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# Deformation information system for facilitating studies of mining ground deformations – development and applications

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## Abstract

The paper presents the concept of the Deformation Information System (DIS) to support and facilitate studies of mining ground deformations. The proposed modular structure of the system includes data collection and data visualisation components, as well as spatial data mining, modelling and classification modules. In addition, the system integrates interactive three-dimensional models of the mines and local geology. The system is used to calculate various parameters characterising ground deformation in space and time, i.e. vertical and horizontal displacement fields, deformation parameters (tilt, curvature and horizontal strain) and input spatial variables for spatial data classifications. The core of the system in the form of an integrated spatial and attributive database has been described. The development stages and the functionality of the particular components have been presented and example analyses utilising the spatial data mining and modelling functions have been shown. These include, among other things, continuous vertical and horizontal displacement fields interpolations, calculation of parameters characterising mining ground deformations, mining ground category classifications, data extraction procedures and data preparation, pre-processing procedures for analyses in external applications.

The DIS has been developed for the Walbrzych Coal Mines area in SW Poland where long-time mining activity has finished at the end of the 20th Century and surface monitoring is necessary to study present day condition of the former mining grounds.

## 1 Introduction

The monitoring of active and former mining grounds with geodetic and other (e.g. remote sensing) techniques and analysis of ground deformations due to mining activity are essential to study the behaviour of surface deformations and to produce maps of mining terrain risk categories used to assess safety to the infrastructure, human population and the environment. The basic spatial information that is used for the identification and interpretation of mining terrain deformations are vertical and horizontal displacement fields and the related deformation parameters, tilt and curvature of the subsidence surface and horizontal strain (Popiolek, 2009).

The studies of mining ground deformations require detailed and up-to-date spatial and attribute information on various aspects of mining activity including geological models, mine plans, surface development, geodetic measurements and other data that are used in complex interpretations of the observed and modelled changes of the ground surface.

These tasks are more and more frequently facilitated with computer technologies. For example, the geographic information technologies (GIT) are now widely used to collect and manage spatial data related to mining deformations (Dolezalova et al., 2010), as well as geodynamic activity (Bogusz et al., 2013), geographic information systems (GIS) are used to prepare data for analyses in external applications such as simulations with the Finite Element Method (FEM) (Blachowski and Ellefmo, 2012) or artificial neural networks (Kim et al., 2009; Lee et al., 2012), as well as visualise results of numerical simulations e.g. mining ground classifications with fuzzy logic (Choi et al., 2010; Malinowska, 2011). GIS are also used for spatial data mining (Blachowski and Stefaniak, 2012) or to perform various ground deformation analyses with spatial data modelling functions, for example determination of subsidence surfaces with interpolation techniques (Kowalczyk et al., 2010) or determination of mining ground deformation parameters such as tilt, curvature or horizontal strain (Chrzanowski et al., 2012).

This paper introduces the concept of deformation information system (DIS) to facilitate studies of mining induced ground deformations, especially in complex and complicated mining conditions and former underground mining areas. The system's main components and functionality have been described on the example of the DIS for the former coal underground mines in the Walbrzych area in SW Poland.

## 2 The structure of the Deformation Information System (DIS)

The deformation information system for augmenting studies of mining ground deformations is based on the modular structure concept. The core of the system is made of the spatial database. The database system manages all of the collected and produced spatial and attributive data related to the mining activity and its influence on the surroundings. It includes, among other things: mining plans (location, geometry of underground workings, mining methods used and mining activity temporal data), locations of geodetic points and results of periodic geodetic measurements, land use and surface development data (Blachowski, 2008).

Then, the main components of the system are: the spatial data mining module for data discovery and data extraction with spatial and attribute query functions, geological modelling module realized with external software and integrated spatially with the system, spatial data modeling module with data processing models for spatiotemporal analysis and mapping of mining deformations and their characteristics (e.g. deformation parameters) and the data collection module based on terrestrial and remote sensing measurements carried out with geographic information technologies. The DIS is also connected with the multivariate spatial data classification module. Another component allows interactive data presentation in the form of two-dimensional maps and three-dimensional visualizations. The general concept of the Deformation Information System has been shown in Fig. 1. In the following sections the development and functionality of its main components are described.

## 3 The Walbrzych Coal Mines

The idea to develop DIS has arisen from the need to study post-mining ground deformations in the former Walbrzych Coal Mines area in SW Poland. The extent of the former mines (Thorez, Victoria, Walbrzych), underground workings, shafts and built-up areas have been shown in Fig. 2. Underground mining of coal had lasted there for several hundred years and ended in the late 1990'ties of the 20th Century. The following mining systems had been used: long-wall and caving (predominately) and long-wall with various forms of fill (pneumatic, dry, dry with material from dead drifts) (Piatek and Piatek, 2002). The hard coal industry has caused significant changes of the surface and its effects are visible in the local landscape to this day (waste dumps, settlement ponds, industrial objects and the general urban system). Because of the observed ground changes the area requires continuous monitoring to analyse and assess the influence of the now ended mining on the present day state of the ground and land development. For this purpose a detailed spatial database of the mines, geology, land use and development, geodetic networks and their measurements have been required.

