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THE USE OF THE CITYGML STANDARD FOR A 3D GIS OF UNDERGROUND AND OPEN-PIT MINES

Purpose. The research aims to address the challenges posed by the integration of diverse methods, focusing on data collection techniques and level of detail (LoD) considerations, which facilitates the creation of detailed 3D models. The CityGML standard is employed for its ability to represent complex urban features, adapted here for mining environments.

Methodology. Combining Unmanned Aerial Vehicle (UAV) and Terrestrial Laser Scanning (TLS) technologies to collect data for open-pit and underground coal mines. These data are processed to generate point clouds, which are then used to create 3D models of mining structures using Sketchup and REVIT. Finally, these models are converted into the CityGML standard using FME SAFE software.

Findings. Through the use of Unmanned Aerial Vehicle and Terrestrial Laser Scanning technologies, precise point cloud data for open-pit and underground structures are acquired. CityGML serves as a suitable framework for digital mine representation, offering standardized data organization and exchange. The proposed methodology optimizes data collection and processing procedures, ensuring accuracy and efficiency in model creation. Notably, the study introduces a nuanced approach to LoD selection, considering the complexity and specific requirements of different mining structures.

Originality. The article innovatively combines UAV and TLS technologies with the CityGML standard to create comprehensive 3D GIS models for coal mines operating with both open-pit and underground methods, addressing the unique challenges of modeling diverse mining structures and terrain features.

Practical value. The practical value of the article lies in its provision of a systematic approach using UAV and TLS technologies, coupled with the CityGML standard, to create accurate 3D GIS models for coal mines employing both open-pit and underground methods. This methodology enhances mine management efficiency, resource estimation accuracy, and safety assessment capabilities.

Keywords: *open-pit, underground mines, CityGML, 3D GIS, UAV, TLS*

Introduction. There are two common mining options used in the excavation, including open-pit and underground. One of the conditions to select these mining methods is the depth of mineral bodies. Open-pit mining is typically the preferred method when mineral resources are close to the earth's surface. This method involves extracting minerals from the surface and is conducted above ground. The design of an open-pit mine is based on the deposit's block model, which represents the ore body and surrounding rock, as well as various attributes such as mining cost, degree of mineralization, location, and the cost of processing the specific block [1]. However, underground mining is usually employed when the economically viable deposit is located deep enough that open-pit mining becomes cost-ineffective. This method involves tunneling into the ground to extract materials beneath the earth's surface, which can lead to issues such as air loss and cave-ins. This is why open-pit mining is considered less dangerous and less intrusive compared to underground mining. There are several underground mining techniques, including open stoping, room-and-pillar, sublevel caving, drift-and-fill, longwall, and block caving. The choice of method is typically based on geotechnical constraints, as well as the size and shape of the deposit [2].

While both open-pit mining and underground are widely used, there is a growing trend towards expanding underground mining. This shift from open-pit to underground mining usually occurs when open-pit mines become depleted or inaccessible, either due to exhaustion of minerals, rocks, and resources, or because they are impractical to build upon. Once the decision is made to transition from open-pit to underground mining, several approaches can be taken: miners can construct spiral tunnels around the desired resources, dig shafts into the ground, or create adits that lie on the side of elevated terrains, such as hills [3].

The existence of both underground and open-pit mines creates challenges to the management of mines. The application of 3D Geographic Information Systems (GIS) could be a solution to this issue as it is able to provide more information about the integrated mines, including both spatial and attribute information in 3D [4, 5]. 3D GIS has been increasingly commonly used in urban management [6, 7]. In a 3D GIS database, 3D digital models are one of the important components. They are digital representations of city objects, including buildings, traffic infrastructure, vegetation, water bodies, relief, and other engineering structures. In the mining industry, 3D GIS can be the same as being used in urban planning, environment management, and urban development. With the increasingly common 3D digital models have become common as they are one of the main components of virtual reality (VR) technology which has been widely used in many fields, such as entertainment, education and training, and the mining industry. In the mining industry, 3D GIS with 3D digital models can be used to improve productivity as they act as the parallel simulator or virtual copy (digital replica) of real mines without impacting operations. However, the building of 3D models of structures and components of both underground and open-pit mines might be challenging. Underground mines have complex engineering structures with many steel objects above the ground, such as hoist rooms, winding towers, and sheave wheels, as well as underground, including shafts, tunnels, and convoys, whereas, for open-pit mines, terrain is the most important. Terrain surface in open-pit mines is formed and changes frequently as a result of excavation.

