500	*8,343*	*2,085.75*	*-4,267.62*	*72.13*	*-4,195.49*	*-0.03*
1.000	*2,084*	*2,084.00*	*-4,267.22*	*72.34*	*-4,194.88*	*-0.05*
2.000	*516*	*2,064.00*	*-4,269.20*	*72.74*	*-4,196.46*	*-0.01*
5.000	*79*	*1,975.00*	*-4,234.29*	*67.00*	*-4,167.30*	*-0.70*
10.000	*19*	*1,900.00*	*-4,484.82*	*32.85*	*-4,451.97*	*6.08*

Results of the hybrid TIN + grid calculation (Table 4) indicate that no or only minimal changes in results were observed up to the grid size of 2.0 m, after which, the accuracy begins to decrease more significantly.

Tab. 5. Results of Trimble RealWorks – calculation from point clouds without filling the holes

Raster size [m]	Number of cells	Surface [m²]	Volume⁺ [m³]	Volume⁻ [m³]	Volume^{total} [m³]	Difference [%]
0.005	41,274,280	1,031.86	-2,079.19	54.48	-2,024.71	0.00
0.010	10,603,110	1,060.31	-2,118.02	55.90	-2,062.12	1.85
0.020	2,688,772	1,075.51	-2,143.47	56.55	-2,086.92	3.07
0.050	435,674	1,089.19	-2,178.92	56.78	-2,122.14	4.81
0.100	110,191	1,101.91	-2,223.91	56.95	-2,166.96	7.03
0.200	28,056.	1,122.24	-2,291.96	57.31	-2,234.65	10.37
0.500	4,772	1,193.00	-2,574.94	57.88	-2,517.06	24.32
1.000	1,344	1,344.00	-3,044.61	60.97	-2,983.64	47.36
2.000	412	1,648.00	-3,730.83	71.37	-3,659.46	80.74
5.000	71	1,773.76	-4,443.70	98.76	-4,344.94	114.60
10.000	30	3,000.00	-4,850.43	224.64	-4,625.79	128.47

Results without interpolating (filling) the holes in data are obviously incorrect (Table 5) when compared to other software solutions and methods. This algorithm is therefore not suitable for this type of data.

Tab. 6. Results of Trimble RealWorks – calculation from point clouds with hole interpolation

Raster size [m]	Number of cells	Surface [m²]	Volume+ [m³]	Volume- [m³]	Volume [m³]	Difference [%]
0.005	74,874,080	1,871.85	-4,407.98	97.63	-4,310.35	0.00
0.010	18,394,970	1,839.50	-4,395.39	76.34	-4,319.05	0.20
0.020	4,657,250	1,862.90	-4,400.21	122.02	-4,278.19	-0.75
0.050	751,024	1,877.56	-4,353.44	121.42	-4,232.02	-1.82
0.100	187,901	1,879.01	-4,369.72	120.34	-4,249.38	-1.41
0.200	47,565	1,902.60	-4,386.66	122.22	-4,264.44	-1.07
0.500	7,753	1,938.25	-4,445.60	116.59	-4,329.01	0.43
1.000	2,073	2,073.00	-4,489.93	137.15	-4,352.78	0.98
2.000	531	2,124.00	-4,429.91	106.12	-4,323.79	0.31
5.000	91	2,275.00	-4,725.00	98.76	-4,626.24	7.33
10.000	30	3,000,00	-4,850,43	224,64	-4,625,79	7,32

When the point clouds were manually edited and holes filled, however (Table 6), the results are better; it is nevertheless still obvious that both the areas and volumes change more significantly with grid size than the other methods.

Discussion

For software comparison, the best achievable results were selected, i.e., grid (step) 0.005m where grid solutions were concerned and the highest allowed number of points where TIN meshes were concerned (to allow a comparison of Leica Cyclone with others, the results for both 500,000 and 2 mils. points are shown as the calculation time differ significantly). Resulting in total volumes, differences when compared to Atlas DMT-TIN method and total computing times are shown in Table 7. The Atlas DMT TIN method was, as mentioned above, considered as a reference method due to using minimum simplification and all points, practically without diluting the point cloud in any way. This, however, goes hand in hand with the computing demands of several hours, which is true even for the grid method but even more so for the TIN method.

It is, however, also obvious that results of the best grid algorithms provide comparable accuracy of the results to those of the best TIN algorithms much faster than the TIN methods. This is in all likelihood caused by the high density of the point cloud used for calculations. We can not, however, extend this conclusion to sparse point clouds (e.g. data cully collected using GNSS or total station survey).