## 4 Development of the Deformation Information System

The system's database and the modeling, data mining and visualization modules have been developed and implemented in the ESRI ArcGIS software environment. Their development and functionalities are described below. The remaining two components have been developed with the Geomodeller software (geological model) and artificial neural networks (spatial data classification module) and integrated with the DIS.

### 4.1 The DIS database

The primary source of information for the database and development of the three-dimensional geometrical model of the underground workings include mine plans, geological and mining documentations. The existing cartographic materials cover the last 200 hundred years of mining operations (since the beginning of the 19th Century). These maps, scales 1 : 1000 to 1 : 5000, have been scanned, registered in the DIS coordinate system (PUWG 1992) and digitized to vector format. This provided information on the geometry and location of coal levels and underground workings. Attribute data obtained from the mine plans included the mining system used and the time of

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coal extraction. The geological documentations provided information on the geological and the geotechnical parameters. The other important data source include the surveying logs with location of the geodetic benchmarks and the results of periodic levelling measurements. Topographic maps and aerial photographs provide information on land use and surface development over the years (1800 to present). In addition information on surface infrastructure damage is collected. The general structure of the system's database is shown in Table 1. The core datasets have been listed only. Detailed information on this part of the system can be found in (Blachowski, 2008). An important part of the database system is the product module that stores all of the feature classes representing results of spatial data analyses and results of analyses performed with external applications and imported to DIS. The structure of the database is open and can be expanded if necessary.

### 4.2 The geological model

The geological model of the Walbrzych Coal Basin in the part shown in Fig. 2 has been developed with the aim to obtain three-dimensional information on the geological structure in the former mining grounds area and to use it to augment studies of natural and anthropogenic processes associated with mining and its effects on the ground surface. Because of the limitations of GIS in modeling 3-D objects a specialized Geomodeller software (Calcagno et al., 2008) has been used for this purpose. It's a software application for advanced 3-D geological modelling. The preprocessing tasks associated with data preparation and postprocessing tasks associated with model visualization and integration have been done with the GIS software.

Data for the geological model included geological and mining maps (scale 1 : 5000), 10 geological cross-sections and profiles. The geological model has been developed based on the equipotential field theory (Lajaunie et al., 1997; Chiles et al., 2004; McInerney et al., 2005; Calcagno et al., 2008). The theory assumes that the geological model is a combination of three types of data: geological formations, the limiting surfaces and the fault surfaces cutting through them (Lajaunie et al., 1997). In this theory two assumption must be met, the boundaries between geological formation in given locations are known and the spatial orientation of the particular layers are known. The model development has been divided into three parts. The first one concerned identification of the spatial extent of the model. This extent has been determined by availability of the data and the extent of the geodetic networks (GPS and leveling) (Blachowski, 2008). The area of the model (7.2 × 6.7 × 0.8 km) covers approx. 49 $\mathrm{km}^2$ (about half of the total area of the former mining grounds). The second stage concerned development of the model using the geostatistical kriging function. Estimation of the spatial range of geological layers has been based on a cokriging function an expansion of kriging used for multivariate data modelling. Cokriging is an unbiased estimator that allows calculation of the mean root square error in geostatistical datasets (McInerney et al., 2005). It has the following form (1) (Calcagno et al., 2008):

$$T(p_0) - T(p) = \sum_{\alpha=1}^{M} u_\alpha \left(T(p_\alpha) - T(p'_\alpha)\right) + \sum_{\beta=1}^{N} v_\beta \frac{T}{u_\beta}(p_\beta), \tag{1}$$

where: $T(p)$ – is the scalar function of any point $p = (x, y, z)$ in 3-D space, $T(p_0) - T(p)$ – is the increment between two points: $p_0$ and $p$, $u_\alpha$ – is the primary data (variable) weight, $v_\beta$ – is the secondary data (variable) weight.

The model contains, from the top to the bottom, the Upper Carboniferous formations in the form of the Zacler, the Bialokamienskie and the Walbrzyskie layers. The last two layers contain coal levels (30 and 48 respectively). The bottom part of the model is made up of the Lower Carboniferous Kulm deposits. The general three-dimensional view of the model is shown in Fig. 8. The top boundary of the model is made up by the ground surface digital elevation model (DEM) and the bottom boundary has been set at −800 m below the sea level. The height coordinate system is the Kronsztadt 1986 system. In the last stage the accuracy of the modeled geological structures have been verified. The verification process has been based on the comparison of the calculated extent of the selected coal levels and tectonic faults with the available mine plans and geological maps. In addition the calculated values of the slope of the particular geological layers and the coal levels have been checked with the available documentations. The methodology of the model development has been shown in Fig. 3.

The integration of the spatial geological model, as a whole or a selected part of the model, with mine plans, and other spatial information is carried out through exporting data to the shapefile format and loading them into the DIS database.

