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Reduction of measurement data before Digital Terrain Model generation vs. DTM generalisation

Wioleta Błaszczak-Bak *¹, Marian Poniewiera ², Anna Sobieraj-Żłobińska ³ and Michał Kowalik⁴

Modern data-acquisition technologies provide large datasets. Such datasets are often cumbersome for rational processing, and their processing is time consuming. Therefore, there are several methods that can enable the reduction of the dataset size. One of them is generalisation of the Digital Terrain Model (DTM) or the reduction method within the initial processing of measurement data. Another method can be the Optimum Dataset (OptD) method. This paper presents two approaches towards decreasing the Light Detection and Ranging dataset. The first approach is based on the process of DTM generalisation, the second one is based on the application of the OptD method. The reduced datasets were used for isoline map creation depicting the overflow land in open-pit mining. It was proved that the reduction needs to be planned deliberately and that the degree of reduction should be performed in a way that allows to maintain the characteristics of the terrain.

Keywords: Dataset, OptD method, LiDAR, data processing, reduction

Introduction

Rapidly developing measurement technologies such as LiDAR (Light Detection And Ranging), MBES (Multi Beam Echo Sounder) allow to collect amounts of data. Those numerous datasets can be used to generate, for example, Digital Terrain Model (DTM) or Digital Elevation Model. However, such data processing due to its amount, and especially possible changes in real-time, makes it practically impossible or very difficult to be achieved (e.g. Liu and Yang 2012).

The processing of LiDAR data for generating DTM includes: pre-processing of data (including gross error elimination), data filtration (separation of datasets depicting the terrain and details point), the main processing (methods of DTM generation) and visualisation (depending on the aim of the study).

Studies on improving the processing of LIDAR datasets are being constantly developed, so they can be used for the construction of the SIS (Spatial Information System). What is more, studies themselves or their results can be a source for many other studies. One of the projects which aims at introducing advanced use of spatial data is the

CAPAP (Centrum Analiz Przestrzennych Administracji Publicznej – Centre for Spatial Analysis of Public Administration). Within this project, the tasks and the tools related to spatial data processing are planned. One of them is the creation of an analytical platform that enables advanced spatial analysis, including 3D data analysis, as well as interpretation and visualisation of the obtained results in a textual and graphical form. Also under the ISOK project (Informatyczny System Osłony Kraju przed nadzwyczajnymi zagrożeniami – Computing System of National Guards against extraordinary threats) surveying resources are gathered in the structure of the DTM with grid size of 1 m for almost the entire Poland. The density of points in the ISOK project is the key fact for DTM accuracy. The average density is 4 points m⁻² in first standard and 12 points m⁻² in second standard for large cities.

Also, in the case of LiDAR measurements used in open-pit mining surveying, a problem with the size of the datasets is likely to occur. The acquired measurement data is a basis for DTMs creation (e.g. Poniewiera and Jelonek 2015, Suchocki *et al.* 2017). Subsequently, generated DTMs are used to analyse the phenomena of overflow land in the mines, to create basins and to indicate the flow direction. In this and many other cases, it is necessary to reduce the size of the datasets.

Theoretical background for the process of dataset decrease

The quantitative reduction of elevation data is reported in the literature as a problem that occurs during DTM

¹Institute of Geodesy, Faculty of Geodesy, Geospatial and Civil Engineering, University of Warmia and Mazury in Olsztyn, Oczapowski St. 1, 10–719 Olsztyn, Poland

²Institute of Mining, Faculty of Mining and Geology, Silesian University of Technology, Akademicka St. 2, Gliwice, Poland

³Department of Geodesy, Gdansk University of Technology, Narutowicza St. 11/12, Gdansk, Poland

⁴Programmer, Herzogstandstr. 142, 85435 Erding, Germany

*Corresponding author, email wioleta.blaszczak@uwm.edu.pl

generalisation (e.g. Bakula 2011, 2014). There are different methods of generalisations, for example: global filtration, mainly used for models with a regular grid; the local filtration involving the selection of key points for the terrain model; heuristic approach associated with the generalisation of the structural lines in DTM (e.g. Weiber 1992, Chen 2012). There are also other divisions of generalisation methods. Zhou and Chen (2011) mention the following methods: generalisation of three-dimensional lines, filtration, additive method, subtractive and objective method. Other methods of generalisation are those associated with image processing techniques, they consider DTM in a grid structure as a raster. One of the examples of such method can be a transformation that is the change in the resolution of the resulting model (e.g. Haile and Rientjes 2005).

Existing software used for LiDAR data processing also includes built-in algorithms for quantitative data reduction, for example:

- (1) methods based on the extraction of breaklines (crest line), commonly used in hydraulic modelling, for creating cross-sections (Briese et al. 2009)
- (2) methods based on the use of hybrid DTM (regular and irregular distribution of points), in the case of hybrid models, it is not possible to use simple, fully automated procedures, the use of classical manual techniques is required (Wolfram 2002)
- (3) methods based on the choice of the so-called ‘relevant points’, including:

(a) the VIP algorithm (Very Important Points), it is a method of acquiring points important for the model in the TIN structure and is often used to reinforce the edges of the processed image to detect objects (Chen and Guevara 1987)

(b) TPI (Topographic Position Index) is based on neighbourhood analysis during DTM analysis to improve the automatic classification of landscape forms associated with slope (Weiss 2001)