In order to effectively support the management of both underground and open-pit mines, 3D GIS can be built, and the international 3D GIS standard CityGML (CityGML is an open standard data model and exchange format designed to store digital 3D models of cities and landscapes. The geometry of these objects is described using the Geography Markup Language (GML). CityGML can be an optimal solution [8]. CityGML has been widely used in many studies [9–11]. The authors of these studies indicated that CityGML could meet the increasingly demanding requirement of describing complex features in urban management. Therefore, it can be used for mining management. In CityGML, the concept of level of detail (LoD) is well-developed for complex structures, such as buildings and bridges, but is vague in the case of terrains and land use [8, 12]. Therefore, in the case of both underground and open-pit mines, CityGML is expected to meet the described requirement of underground structures but needs an improvement for the representation of the mining terrain surface.

For open-pit mines, the 3D digital presentation of terrain is the most important as it reflects mining operations [13]. The continuous activity of excavation in open-pit mines makes terrains quickly change. In addition, this change has to be accurately measured to determine the volume of rock and mineral resources. Therefore, it is important to note that the 3D digital representation of the mining terrain surface needs to be correspondingly accurate. Two of the most common models of terrains in GIS are Triangulated Irregular Networks (TIN) and Grids. In comparison, the former can be used to present complex terrains that the latter cannot do, such as cliffs, and vertical walls. Therefore, in order to meet both the described requirements of underground and open-pit mining structures, TIN models could be a reasonable solution. However, TIN has also disadvantages, such as challenges in storing massive TINs, only the geometry of the terrain dataset stored, and very little topological information stored [12].

For data collection, the terrain and its changes are measured using surveying methods, such as total station, Global Navigation Satellite System (GNSS), Unmanned Aerial Vehicle UAV survey, and Lidar. Recently, UAV and Lidar technologies have been commonly used to collect point clouds of open-pit mines [13, 15]. The advantages of these technologies are the reduction of labour and time in the field, so they help to increase the productivity of data collection. In terms of accuracy and level of detail, they are accurate enough to satisfy the requirement of mine surveying, and with a high density of points at centimetre and millimetre accuracy levels (UAV and Lidar, respectively) [16, 17]. Therefore, in both underground and open-pit mines, while Terrestrial laser scanning (TLS) can be employed to collect data for the underground part, UAV can be used for collecting data for the open-pit part.

In this study, we created a 3D GIS database for a coal mine which is operated by both underground and open-pit methods using the CityGML standard and proposed a workflow to build this 3D database using UAV and TLS technologies. This procedure includes data collection and the selection of suitable Levels of Detail (LoDs) for each component of the mining 3D model using CityGML standards.

Study area. According to Decision 403/QD-TTG issued by the Government of Vietnam, open-pit mines will contribute to 11 % of production until 2030 [18]. Currently, in Vietnam, there have been many coal mines starting to transfer from open pit to underground operations, for example, Ha Lam, Ha Long, Nui Beo, etc. For this transition, these mines continue their open-cast operation, but starting to access deeper coal seams via mine shafts.

Nui Beo coal mine located in Quang Ninh Province of Vietnam is selected for 3D modeling in this study (Fig. 1). The mine's area is about 100 hectares with an area of 12 hectares for underground and the remaining area for open-pit.

The mining surface has a difference of 110 m in elevation, ranging from –85 to +25 m, with features of an open-pit mine (Fig. 2), including benches, slopes, haul roads, and pit floor. The 12-hectare plant infrastructure area of the mine is located at an elevation level of +35 m with a flat terrain. Mine shafts are used to access multiple coal seam bodies located from 300 m to 500 m under the surface. There are many concrete and steel structures in this area, including factory plants, office buildings, hoist rooms, winding towers, and sheave wheels. These structures feature the coal mining industry of Vietnam and vary in shape, size, and material.

Methods. ***CityGML and Level of detail (LOD).*** The City Geographic Markup Language (CityGML) is a standard developed by the Open Geospatial Consortium (OGC) and is part of the ISO 19100 series. It is designed for 3D Geographic Information Systems (GIS). The CityGML schema is modular and consists of a mixed geometrical-topological module and several thematic modules that correspond to urban map layers. The conceptual model is logically implemented using XML technology tools. CityGML allows for the modeling of most 2D and 3D vector representations, as well as raster representation.

Data in CityGML is managed in five hierarchical top-down levels of detail (LOD) [19], including LOD0 (Region and Landscape), LOD1 (city and region), LOD2 (city, city district, and project), LOD3 (city district, exterior architectural model and landmark), and LOD4 (landmark and interior architectural model). Higher levels use increasing structural complexity and accuracy, degrees of resolution, and accuracies and minimal dimensions of objects [20].