### 4.3 The Spatial Data Mining Module

With the aim to automate data query and data extraction procedures used in studies of mining ground deformations an interactive application based on the Visual Basic for Applications (VBA) programming language, ESRI ArcObjects platform (Burke, 2003) and the Microsoft .Net framework have been developed. The application is available as a toolbar that can be added to the graphical user interface of the ArcGIS software. It contains tools that enable data exploration in the DIS databases using the concept of the Knowledge Discovery in Database (KDD) (Frawley et al., 1992). The data exploration tools include the find and selection operations that use any of the following criteria: mining system type, time of mining, location (Fig. 4). In response to the input criteria (e.g. longwall with pneumatic fill mining system) the system selects and highlights coal parcels meeting the given criterion or criteria and returns a report. The results allow analysis and assessment of the use of a given mining system, extent of mining, volume of extracted material as a function of time in a given coal production level or an area (multiple production levels).

### 4.4 The Spatial Data Modelling Module

With the same aim to automate complex and repeated spatial analysis procedures, data geoprocessing models using the ArcToolbox application and the Python language scripting have been prepared based on the GIS data management functions and spatial data modelling functions including the map algebra concept (Tomlin, 2008). This method of spatial data processing generates new spatial data (i.e. map layers) based on input spatial data and numerical operations performed on them (Heywood et al., 2006). The spatial data are regarded as spatial variables and the applied cartographic functions are equivalent to algebraic operations (Tomlin, 2008).

The developed models in the DIS for deriving new spatial data based on the data stored in the geodatabase are available as a toolbar that can be added to the graphical user interface of the ArcGIS software or as geoprocessing models in the ArcToolbox application. The geoprocessing models use a sequence of algebraic operations realized on vector and raster datasets. The following spatial data analysis operations are available on the additional toolbar: extract, slope, aspect and depth.

The *extract model* returns the area and volume of coal parcels mined, percentage of each mining system used and average value of surface subsidence inside boundaries of a user defined rectangle. The *slope model* calculates inclination of a given coal production level. This operation requires conversion of 3-D vector data to TIN (Triangulated Irregular Network) representing elevation of the coal level above sea level and calculation of inclination. The results are returned as raster whose cells represent value of slope. The *aspect model* calculates the direction of slope and works in the same way as slope tool. The *depth model* calculates depth of a selected coal production level below the ground surface. The raster surface representing depth of a coal level is calculated as a difference of DEM (Digital Elevation Model) and the raster with elevation of this coal level.

The other analytical functions for facilitating deformation analyses developed in the DIS are available as geoprocessing models and scripts. These are: vertical and horizontal subsidence surface, deformation parameters surfaces (tilt, curvature and horizontal strain) and the mining ground category classifications.

The *vertical displacement surface model* calculates continuous subsidence field from the scattered discrete measurement points (geodetic benchmarks) using the spline and the kriging interpolation functions. These models use the standard tools available in the GIS software. However, the subsidence surface is calculated for the optimised interpolation parameters that is those that generate the smallest estimation errors based on the results of cross-validation (Hofierka et al., 2007). The *horizontal displacement surface model* calculates the continuous horizontal displacement field taking into consideration its non-linear characteristics. First the continuous displacement fields in the $x$ and the $y$ directions are calculated using the above mentioned interpolation functions and the cross-validation method for estimation of the best fitting interpolation function. Then the final horizontal displacement field surface is obtained by combination of the displacement fields in the $x$ and the $y$ directions. The input data for this interpolation are the results of periodic GPS satellite observations (the measured horizontal displacements). The *tilt parameter model* uses the subsidence surface as the input spatial variable to calculate the continuous surface representing the tilt parameter (the first derivative of the subsidence surface). The curvature parameter model uses the subsidence surface as the input spatial variable to calculate the continuous surface representing the curvature parameter (the second derivative of the subsidence surface). The strain parameter model uses the continuous horizontal displacement field surface to calculate the continuous surface representing the horizontal strain parameter.

The resulting raster surfaces store the values of each parameter that are used as input spatial variables to assign a mining ground category (0 – least influence of mining to $V$ – greatest influence of mining) using the Polish classification given for example in (Popiolek, 2009). The mining ground categories in terms of each parameter are given in Table 2.

An algorithm for calculation of the tilt and curvature parameters is shown in Fig. 5.

### 4.5 The Spatial Data Classification Module

We believe that the use of self-organising maps (SOM) and weighted regression methods in the research of mining grounds allows to identify and analyse the relationships between possible mining ground deformation factors and the observed surface subsidence. This approach is associated with the process of multi-contextual extraction of information from the database and ultimately acquiring knowledge on the present and future state of the ground based on the analysis of these factors. This information is associated with the factors having influence on the deformation of mining terrains, presence of certain regularities in the data and existence of hidden characteristics of the deformation process. Thus, through construction of a behaviour model as a system of time-varying parameters, supported by statistically reasonable set of examples a better understanding of this phenomenon and prediction of deformation areas are possible. The spatial nature of this problem calls for the use of GIS technology.