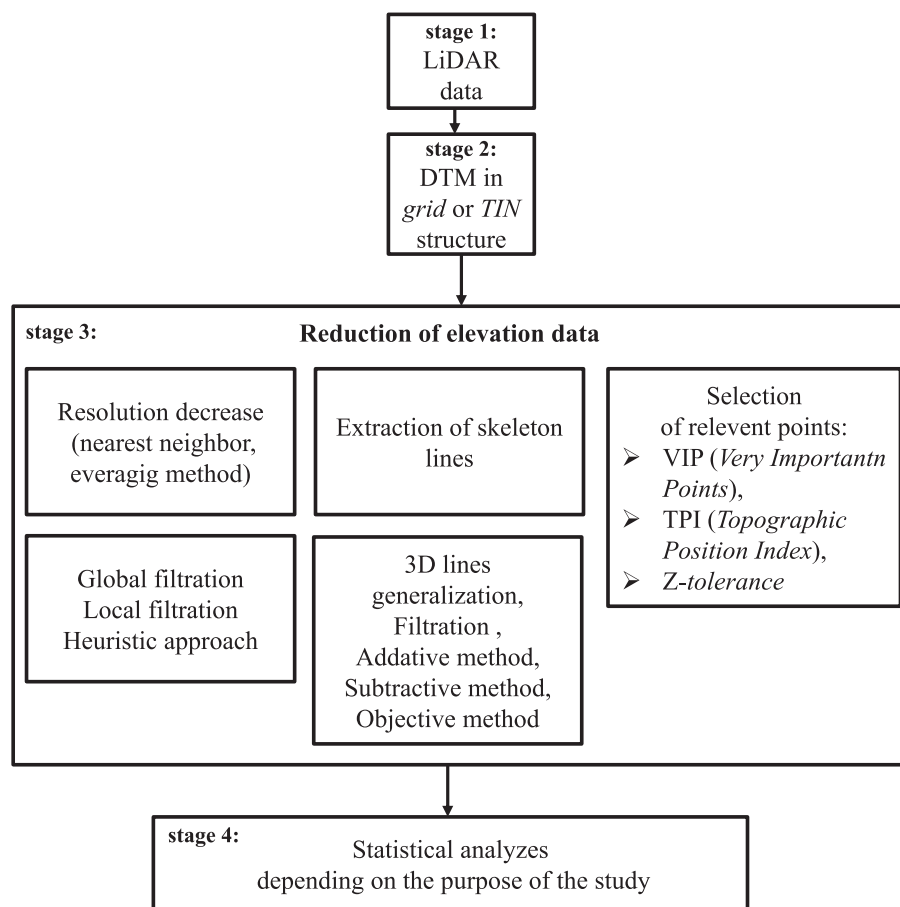
(c) Z-tolerance, it creates pyramids for the TIN model, reducing data along with decreasing the scale (de Floriani 1989).

These algorithms have been implemented, inter alia, in known software such as: Terrascan, ArcGIS, DTM Master.

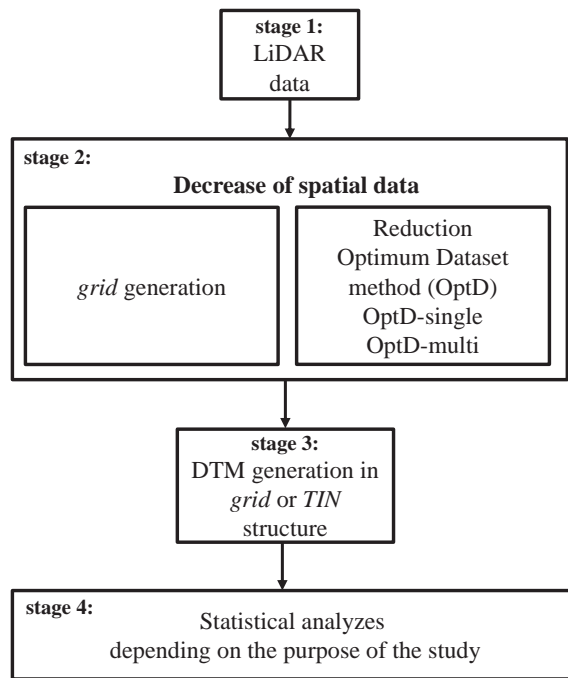
Summarising, the existing methods are used in the already completed DTM. Schematically it is presented in Fig. 1.

The presented solutions for the reduction of elevation data are based on a finished DTM. It means, that all measurement points were used for DTM construction. Another approach is presented in Błaszczak-Bąk (2016), Błaszczak-Bąk (2016) and Błaszczak-Bąk et al. (2017). Schematically it is presented in Fig. 2.

In the proposed approach, the reduction of the dataset takes place before the DTM generation stage. The decrease can be achieved with the use of two methods, generation and reduction, which were presented and compared in Błaszczak-Bąk (2016). The process of generation



1 Reduction of elevation data for DTM (DTM generalisation)



2 Decrease of spatial dataset for DTM generation

is associated with decreasing the size of the dataset by creating a grid. In this method, new points are obtained instead of points with the original coordinates, e.g. Bauer-Marschallinger *et al.* (2014). Reduction decreases the dataset by removing some points according to the given algorithm. The remaining points are original points from the measurement (Błaszczak 2006, Błaszczak-Bąk, *et al.* 2011, 2012).