The overview of CityGML 3.0 model is presented in research [21]. The latest version, CityGML 3.0, has been released and has potential applications. This version introduces 11 thematic extension modules, including Building, Bridge, Tunnel, Construction, CityFurniture, CityObjectGroup, LandUse, Relief, Transportation, Vegetation, and WaterBody. These modules provide

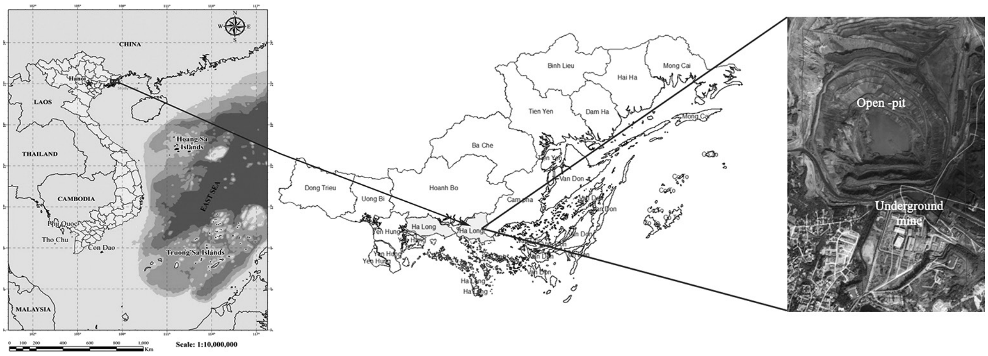

Fig. 1. Location of the study area

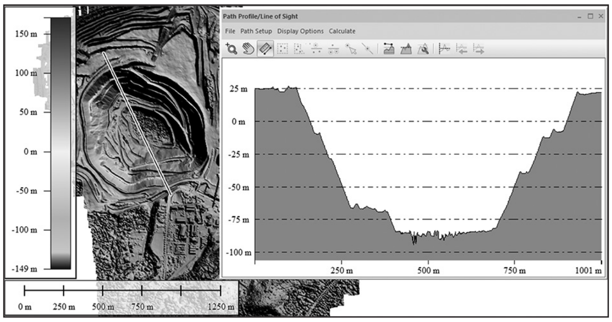

Fig. 2. Characteristics of terrain in the study area (Cross section of Nui Beo open-pit mine)

models for the most important types of objects within virtual 3D city and landscape models. CityGML is an open standard for storing and exchanging 3D city models, including their geometry, semantics, and graphical appearance [8].

The Level of Detail (LOD) concept for terrains in CityGML, developed by [22], consists of four levels: LOD0 to LOD3. LOD0 is the most generalized and coarsest representation of city objects in CityGML. For terrains (TINRelief), LOD0 is a strict 2.5D TIN representation without vertical surfaces and overhangs, essentially a simple Delaunay triangulation of the ground without man-made objects and vegetation embedded in the TIN.

LOD1 terrain extends the 2.5D Digital Terrain Model (DTM) to support the representation of vertical triangles and overhangs in the TIN, making it a 2.5D+/2.75D model. LOD2 terrain is a semantically enriched strict 2.5D DTM with information about the city objects integrated into the terrain. In this case, a LOD2 terrain is a constrained Delaunay triangulation where the boundaries of the city objects such as buildings, roads, etc., act as constraints in the triangulation.

Finally, a LOD3 terrain is a semantically enriched 2.5D+/2.75D extended DTM with information about the city objects integrated into the terrain. This comprehensive representation provides a detailed and accurate model of the urban environment.

Description of proposed procedure. The proposed procedure is described in Fig. 3. With the aim of 3D modeling both underground and open-pit coal mines, the procedure contains four phases, including model design, data collection, data processing, and 3D modeling. From the above analysis, we proposed a strategy to optimize this procedure to create 3D models of underground and open-pit structures and features. For the design of models, the CityGML standard is selected for the model of the mine. As structures of underground coal mines are more complicated than those of open-pit ones, their CityGML LODs are decided based on their complexity. In this study, we adopted the definition of LOD proposed by [12] and improved by [22] to choose the LOD of mining terrain.

LoDs for 3D modeling underground coal mine. As the high detail requirement of representing structures of an underground coal mine, the highest level of detail (LOD4) is selected. To well fit the model of these structures, the terrain around the mine shaft and other important structures can be modeled with LOD3.

LoDs for 3D modelling open-pit coal mine. The terrain is the most important feature to be modeled for the open-pit coal mine. To reasonably model its terrain, there are several factors to be considered, including the representation and accuracy of terrain, and data storage. For the accuracy of the terrain, we use the accuracy requirement described in the Vietnam standard for mine surveying [23]. The accuracy of mapping terrain in open-pit mines is to satisfy the accuracy of volume calculation which in turn is used to support mining operations. Therefore, the 3D presentation of mining terrains needs to be correspondingly accurate. As there is almost no permanent and important infrastructure such as buildings, plants, and facilities on the open-pit mine, and it is featured by benches with slope walls, LOD1 is the most suitable in terms of accuracy and data storage. This is to avoid the use of LOD0 resulting in the loss of triangles representing the vertical walls which distorts the geometry of the model [24] and unnecessary information from using LODs 2 and 3.