Very good results, actually the best when considering the time demand/accuracy ratio were achieved by CloudCompare, which only allows a grid computation. Moreover, CloudCompare is the only tested software available free of charge; hence the price/performance ratio is absolutely unmatched among the tested software solutions.

Tab. 7. Overview of resulting (most accurate) volumes for individual programs

software	method	Volume ^{total} [m³]	Difference [%]	Total time
Atlas DMT	TIN	-4,207.08	0.00	4.5 hour
	grid	-4,207.08	0.00	1.5 hour
CloudCompare	grid	-4,207.09	0.00	10 minutes
Leica Cyclone	TIN (2 mils. points)	-4,207.70	0.01	4 hours
	TIN (500,000 points)	-4,211.00	0.09	5 minutes
3D Reshaper	TIN	-4,175.21	-0.76	10 minutes
Trimble RealWorks	TIN/grid	-4,196.80	-0.24	15 minutes
	grid	-4,310.35	2.45	15 minutes

Fig. 3 compares the results of programs with respect to the various raster sizes. The graph shows that up to the step of approx. 1m, the volume calculation yields a minimum deviation for most software solutions (in our case, approximately 2,000 squares forming the grid). When increasing the step (lowering the grid resolution) further, both the area (Table 1,2,5,6) and volume change significantly. This may possibly be caused by the grid cells on the edges of the point cloud where a substantial portion of the area may be outside the data (Fig. 4 right) and therefore confound the calculation. For example, in Table 2, we can observe the growth of the area with the grid raster. In general, almost all grid algorithms yielded near identical results; the only exception is the Trimble RealWorks software providing different results in all grid sizes (Fig. 3).
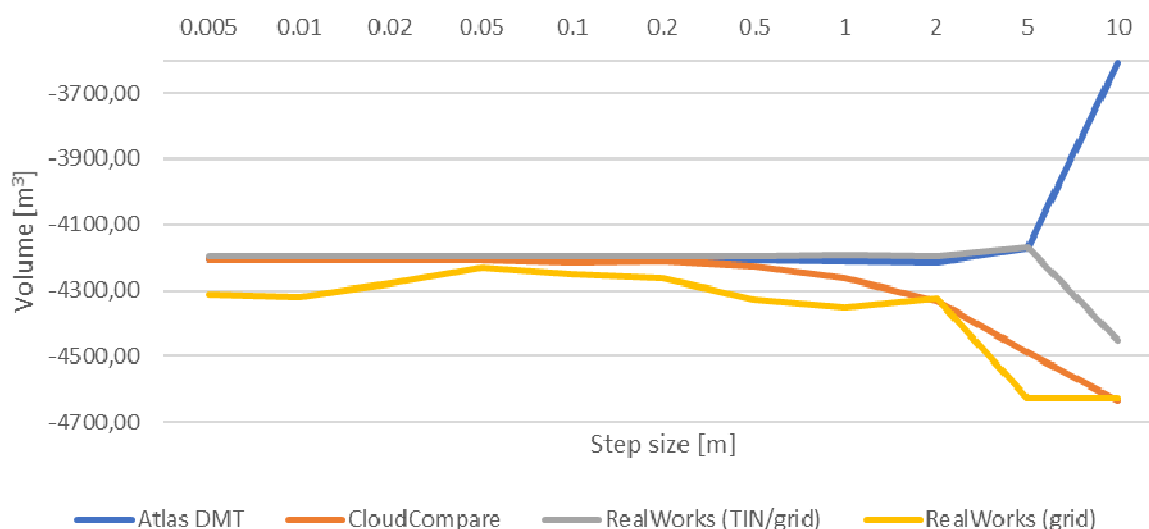

Fig. 3. Comparison of the grid methods

From the perspective of the calculation methods, grid algorithms are very simple and fast when compared with the TIN algorithms, where the TIN mesh must be generated first, and only then the volume can be calculated. This usually requires a dilution of the input point cloud to prevent excessive demands on the computer processing capacity and memory. This can be demonstrated on the Atlas DMT, which does not perform such dilution and the resulting processing time is then extremely high (see Table 7). Curiously enough, however, the processing time using Leica Cyclone, which dilutes the point cloud significantly even with the highest settings (2 mils. points), was almost as high as that of Atlas DMT (using full 6.2 mil. and 3.2 mil. points for individual networks), which suggests that the algorithm in Atlas DMT is less demanding on the processing power than Leica Cyclone. Further dilution of the point cloud in Leica Cyclone (to 500,000) however significantly reduced the processing time.