In the case, where the point cloud is the source data for the study, it is better to perform the reduction, because the user can work on real measurement data.

The choice of proposed data reduction approaches is determined by the purpose of the study. The problem of data reduction is diverse issue. It can be associated with:

Reduction – decrease of the number of points in the measurement dataset before the DTM generation, by removing some points. The simplest method of reduction is to remove the i -th point. It is important, however, to remove irrelevant points. After the reduction, the actual measuring points will remain in dataset (Błaszczak-Bąk *et al.* 2012).

Generalisation of the DTM – simplification of the model, which allows to preserve and incorporate all the topographical rules forming the model without compromising its continuity and maintaining the main morphological characteristics of the model (Bakula 2011, Koziol *et al.* 2012).

Generalisation of linear objects – simplification or selection of points, for example by eliminating certain vertices of a line, so that its shape becomes simpler (Nyerges 1991).

Generation – the process of creating new coordinate points based on interpolation methods (Bauer-Marschallinger *et al.* 2014).

In the proposed solutions presented in Fig. 1, the reduction of elevation data for the finished DTM is carried out in order to simplify the model. It means that the proposed reduction methods are included in the tasks of generalising the DTM.

Fig. 2 presents the stages of the spatial data reduction. The proposed Optimum Dataset (OptD) method (Błaszczak-Bąk 2016, Błaszczak-Bąk *et al.* 2017) removes from the measurement dataset those points which do not affect the terrain characteristics and can be omitted, for example, in the process of DTM generation. The OptD method uses linear object generalisation methods, but the calculations are done in a vertical plane, which allows to accurately check each elevation. The method of generalisation used so far in the OptD is Visvalingam-Whyatt method proposed by Visvalingam and Whyatt (1992) and Douglas-Peucker method proposed by Douglas and Peucker (1973). Digital Elevation Data are available in digital format, including ASCII TBD, LAS. DTM data are in the formats: ESRI TIN, Intergraph TTN, Intergraph GRD, DGN/DXF, ASCII XYZ GRID, ARC/INFO ASCII GRID. After applying the OptD method, a text file is obtained.

The OptD method can be performed in two variants:

- OptD method with single criterion optimisation called the OptD-single
- OptD method with multi criteria optimisation called the OptD-multi.

In the OptD-single method, a dataset that meets one strictly defined condition is searched. If the user opts to perform the processing by means of OptD-multi, he will obtain several datasets, from which the best one can be chosen.

The paper presents the reduction of spatial data by means of the OptD method. The reduction was performed on data from the Airborne Laser Scanning (ALS) measurement, and the reduced dataset contains actual measurement points. Such dataset was used to generate the DTM, and then to create the isoline maps depicting the overflow land in the open-pit mining. For comparison, DTM generalisation was also performed. All obtained optimised datasets were used.