For the change of mines, CityGML 3.0 offers attributes to represent transaction time, such as *CreationData, TerminationDate*. However, because of the complexity of its hierarchical structure, syntactic and geometric ambiguity, and graphical and semantic combination in one place [25], the CityGML model of mines is replaced instead of updated.

In addition, the procedure of collecting and processing data is established to optimize the overall process (Fig. 3). The data collection procedure is designed with the consideration of the characteristics or condition of underground and open-pit mines, as well as the LoD of models. For the data collection, a UAV survey is used for collecting the data of open-pit coal mines, whereas TLS is used for that of underground coal mines. This is to ensure both the effectiveness and accuracy of data for 3D modeling open-pit and underground coal mines.

To construct 3D CityGML models, the shape and size information of features can be derived from the extracted point clouds. This information is crucial for designing both the exterior and interior of objects, such as buildings, mine shafts, and tunnels in the study area at Level of Detail (LOD)3. Two common types of 3D modeling software, Autodesk REVIT and Trimble Sketchup, were utilized to accurately draw walls, roofs, and steel frames and bars. Each software has its own strengths: Autodesk REVIT excels in point cloud filtering and measuring the geometry of objects, while Trimble Sketchup is advantageous in displaying the 3D model. Furthermore, tex-

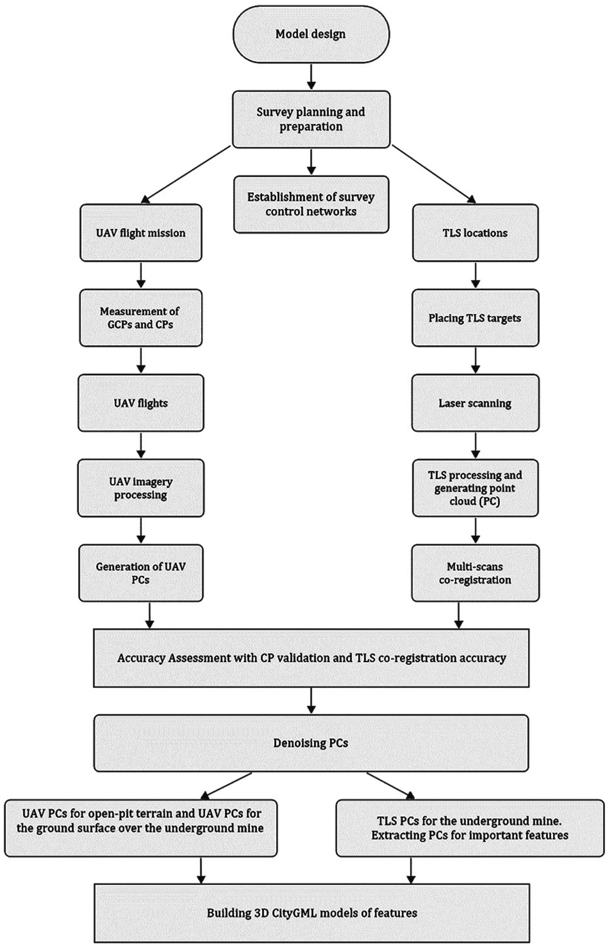

Fig. 3. Workflow of building 3D CityGML model of the both underground and open-pit coal mine

tures obtained from Unmanned Aerial Vehicle (UAV) (oblique) and Terrestrial Laser Scanning (TLS) photos were applied to the surfaces of the objects. The models were then converted to CityGML using the Feature Manipulation Engine (FME) software. FME is a powerful tool for converting and processing geospatial data. When it comes to converting 3D models to CityGML, FME provides a robust solution. The procedure includes of following main steps:

1. Read the 3D model data.
2. Transform it to CityGML format.
3. Specify the desired LoD.
4. Write the resulting CityGML dataset. There are two parts, including converting the geometry of models from different formats to CityGML (Fig. 4) and generating their attributes (Fig. 5). For 3D modeling of the open-pit mine's terrain at LODs 2 and 3, the software developed by [22] was used.

The attributes of tunnels include length, face area, material, name of tunnel, ID, Structure, Constructed date, Constructors, Level Range, gml_id, and gml_parent_id. Table 1 shows more details about the definition of attributes, such as attribute type, define cell width and values.

UAV and TLS surveys. The principle of UAV survey is UAV photogrammetry, which is based on the Structure-from-Motion (SfM) method with the key algorithm, namely the Scale-Invariant Feature Transform (SIFT) [26]. The method includes some important steps: 1) feature extracting; 2) image matching; 3) Internal and external camera orientation; 4) Point cloud generation through dense image matching algorithms [27]. UAV technology has been proven as an effective tool for mapping open-pit mines and is widely employed in the mining sector.