The models for deriving spatial data from the DIS geodatabase used as input variables for self-organising map (SOM) classifications with neural networks (in external software) and geographically weighted regression analyses (GWR) (in GIS software) are: the coal level thickness, the mining system, the time of mining, depth below the ground and the slope. These models divide the analysed area into uniform cells of a given dimension e.g. 100 × 100 m and assign values of the particular variable to the cells. The two example algorithms used to obtain layers representing the mining system parameter and the depth below the ground parameter are given in Fig. 6. The methodology is similar for the remaining procedures. In the first one shown in Fig. 7, the vector polygon data is converted to integer raster data where the raster pixels are assigned values based on the values of the mining system attribute from the attribute table. The pixels falling outside the geometrical extent of the coal parcels are assigned NODATA value. The raster value attribute table (text codes) is then reclassified to numerical values e.g. the long-wall and caving mining system is assigned the value of 1 and the other systems 2, 3 and so on. The reclassified raster may be converted to point vector data for further analyses. In the second procedure a DEM surface is created from the input vector polygon data representing the mined coal parcels in a given coal level. The DEM is converted to raster that is then subtracted from the DEM representing the surface using map algebra subtract operation. The resultant raster storing depth below the surface values is modified to the spatial extent of the initial vector polygon data again using map algebra operations. The data can then be converted to point vector data the points representing values of individual pixels.

These models automate data extraction from the DIS and data preprocessing for the purpose of various classifications such as self-organising maps and analyses using geographically weighted regression functions to examine spatial relationships between the input variables and the observed surface subsidence.

The three-dimensional representation of the variables extracted for any coal production level is shown in Fig. 7.

### 4.6 The Data Collection Module

The geodetic and remote sensing measurement techniques used for collecting deformation and other data can be, in our opinion, regarded as another module of the System. The electronic data transfer applications allow integration of the results of geodetic measurements with the DIS database. The measurement results used in the described case include, archival and current precise and technical levelling realised in various parts of the Walbrzych area, GPS satellite observations carried out in the Walbrzych monitoring network, as well as part of the GEOSUD geodynamic network (Kontny et al., 2006).

### 4.7 The Visualisation Module

Another product of integrating and analyzing the geometrical and attribute data collected in the database is an interactive, three-dimensional model of the underground mines in the Walbrzych. The DIS allows two and three-dimensional visualisations and interactive animations of the geometry of underground workings and production levels, as well as of the geological model. These models allow development of smaller, local models for any part of the former mining area, as well as the development of vertical profiles. Example visualisations have been shown in Figs. 8 and 9. The first one presents classification of the coal parcels according to the mining system used for a selected part of the Thorez mine. The second one shows numerical geological model of the part of the former mining area. The three-dimensional models are used as data sources for numerical modelling and for performing spatial analyses related to deformation studies. The other forms of data visualization are described in part 4.

## 5 Application and discussion

The principal purpose of the DIS is to support and facilitate the studies of mining related ground deformations in the Walbrzych former mining area with connection to regional geodynamics. These studies concern the period of mining (i.e. up to 1996), as well as the present day (after the end of mining activity) monitoring of the condition of the ground and its effects on the surface infrastructure based on the repeated geodetic measurements in connection to the mining, geological and other data integrated in the system.

In addition the mining and the geological models are used in Finite Element Method modeling of the ground deformations and deformation predictions and the system is used for visualisations of these numerical analyses (Blachowski et al., 2009; Milczarek, 2011; Blachowski and Milczarek, 2011).

Examples of other types of analyses whose results are used in studies of the ground deformation caused by mining activity are given below on the case of a single coal production level (424/425) and inside a protective pillar established around two mining shafts.

The first one concerns analysis of mining activity in time in a given area. The results are shown graphically in Fig. 10, which presents the time of mining of the generalised coal parcels and the sequence of mining presented with arrows. In this case mining in the analysed area took place from the year 1824 to 1929.

The second one concerns analysis of the slope of the coal production level (424/425) within boundaries of the protective pillar of the two mining shafts. The results have been shown graphically in Fig. 11. In the presented case the slope of the analysed coal level varies from 10 to 50 degrees.

The third one concerns correlation of the predicted total subsidence (Kowalski and Jedrzejec, 2010) with the depth and the slope of the 424/425 production level. The result of this analysis is shown in Fig. 12. The longwall and caving mining system was used in this case.