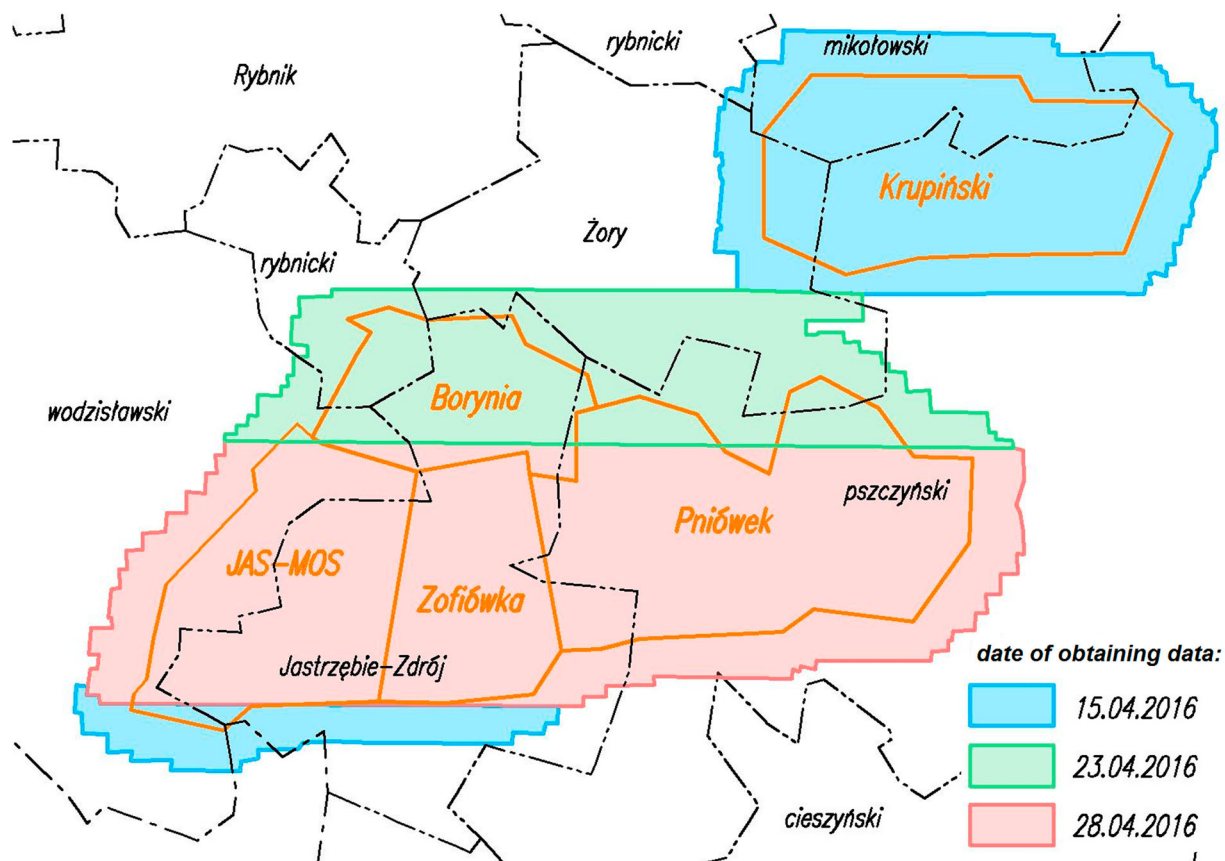
Research plans

The paper presents two approaches for data processing which resulted in DTM generation based on a reduced dataset.

Approach 1: DTM generalisation

- (1) Original ALS point cloud;
- (2) DTM generation in the TIN structure in AutoCAD Civil 3D 2018. This software was chosen, because it is the most often one used by surveyors for developing the surveying results conducted for mines;
- (3) generation of TIN structure by Maximum Change in Elevation method with the AeccSimplifySurface function in the AutoCAD Civil 3D 2018;
- (4) export of the triangular vertices file (TIN nodes);
- (5) DTM generation, DTM in *grid* structure;
- (6) DTMs accuracy analysis;
- (7) creation of isolines in the Geolisp software in order to show the characteristic features of the area (e.g. ditches).

It should be noted that point 2, DTM creation in the TIN structure from the original point cloud, is very time-consuming. To obtain the DTM based on a reduced dataset, DTM must be first generated on the basis of the whole point cloud. This approach requires a lot of work.



3 Coverage of laser scanning measurement

Step 5, re-generation of DTM, can be omitted, however, models in grid structure are more commonly used and easier to compare with other models.

Approach 2: reduction based on the OptD method

- (1) Original ALS point cloud;
- (2) application of the OptD method for reducing the amount of points in the ALS dataset;
- (3) export of the coordinate point file that remained in the dataset after reduction;
- (4) DTM generation in *grid* structure;
- (5) analysis of DTMs accuracy;
- (6) creation of isolines in the Geolisp software.

This approach enables obtaining a reduced dataset of points with real coordinates. Determination of the optimisation criteria in the OptD method allows to quickly obtain an optimised dataset that meets user's input goals. Additionally, processing a text file with coordinates is easier than processing DTMs in the TIN structure.

The experiment

The research object was the 'Pniówek' Coal Mine. ALS took place on: 15 April 2016, 23 April 2016 and 26 April 2016. The scope of research is presented in Fig. 3.

The measurements were made using the Z/I Inflight airborne navigation system, the CCNS navigation system, the LiteMapper LMS6800 scanning system, the Hasselblad 39/50 digital flight camera and the AreoCONTROL

GPS/IMU system. The flight height was 650 m and the scan density was $4.8 \text{ points m}^{-2}$. The following reference systems were adopted: horizontal – PUWG 2000s6, the vertical – Kronstadt 86.

The dataset consisted of 54 files and contained over 226 mln points. One measurement file containing 2 555 472 points was used for practical research. This dataset is called **DS**.

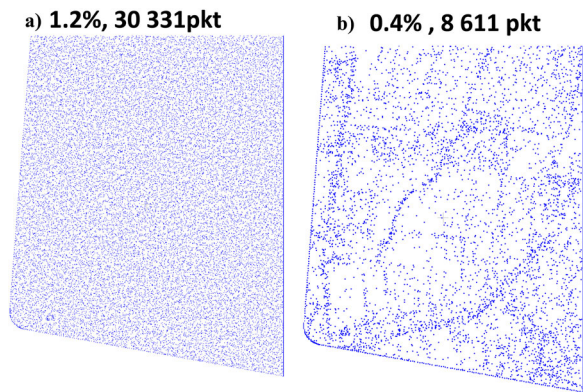
DTM generalisation

On the basis of the whole DS, the DTM in TIN structure was generated. It should be noted that DTM generation based on such large files is very time-consuming and requires high computing power. Subsequently, the model was generalised in AutoCAD Civil 3D 2018 using the Maximum Change in Elevation method. This method specifies the maximum acceptable difference between the elevation of the original surface and the elevation of the simplified surface. In this generalisation method, two options were adopted: 0.5 and 1.0 m.

As a result of generalisation, two DTMs were obtained in the TIN structure: TINg1 and TINg2.

Based on TINg1 and TINg2, two result sets were obtained/exported and named, **DSg1** and **DSg2**, respectively. DSg1 has 1.2% of all DS points, while DSg2 has 0.4% of points. These datasets are presented in Fig. 4.

The time needed to execute the DTM in the TIN structure, followed by the generalisation of the model which is based on the dataset including more than 2.5 million data, was about 20 min.



4 Sets after DTM generalisation: a DSg1, b DSg2 (source: own study in CloudCompare v.2.6.0)

Table 1 The characteristics of DS

Parameter	Value
Number of points	2 555 472
Z _{max} [m]	282.282
Z _{min} [m]	267.270
Mean height [m]	277.337
SD [m]	2.754
Mean point distance [m]	0.499

Note: Where Z_{max} is the maximum height in ALS dataset, Z_{min} is the minimum height in ALS dataset and SD is the standard deviation.