TLS technology allows one to quickly and accurately collect millions of 3D points of object surfaces. In general, there are some steps, including project planning, one or more scans, registration and georeferencing of scans, filtering, and data visualization. Project planning includes survey planning and preparation, TLS locations for one or more scans, targets and control point establishment for registration and georeferencing of scans, and denoising and extracting point clouds of features for filtering and data visualization (Fig. 5).

Hardware platform. In this study, the specification of the hardware platform is shown in Table 2.

Results and discussions. ***Data collection.*** *Establishment of Ground control points.* The distribution of Ground control points (GCPs) is shown in Fig. 6, *a*. They were placed on flat ground surfaces with cross marks (Fig. 6, *b*) and some were attached to facades of high buildings or structures (winding towers) with chessboard sheets (Fig. 6, *c*). The aim of these GCPs is to transfer UAV point clouds to a local coordinate system (VN 2000). These GCPs were measured by traditional survey methods, such as GNSS (Fig. 7) and total station.

The Comnav T300 receivers were used to measure GCPs, with horizontal accuracy: 10 mm + 0.5 ppm; and vertical accuracy: 20 mm + 0.5 ppm, and each GCP was measured three times and averaged to have final values. For GCPs on facades, Leica Flexline TS09 Plus with a distance accuracy: 1.5 mm + 2 ppm, and an angle accuracy of 1" was used to measure their coordinates, with the non-reflector mode.

The UAV survey of an open-pit coal mine. The drone used for the UAV survey was DJI Phantom 4 Advanced (P4) which is equipped with a GNSS device (receiving both GPS and GLONASS signals), a camera with a Sony CMOS 1" sensor, a resolution of 20 Megapixels. There were two different flight modes used in this study, including circular and linear orbit modes. The circular flight is used when surveying tall structures, such as towers, while the linear is quite common for mapping large areas. With linear flight mode, UAV flight planning software offers two modes, including GRID for 2D maps, and Double GRID for 3D maps with nadir and oblique cameras, respectively. The former was used to capture photos over the open-pit mine, while the latter was used for the ground surface surrounding the mine shafts of the underground mine. For tall structures like winding towers, the circular orbit flight mode was used. The parameters of flight plans are shown in Table 3, and the result of UAV data collection is shown in Table 4.

There are a total of eight missions in which five missions for GRID, one for Double GRID, and three for Circular flights. The UAV survey produces 1506 photos with 1,030; 219 and 257 for GRID, Double GRID, and Circular, respectively. The highest resolution of 0.5 cm is captured from circular flights, followed by 2.74 cm for GRID flights.

UAV photos were processed in Agisoft Metashape. The processing procedure includes photo alignment, camera optimization, building dense clouds, and ortho-photo. For the accuracy assessment, Table 3 illustrates errors of seven CPs in three directions, including *X, Y,* and *Z*.

The result of processing UAV data provided 148 million points (Fig. 8). The point cloud is divided into two sub-point clouds for open-pit terrain and the ground over the underground mine.

The TLS survey for the underground coal mine. In this study, TLS survey was designed with both external and internal scans. External scans were located at ground level, surrounding complex structures, whereas, internal scans were mainly used indoors, with shafts, and tunnels. To enhance the precision of scan registration, both chessboard and sphere targets were utilized. These targets are commonly used in 3D scanning as they provide high-contrast, easily identifiable markers that can be detected and tracked by the scanning software. This helps to align and register multiple scans accurately, ensuring a high-quality 3D model. Some of them were measured by the total station to transfer the TLS point clouds to a local coordinate system. Faro FOCUS 130X and Topcon GLS 2000 were used to scan the study area. The scanning parameters include the scanning resolution and the quality. These parameters were chosen based on each scanning location regarding its environment, such as on the ground, in the shaft, and tunnels. TLS point clouds for mine shafts are shown in the Fig. 9.

3D modeling of terrain surface. The model used to represent the terrain of the study area was TIN. The UAV point cloud was separated into two sub-point clouds. The first one was for the open-pit mine, the second one was for the ground surrounding the mine shafts. While the terrain of the open-pit mine was modeled at LOD1, that of the underground mine was modeled at LOD3. The density of the UAV point cloud was 03cm, so it was subsampled to the coarser point cloud with an average distance between points of 20 m