The processing time and results of TIN-based methods are directly dependent on the constructed TIN mesh, which does not have to be identical for individual programs as each software uses a different method for diluting the point cloud. In some programs, rules for generating the TIN triangles can be set up while others use a fixed algorithm without giving the user a possibility to interfere. For example, the Atlas DMT allows relatively detailed settings of parameters for creating TIN and of manual correction of the automatically generated mesh, Leica Cyclone allows one parameter (the number of points) while 3D Reshaper allows almost no customization.

The volume calculation can also be affected by the convex envelope (Fig. 4) interpolating surrounding data, despite the fact that the real surface can be different.
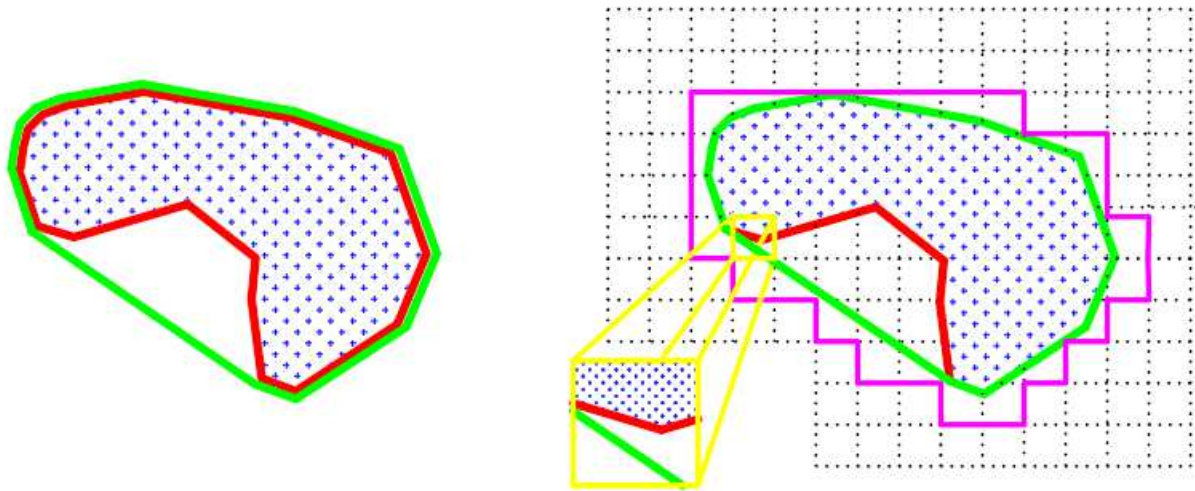

Fig. 4. Convex area (left) and rasterization (right) in CloudCompare (blue points = point cloud; red line – real data borders; green line (left) – delimiting the area for computation using convex envelope, (right) rasterization of the convex envelope with grid cells containing only partial data on the edge of the point cloud; when using a finer grid, the peripheral cells would stick more closely to the edges

Conclusion

This study reports volume calculation and comparison between two states in several software solutions using various algorithms and settings. The data used for the experiment originate from a real TLS scanning in a quarry, complemented by GNSS survey.

Both grid-based and TIN-based algorithms were used. The obtained results were compared to find out how a method of calculation (algorithm, settings, software) affects the resulting volume. Principally, the most accurate results should be those from Atlas DMT, which uses no simplification and utilizes all points (except for duplicate points) for the calculation. However, most raster methods yielded practically identical results up to the grid size of 1 m. Most of the other TIN-based algorithms also yield very similar results.

In conclusion, we can state that the practical effect of the selected software or algorithm is minimal as long as a reasonable raster size or number of TIN points are used. The only exception is represented by Trimble RealWorks, the results of which are mildly different from those provided by all other programs. For raster methods, we can say that dividing the area of our size into 2,000 cells is generally sufficient if dense data is used (as in our case).

Where we can see a significant difference, however, is the necessary processing time. Raster methods are generally significantly faster than TIN methods. If diluting the point cloud sufficiently, the time can be nevertheless similar for both types of algorithms, with only a mild decrease in results accuracy (see Leica Cyclone).

The tested software solutions are designed for various applications. If however only considering volume calculations, the freeware CloudCompare is absolutely sufficient and provides results identical to those computed by the best commercial solutions. The only caveat when using this software lies in the method of calculating the convex envelope, which can potentially distort the results.

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