Data reduction based on the OptD method

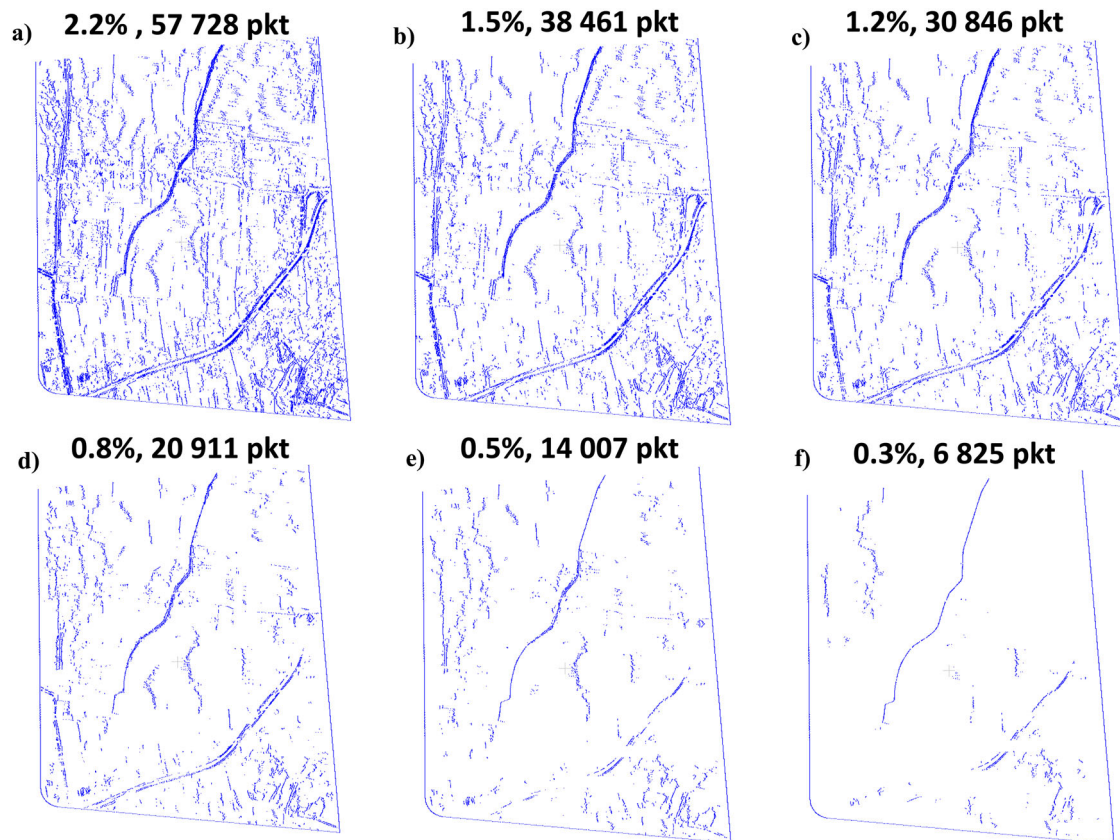
The DS was processed by means of the OptD-single method. It was based on statistical analysis of the DS. Table 1 summarises its characteristics.

For the reduction, the OptD method was used with one optimisation criterion (OptD-single). As the optimisation criterion, the per cent of points in the dataset after the reduction was assumed. To meet this criterion, in the OptD-single method six different variants were adopted:

- (a) action reduce – width 0.050 – tolerance 0.250, obtained dataset: **DSr1**
- (b) action reduce – width 0.050 – tolerance 0.400, obtained dataset: **DSr2**
- (c) action reduce – width 0.050 – tolerance 0.500, obtained dataset: **DSr3**
- (d) action reduce – width 0.025 – tolerance 0.700, obtained dataset: **DSr4**
- (e) action reduce – width 0.020 – tolerance 1.000, obtained dataset: **DSr5**
- (f) action reduce – width 0.020 – tolerance 1.200, obtained dataset: **DSr6**.

The values for width and tolerance are presented in metres. The selected search strip widths were less than the mean distance between points in the dataset, while the Douglas–Peucker tolerance (Douglas and Peucker 1973) was first taken as half of the average distance between points in the dataset, then increased up to 1.200 m. In Fig. 5 reduced datasets are presented.

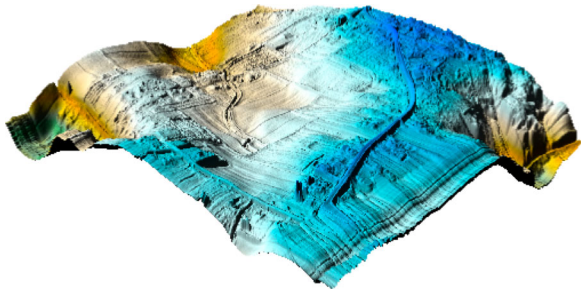
The time needed to perform the reduction by means of the OptD method for the analysed dataset was from 5 up to 20 s (depending on the degree of reduction).