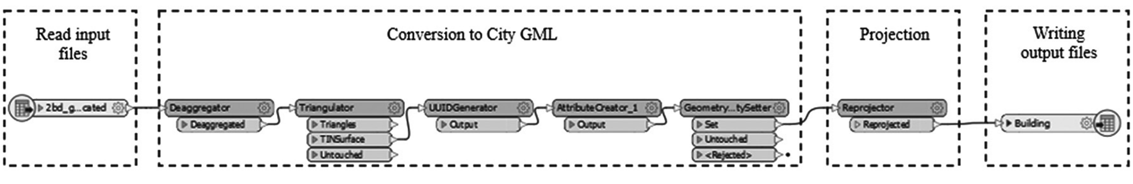

Fig. 4. CityGML conversion process using FME

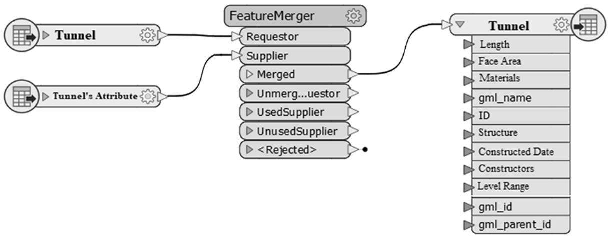

Fig. 5. Attribute addition for CityGML models using FME

Table 1

Definition of tunnel attributes

Name	Type	Cell Width	Value
ID	xml_16int	20	1
Name	xml_char	50	Transportation
Structure	xml_char	50	Tunnel
Constructed Date	xml_date	20	June 2015
Constructors	xml_char	50	VINCOMIN
Material	xml_char	50	Steel
Level Range	xml_char	20	-350
Length	xml_decimal	20	356.85

Table 2

Hardware platform specifications used in the study

CPU	X86-64 Intel CPU with 32+ cores
Graphics Card	NVIDIA graphics card supporting OpenGL 4.5+ and display output with 4GB+ VRAM
Monitor	A display with at least 1920×1080 resolution
Driver	4TB+ NVMe drive
RAM	128GB+ of high-speed RAM

(equivalent to the required point density of 1 : 1,000 topographic mining maps (ref to Vietnam standard for mine surveying). The main feature of an open-pit coal mine is terrain with benches. Therefore, the terrain is the main feature to be 3D modeled for the open-pit part of the mine. According to the VN standard for mine surveying, the scale of mining topographic maps is 1 : 1,000 which requires the density of

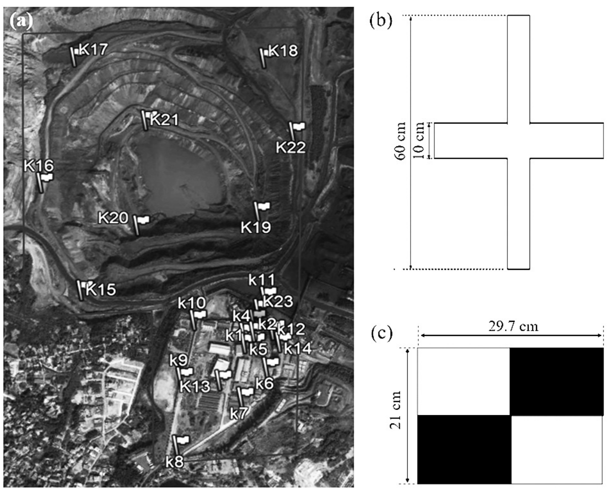

Fig. 6. Ground control points for UAV survey and TLS:

a – distribution of GCPs; b – cross-shaped markers placed on the ground for UAV; c – chessboard for TLS

Fig. 7. Measurement of GCPs using the GNSS/T300 receiver

Table 3

Flight planning parameters

Flight modes	Flight height, m	Photo resolution GSD, cm	Overlay forward–side, %	Camera angle
GRID	100	2.74	75–75	90°
Double GRID	100	2.74	80–80	45°
Circular	50–80	0.5	80–80	45 and 60°

Table 4

Result of UAV data collection

Flight modes	Number of missions, m	Number of photos	Photo Resolution GSD, cm
GRID	5	1,030	2.74
Double GRID	1	219	2.74
Circular	3	257	0.5

Table 5

Errors of CPs

Point name	Error, cm				Location
	Δ*X*	Δ*X*	Δ*XY*	Δ*Z*	
K2	–0.5	0.8	0.9	1.1	Winding tower facades
K7	–1.5	1.8	2.3	–2	Ground surrounding winding towers
K9	0.9	1.7	1.9	1.8	
K23	–2.7	–1.5	3.1	–1.9	
K16	1.9	1.3	2.3	–2.5	Open-pit terrain
K20	–3.1	3.3	4.5	–4.2	
K22	–1.8	–1.5	2.3	–3.1	