## 6 Conclusions

The structure and methodology of developing the Deformation Information System an indispensable means to support and facilitate mining ground deformations studies have been described. The presented approach uses modular system structure that includes the following components: geodetic data collection, spatial data mining, spatial data modelling, geological modelling, spatial data classifications and visualisations. The system integrates spatial and attributive data, as well as utilises interactive three-dimensional geological and mine models used for mining ground deformation studies. The DIS provides spatial data extraction and visualisation functions and analytical functions for studies of the spatial and temporal changes of the mining activity in the past 200 yr and the present-day monitoring of ground deformation in relation to the locations of the former mines. The selected analytical operations allow interpolation and visualization of mining subsidence surfaces including continuous horizontal displacement fields, calculation of the surface deformation parameters, i.e. tilt, radius of curvature and horizontal strain, classification of mining ground categories based on the accepted (in Poland) mining ground classifications for any identified point is space, pre-processing and post-processing of data for advanced analyses such as the spatial data classifications and numerical (FEM) modelling of ground deformations. The development of the DIS has been shown on the example of the coal mines in the Walbrzych area in

SW Poland. Further work on the system include incorporation of remote sensing data, expansion of the analytical modules in spatial data classifications and spatial statistics related for example to recorded mining damage locations.

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**Table 1.** The general structure of the DIS database.

| Dataset group | Dataset subject | Type/Geometry | Main attributes | Comments |
|---|---|---|---|---|
| Mining | Coal production levels | 3-D polygons | Area, volume, thickness, mining system, time of activity (years) | Each level for each mine in a separate feature class |
| | Underground workings | 3-D polygons, polylines, points | – | Underground drifts shafts, protection pillars, etc. |
| | Surface mining infrastructure | 2-D polygons and points | Name, status, function | Industrial objects and sites, waste dumps and settlement ponds |
| Geology | Geology | 3-D polygons, polylines | | Geological formations, tectonic faults and discontinuities |
| Geodesy | Geodetic networks | 2-D points and polylines | ID, class | Location of geodetic benchmarks, GPS stations and leveling lines |
| | Geodetic measurements | Tabular data | ID, measured elevation, measurement time | |
| Reference data module | Road and railway system | 2-D polylines | | |
| | River network | 2-D polylines | | |
| | Land use | 3-D polygons | | |
| | Administration and polylines | 2-D polygons | Name, type | Boundaries of mining grounds and administrative units |
| | Infrastructure damage | Vector/2-D points | Type, description, image | |
| Source data module | DEM | Raster data, TIN data | Spot elevation | Digital elevation model |
| | Mine plans | Raster data | – | Scanned documents |
| | Topographic maps | Raster data | – | Source raster datasets |
| | Aerial images | Raster data | – | Source raster datasets |
| Product module | Derivative datasets | Vector/raster | | Feature classes and raster files with results of analyses |

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**Table 2.** Risk classification of mining grounds (after Popiolek 2009).

| Mining ground category | Tilt $T$ [mm m$^{-1}$] | Radius of curvature $K$ [km] | Horizontal strain $\epsilon$ [mm m$^{-1}$] |
|---|---|---|---|
| 0 | $T \le 0.5$ | $40 \le \lvert R \rvert$ | $\lvert \epsilon \rvert \le 0.3$ |
| I | $0.5 < T \le 2.5$ | $20 \le \lvert R \rvert < 40$ | $0.3 < \lvert \epsilon \rvert \le 1.5$ |
| II | $2.5 < T \le 5$ | $12 \le \lvert R \rvert < 20$ | $1.5 < \lvert \epsilon \rvert \le 3$ |
| III | $5 < T \le 10$ | $6 \le \lvert R \rvert < 12$ | $3 < \lvert \epsilon \rvert \le 6$ |
| IV | $10 < T \le 15$ | $4 \le \lvert R \rvert < 6$ | $6 < \lvert \epsilon \rvert \le 9$ |
| V | $15 < T$ | $\lvert R \rvert < 4$ | $9 < \lvert \epsilon \rvert$ |