5 Datasets after the OptD-single application: a DSr1, b DSr2, c DSr3, d DSr4, e DSr5, f DSr6 (source: own study in CloudCompare v.2.6.0)

Table 2 The characteristics of obtained datasets after DTM generalisation and reduction by the OptD application

Parameter	DSg1	DSg2	DSr1	DSr2	DSr3	DSr4	DSr5	DSr6
Z_{\min} [m]	267.270	267.270	267.270	267.270	267.270	267.270	267.270	267.270
Z_{\max} [m]	282.220	282.220	282.282	282.282	282.282	282.282	282.282	282.282
Mean height [m]	277.281	277.166	277.370	277.249	277.149	277.068	276.771	276.525
Mean point distance [m]	4.652	9.687	3.402	4.221	4.776	5.737	6.817	10.018
Number of terrain points	30 331	8 611	57 728	38 461	30 846	20 911	14 007	6 823
SD [m]	3.270	3.109	3.080	3.162	3.208	3.220	3.251	3.620
ABS (SD DS – SD DSg or SD DS – SD DSr) [m]	0.516	0.355	0.326	0.408	0.454	0.466	0.497	0.866



6 DTM based on DS (source: own study in Surfer Demo v.9)

Statistical analyses of obtained datasets

The obtained datasets after DTM generalisation and after OptD reduction are characterised in Table 2.

SDs presented in Table 2 are calculated on the basis of the same mean height computed for the original set (277.337 m). The mean height in the dataset after reduction decreased, or increased with higher reduction degree. For the DSr1 it decreased by 0.033 m, while for the dataset with the lowest number of points SD was smaller by 8.812 m.

The standard deviation is the smallest for the DSr1 obtained after using the OptD method and it is 3.080 m. In comparison to the DSg1 (where the similar number of points in reduced dataset) standard deviation is 0.516. However, it should be noted, that in the datasets after the DTM generalisation the highest value of height has not been preserved.

DTM generation

On the basis of the original DS, DTM was generated (Fig. 6). A 1 m grid was adopted, and the Kriging method was used for interpolation.

Then following models were generated:

- (a) DTMs based on datasets obtained after the DTM generalisation (Fig. 7), and
- (b) DTMs based on datasets after the OptD-single method application (Fig. 8).

Generated DTMs are different depending on the size of the measurement dataset. Similar DTMs are those containing more than 30 000 points. These datasets, which contain less than 1.2% of the measurement points, gave worse DTMs. The detailed analysis is presented in the following section.

DTM accuracy

In order to compare the height accuracy of the generated DTM, the following indicators were used:

- (a) average height difference:

$$\Delta h_{\text{mean}} = \frac{\sum_{i=1}^k (\tau)}{k} \quad (1)$$

where $\tau = Z_{DTM \text{ from original data}} - Z_{DTM \text{ after OptD or DTM generalization}}$

- (b) extreme height values Z_{\max} and Z_{\min}
- (c) root-mean-square error (RMS)

$$RMS = \sqrt{\frac{\sum_{i=1}^n (\tau)^2}{n - 1}} \quad (2)$$

- (d) correlation coefficient, which is a measure of similarity between the two measured DTM node heights (reference – R and processed – P)

$$\text{cov}(x, y) = \frac{\sum_{i=1}^n (Z_{Ri} - Z_{\text{mean}Ri})(Z_{Pi} - Z_{\text{mean}Pi})}{\sqrt{\sum_{i=1}^n (Z_{Ri} - Z_{\text{mean}Ri})^2} \sqrt{\sum_{i=1}^n (Z_{Pi} - Z_{\text{mean}Pi})^2}} \quad (3)$$

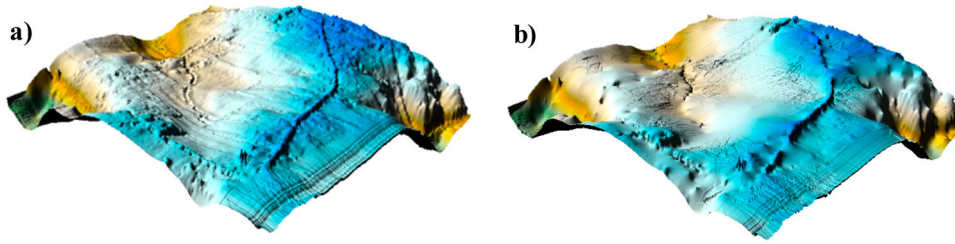
where Z_{Ri} is the point's height in the DTM model generated from the original dataset (reference), $Z_{\text{mean}Ri}$ is the mean point height in the DTM model generated from the original dataset (reference) and Z_{Pi} is the point's height in the DTM model generated from the dataset after applying the OptD method, $Z_{\text{mean}Pi}$ is the mean point height in the DTM model generated from the dataset after using the OptD or DTM generalisation method.

- (e) the coefficient of determination, which is the measure of the fit of the model (the closer to the value 1, the better the model is fitted to another model:

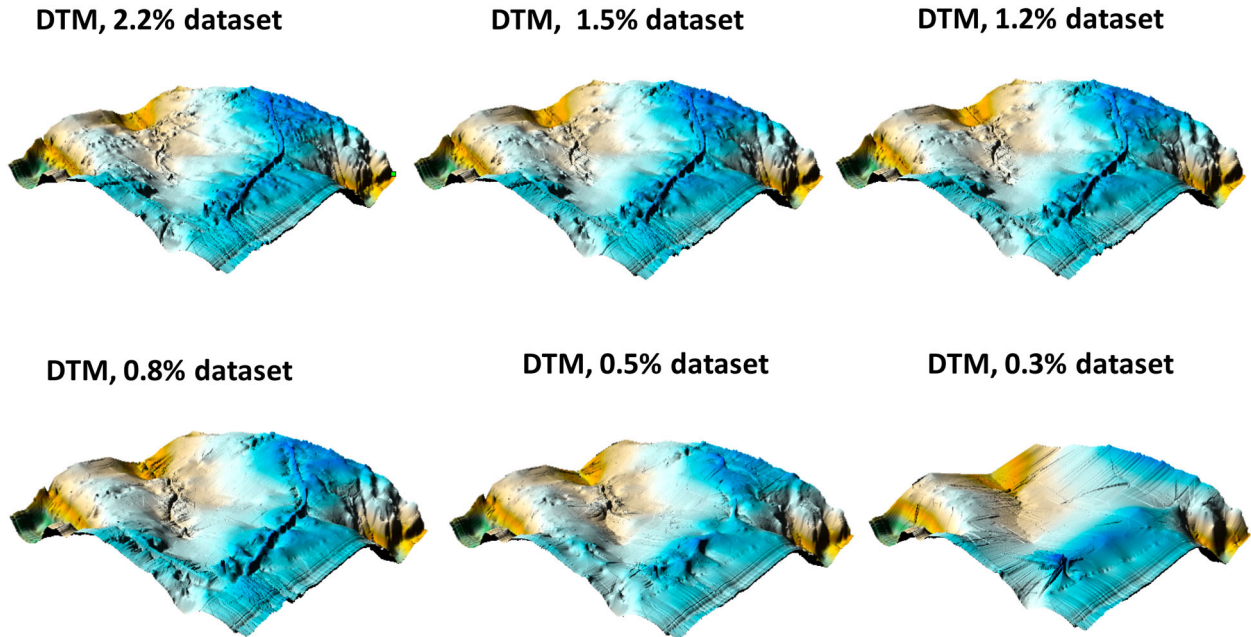
$$D^2 = \frac{\sum_{i=1}^k (Z_{DTM \text{ originalny}} - Z_{\text{mean originalny}})^2}{\sum_{i=1}^k (Z_{DTM \text{ after OptD or DTM generalization}} - Z_{\text{mean after OptD or DTM generalization}})^2} \quad (4)$$

The authors did not have any results of measurements from other sources, so the DTM generated on the basis of the original dataset was adopted as a reference model. Subsequent values of the RMS parameter were calculated for height difference between the DTM generated from the dataset obtained after using the OptD or DTM after generalisation and the height of the points from the reference model.

The calculated parameters are summarised in Table 3.



7 DTM based on: a DSg1, b DSg2 (source: own study in Surfer Demo v.9)



8 DTM based on: a DSr1, b DSr2, c DSr3, d DSr4, e DSr5, f DSr6 (source: own study in Surfer Demo v.9)

Table 3 Calculated parameters for DTMs

		Parameters					
Name of dataset		Δh_{mean} [m]	Z_{max} [m]	Z_{min} [m]	RMS [m]	cov(x, y)	D^2
DTM based on:	DS	–	282.273	267.268	–	–	–
	DSg1	0.010	282.218	267.280	0.307	1.001	0.974
	DSg2	–0.005	282.189	267.272	0.115	0.999	0.982
	DSr1	–0.009	282.273	267.272	0.106	0.999	0.996
	DSr2	–0.029	282.286	267.271	0.152	1.001	0.999
	DSr3	–0.037	282.410	267.271	0.180	1.003	0.998
	DSr4	–0.049	282.425	267.271	0.248	1.010	0.996
	DSr5	–0.051	282.702	267.271	0.294	1.012	0.995
DSr6	–0.062	282.721	367.271	0.310	1.014	0.993	

The analysis of the results presented in Table 3 shows that Δh_{mean} is the smallest for DSg2, and the largest for DSr6. The values of Z_{min} and Z_{max} in the generated datasets also changed. It should be noted, that after using the OptD method the values of these parameters were the same as in the original set. Therefore, observed changes resulted from the interpolation method.

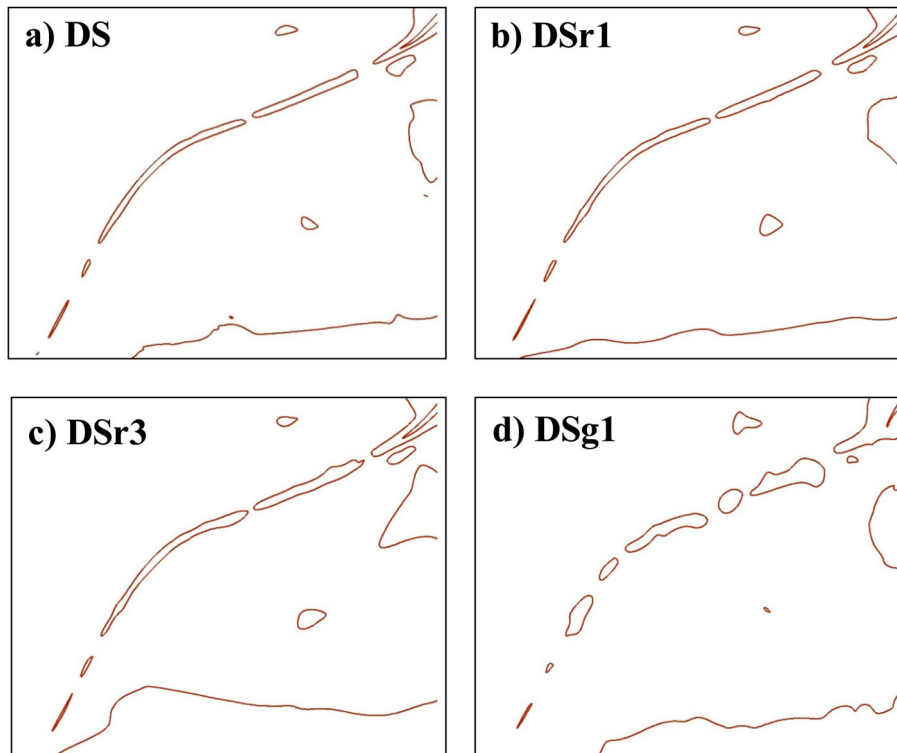
The lowest RMS is calculated for the DTM generated from the DSr1 (dataset with the largest number of points), and the largest standard deviation