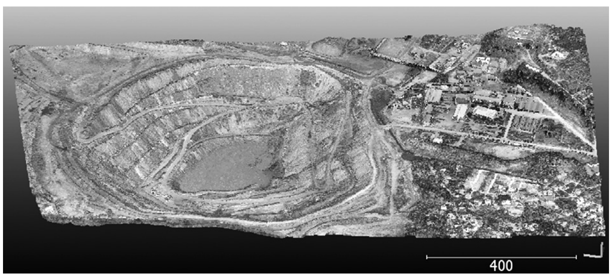

Fig. 8. UAV point cloud of the study area

points of 20 m per point. In fact, the terrain surrounding the mine shafts is flat and simple, therefore, the density of point cloud for the ground surface in this area is not high. The

Fig. 9. TLS point clouds for mine shafts (shown in RECAP software)

UAV data processing using Agisoft Metashape resulted in 148 million points with the reconstruction quality of medium which implies processing photos with the original image size downscaling by factor of 4. However, with the image resolution of 0.3 cm, this density of point cloud was enough to obtain detailed and accurate geometry of open-pit mine's terrain. As the requirement of 1 : 1,000 togographic maps for the density of topo points is from 15 to 20 m to have one point, the UAV point cloud was subsampled. The subsampled point cloud has 9,023 points. This point cloud was devided into sub-point clouds for the open-pit mine's terrain and the ground surface surrounding the mine shaft, with 7,915 and 1,108 points, respectively.

3D modeling of underground structures. Underground structures include shafts and tunnels. These structures are different in shape, size, and material. As TLS point clouds were collected from their surface, other size information can be derived from the tape-based measurement and design plans.

The Terrestrial Laser Scanning (TLS) point clouds of these structures were imported into Sketchup and Revit to generate 3D models (Fig. 10). These models were created with the highest level of detail, known as Level of Detail 4 (LOD4). According to [8] at LOD4, not only are architectural models with detailed wall and roof structures of buildings potentially including doors and windows at LOD3 produced, but interior structures of buildings are also added. This means that LOD4 provides a comprehensive representation of the building, including both its exterior and interior architectural details. This level of detail is particularly useful for creating accurate and realistic 3D models of structures. For the underground coal mine, the special mining structures which were 3D modeled include arch steel support (lagging, collar brace), and mine shafts (concrete lining and cage guides).

Creation of CityGML models for open-pit and underground mining features. To generate the CityGML model of mining features, a data conversion process was performed using SAFE FME software. Fig. 11 illustrates the data input which includes two main parts: open-pit terrains and underground structures.

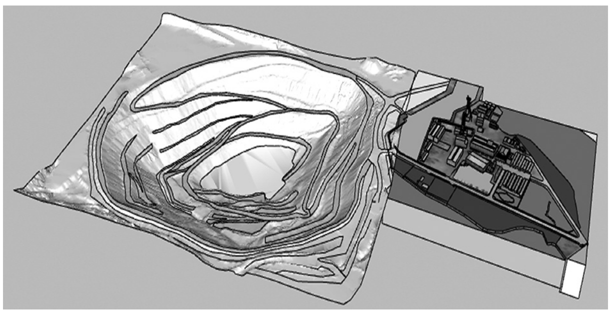

Fig. 10. Overview of 3D models of underground and open-pit mines

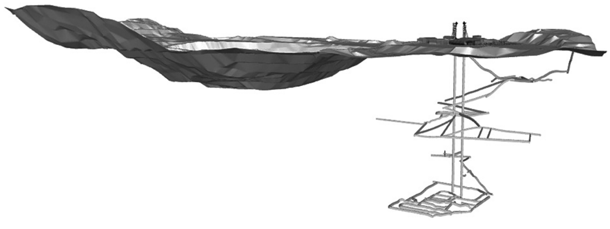

Fig. 11. 3D models of open-pit and underground coal mines

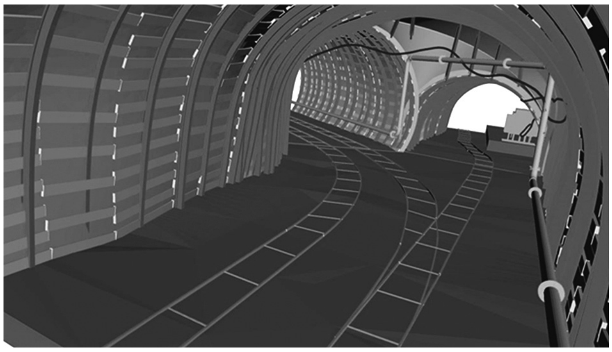

Fig. 12. CityGML model of tunnels with steel frames, pipes, railway tracks, and electrical cabinets

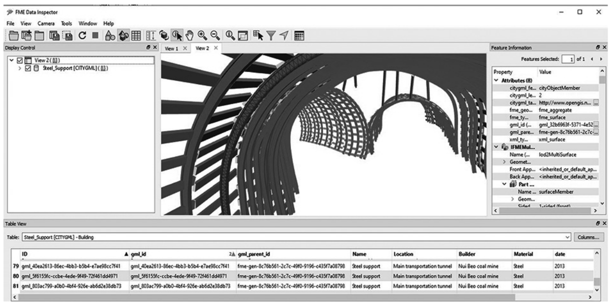

Fig. 13. Attribute of transportation tunnel

After reading the input data, 3D models of buildings, tunnels, and other mining facilities are converted into CityGML using the following transformers using FME software: Deaggregator, Triangulator, IDGennerator, AttributeCreator, and GeometryPropertySetter, before being projected to the local coordinate system. Fig. 12 shows the CityGML model of tunnels and their facilities.