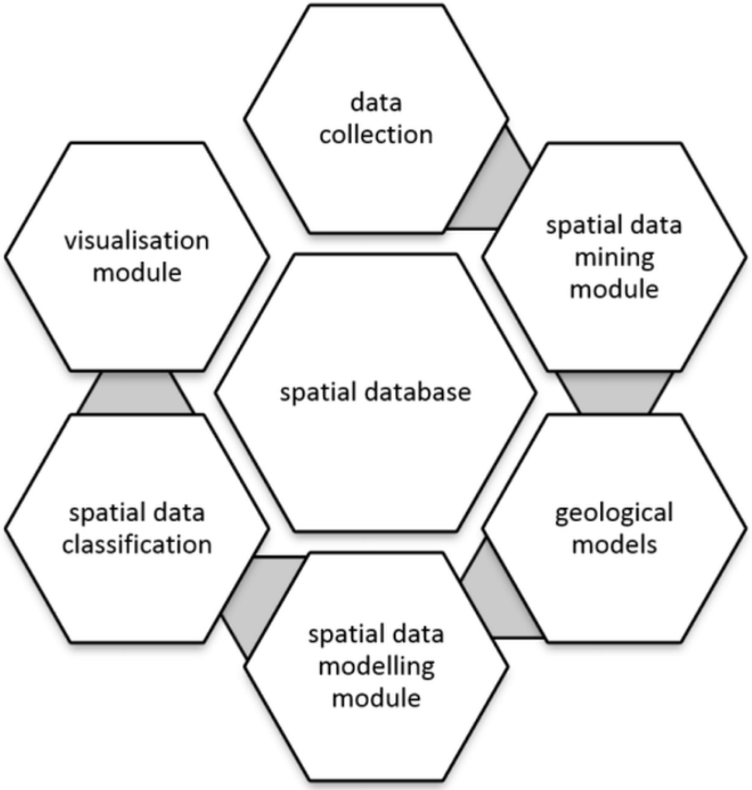


**Fig. 1.** General structure of the Deformation Information System.

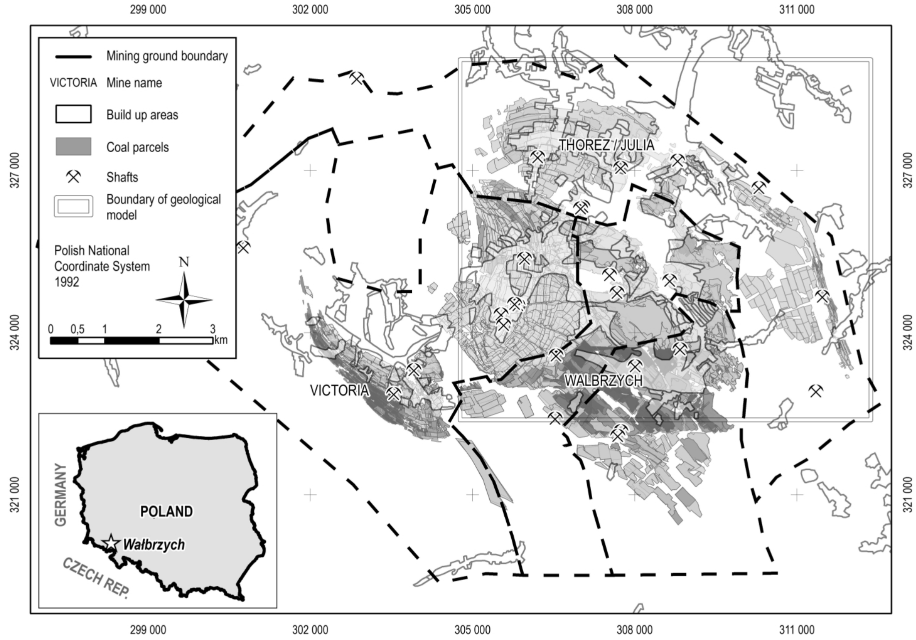


**Fig. 2.** Location of the former Walbrzych Coal Mines (Blachowski and Milczarek, 2011).

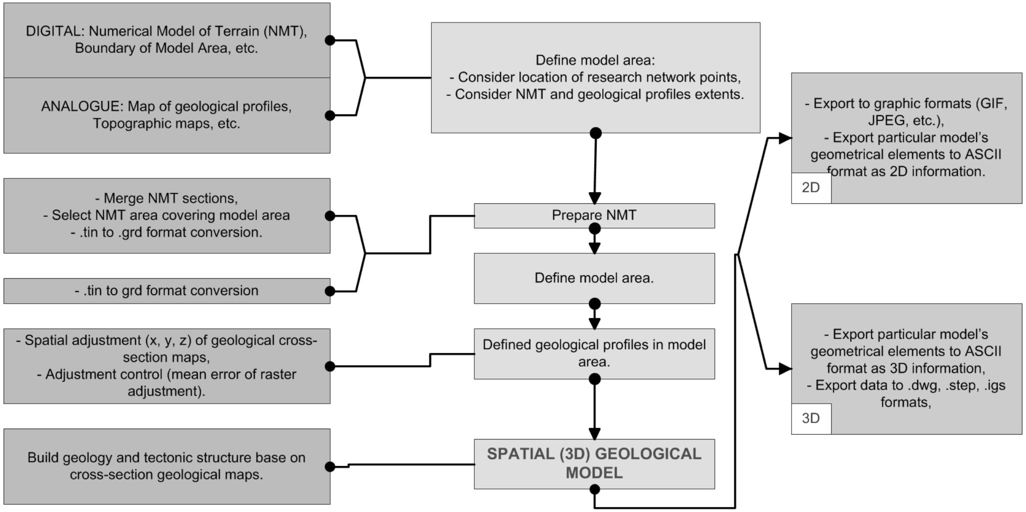
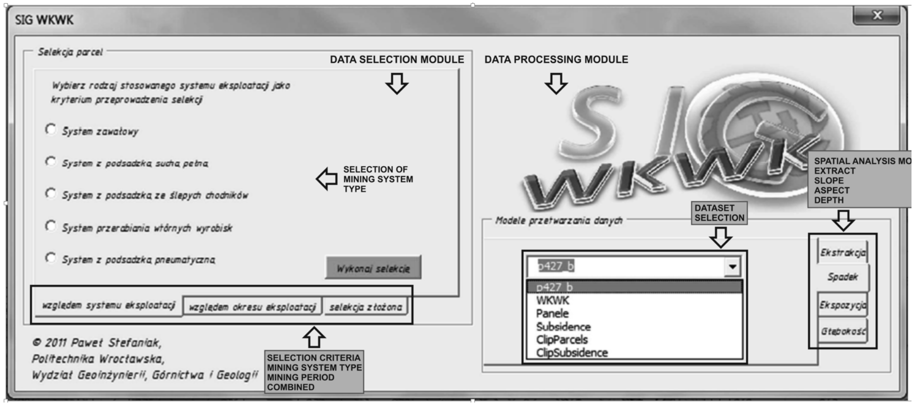