is for the DSr6 (dataset with the lowest number of points).

The coefficient of determination is best for the DTM generated from the datasets DSr2 and DSr3.

Isoline creation

Based on the generated DTMs, isoline maps with an interval of 1 m have also been created, which show overflow land. Only four datasets were presented:



9 The isolines of overflow land created on the basis of: a DS, b DSr1, c DSr3, d DSg1 (source: own study in Geolisp software)

- (a) original DS, containing 2 555 472
- (b) DSr1, containing 57 728 (dataset after application of the OptD method)
- (c) DSr3, containing 30 846 (dataset after applying the OptD method)
- (d) DSg1, containing 30 331 (dataset after the DTM generalisation).

These datasets accurately show differences in the appearance of overflow lands due to applied methodologies. The overflow land is depicted in Fig. 8.

It can be seen that the OptD method gives the best results, it preserves the complex terrain relief (e.g. hollow about 1 m deep and 4 m wide). In Fig. 9c and d overflow land is presented, it is formed from a very similar number of points in the dataset. Definitely, the DSr3 better reflects the correct shape of the overflow land. Fig. 9 shows that the use of a model created on the basis of a reduced dataset for mapping overflow land within the open-pit mining, including generation of contours, is justified.

Evidently, the dataset can not be reduced without the process of earlier specification and proper selection the optimisation criterion, only then DTM and the isoline map can be executed correctly.

Conclusion

Processing of measurement datasets from LiDAR is very time and labour consuming process, especially when all points from the dataset are used. However, such large amount of data is not needed for the correct execution of many projects. Therefore, two approaches were presented and compared. The first one is based on the DTM generalisation, the second one relies on the reduction of points in the dataset. They concern the development of the ALS point cloud for the purposes of DTM generation and mapping overflow land within the open-

pit mining areas. After data collecting, the analysis and the comparison of two approaches the following conclusions can be drawn:

- (1) the approach based on the OptD method is less time and labour consuming than the approach based on DTM generalisation. It results from the fact, that before the DTM is generalised, it must be first built from the original point cloud. If the OptD method is used, dataset will be quickly reduced and DTM will be generated on the basis of the optimal dataset. During the DTM generalisation, the time needed to reduce the dataset was about 20 min, while for reduction using the OptD method it was up to 20 s
- (2) in both approaches, datasets can be reduced by up to 98%. Usually, they are not useful for further analysis. However, it is important, that datasets with different degrees of reduction are obtained
- (3) DTM generalisation does not always lead to a dataset with different degree of point density, as it is visible in Fig. 4. However, applying the OptD method always provides different densities depending on the complexity of terrain
- (4) the OptD method allows total control over the number of points in the dataset after reduction, while the DTM generalisation allows to reach the reduced dataset after several attempts of processing and testing
- (5) well-set optimisation criteria in the OptD method allow to obtain a reduced dataset with the specified standard deviation, while during the DTM generalisation user has no influence on the accuracy of the obtained dataset
- (6) the resulting DTMs generated from the reduced datasets (Figs. 7 and 8) show that their quality is very close to the DTM generated from the original point cloud (Fig. 6). Obviously, the datasets with very small

number of points do not retain all the characteristic features of the area

(7) the isoline maps of overflow land in open-pit mining (Fig. 9) showed that, a very similarly reduced datasets obtained by applying two different approaches gives various results. The isoline map formed on the basis of the OptD dataset is better than the map based on the dataset obtained after the DTM generalisation. It shows more details of the complex structure. The shape of the overflow land presented on the map based on the dataset reduced by the OptD method is very similar to the shape obtained by applying the original point cloud, although only 1.2% of the points cloud from the LiDAR measurement dataset were the DSr3.

More detailed conclusions concern the value of parameters related to the evaluation of the generated DTMs' accuracy. The calculated RMS is the smallest for the DTM generated from the DSr1 (the largest dataset), and for the DSr6 (the lowest dataset) RMS is the largest. The coefficient of determination is the best for the DTM generated from the DSr2 and DSr3. The proposal of using the OptD method at the stage of preparing data for DTM including overflow land areas, as well as for isoline maps of open-pit mining is very well-founded. The method results appeared satisfactory.

ORCID

Wioleta Błaszczak-Bąk  <http://orcid.org/0000-0001-6169-1579>

Marian Poniewiera  <http://orcid.org/0000-0003-0855-7105>

Anna Sobieraj-Żłobińska  <http://orcid.org/0000-0002-1668-0632>

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