**Fig. 3.** The generalised procedure of developing the spatial geological model (Milczarek, 2011).



Wybierz rodzaj stosowanego systemu eksploatacji jako kryterium przeprowadzenia selekcji

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Wydział Geoinżynierii, Górnictwa i Geologii

**Fig. 4.** The spatial analysis application in the Deformation Information System.

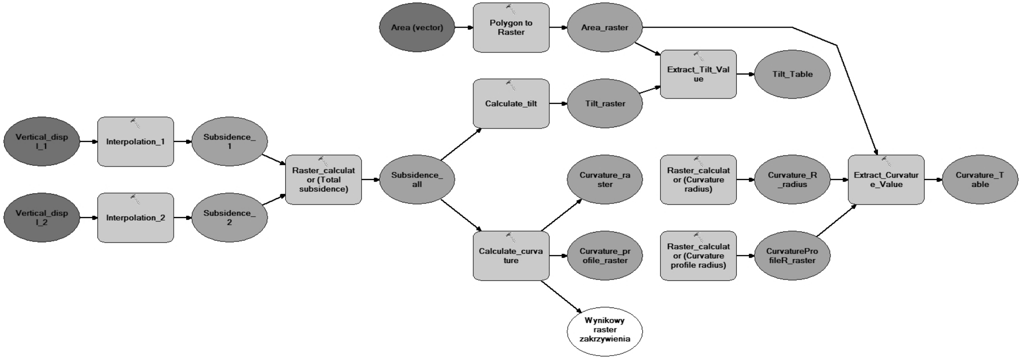

**Fig. 5.** Diagram of the geoprocessing model for the calculation of the tilt and radius of curvature parameters of the subsidence surface.

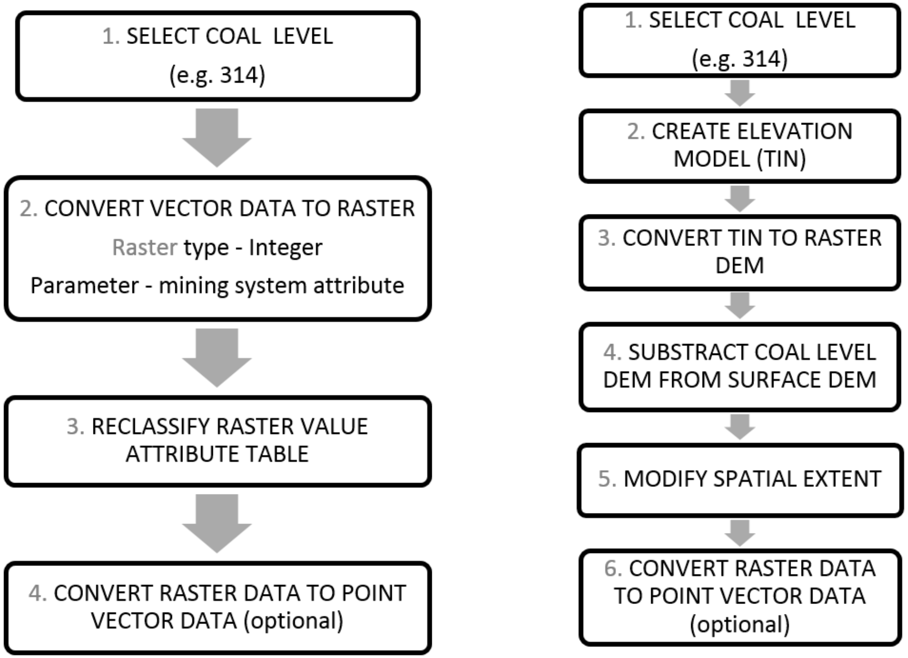

**Fig. 6.** The simplified procedures to extract data for analyses, left – mining system variable, right – depth below the ground variable.

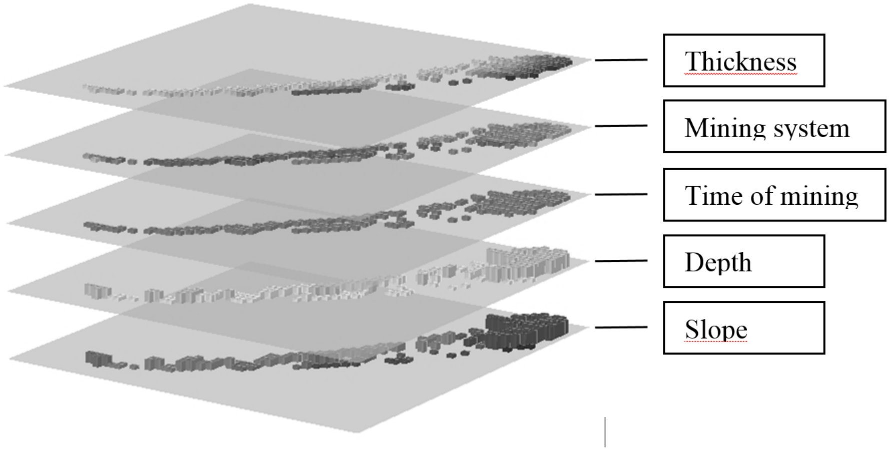

**Fig. 7.** Three-dimensional visualisation of the coal thickness, mining system, time of mining, depth below the ground and slope variables derived for a selected coal production level and used for spatial data classification.

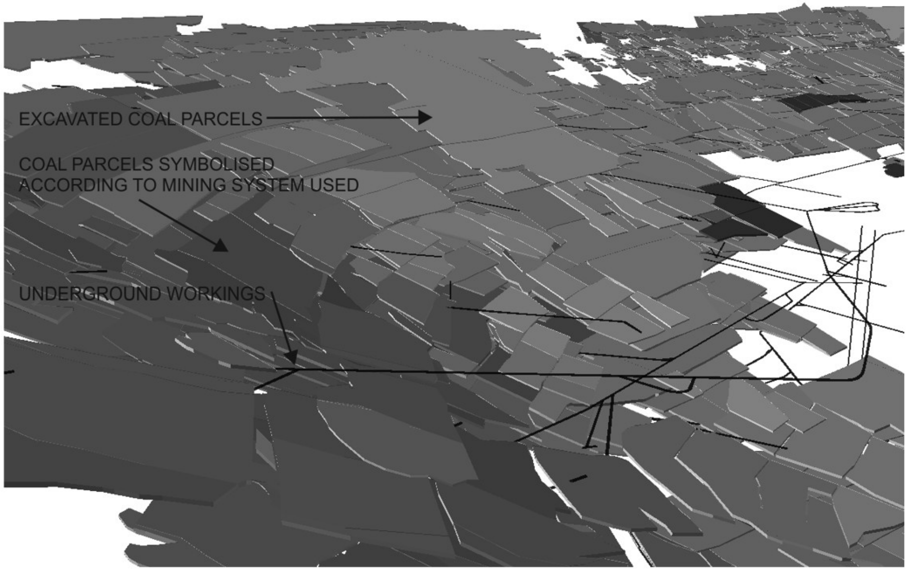

**Fig. 8.** Three-dimensional visualisation of the selected underground workings and coal parcels classified according to the mining system used.

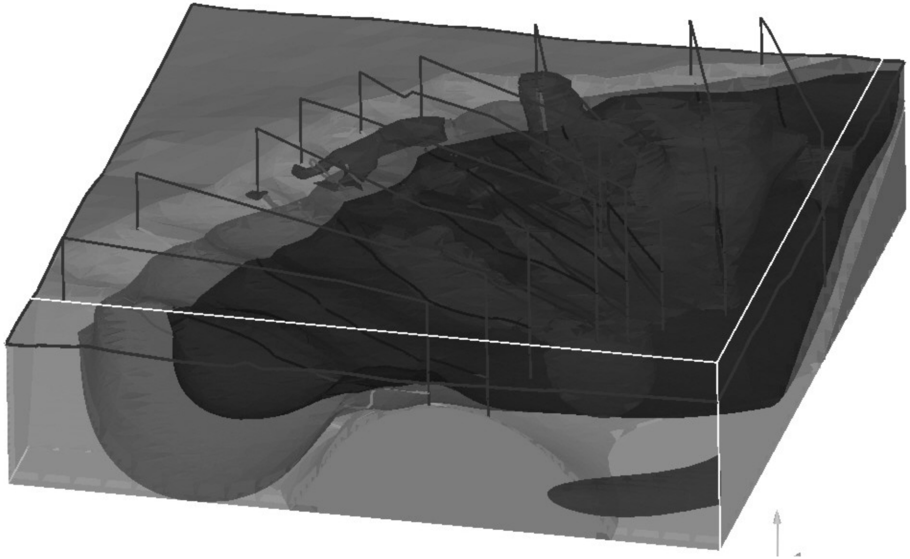

**Fig. 9.** Three-dimensional numerical geological model for the part of the former mining area shown with the black box in Fig. 2.

**Fig. 10.** Mining activity analysis for the 424/425 coal production level within the boundaries of the protection pillar.

**Fig. 11.** Slope analysis for the 424/425 coal production level coal within the boundaries of the protection pilla.

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**Fig. 12.** Subsidence analysis for the 424/425 coal production level the boundaries of the protection pillar.