The 3D GIS model of the mine allows users from different labor units to access the information they want. For example, mining engineers may enquire about important information about the tunnel's frames. Fig. 13 illustrates the specification inquiry of frames, with some information, such as material, location, and construction date. Meanwhile, electric-mechanic engineers can quickly get some information about electrical cabinets placed in ventilation tunnels (Fig. 14). In addition, the attribute of railway tracks built in transportation tunnels can be stored and enquired about (Fig. 15). These examples have proved that the 3D GIS of the mine is able to quickly provide both spatial and attribute information to mine operators. In comparison with the Building Information Model (BIM) which is widely used in the field of construction [28] and recently applied in mines [29], this 3D GIS model provides geographical information on mining features; meanwhile, their level of detail and accuracy is the same as that of BIM. This is because these models are built using TLS point clouds which are commonly used to build BIM models. In addition, these CityGML models can be integrated with city models which have been increasingly common [30], as they share the same standard.

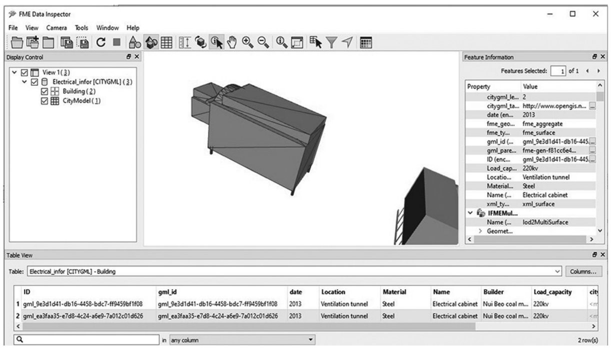

Fig. 14. Attribute of facilities in the tunnel

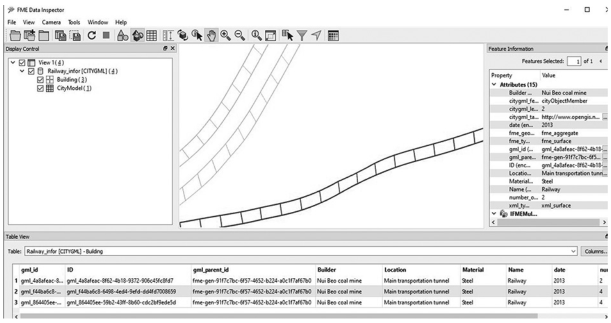

Fig. 15. Attribute of railway tracks in the transportation tunnel

To present these models as the above Figures, the FME Data Inspector software was used. This software allows users to view CityGML models with their both geometric and attribute features.

Conclusions. In this paper, the 3D GIS model of a coal mine that operated by both underground and open-pit methods was created using the CityGML standard. For the data collection, UAV and TLS were used to capture data for open-pit and underground coal mines, respectively. The accuracy assessment of this data was performed to ensure its accuracy requirements. The processing of data resulted in UAV and TLS point clouds.

Based on these point clouds, 3D models of mining structures were created using Sketchup and REVIT before converting into the CityGML standard using FME SAFE software. Finally, the attribute of objects was added to their CityGML models. For the level of detail of 3D models, LODs 1 and 3 were selected for the terrain of the open-pit mine and the ground surface surrounding the underground mine's shafts, respectively. As there are no surface features, such as buildings and vegetation on the open-pit mine, there is no need for storing information about the boundary and location of these objects. Therefore, LODs 2 and 3 are not necessary. However, many surface structures are on the ground where the mine shaft is located, so LOD 2 or 3 is necessary. In addition, the density of UAV point clouds for the terrain influences the accuracy of the terrain and its details. For mining structures, LODs 3 and 4 were used as they are at a high level of complexity. In addition, these levels of detail can satisfy both the management and operation requirements of the mine.

In general, while the CityGML standard is popular in the field of digital twins as it has been widely used for building 3D city models, this study provides a solution to build a 3D GIS model for the management of both open-pit and underground mines using the CityGML standard. With the utilization of UAV and TLS technologies for collecting data, this solution ensures a high level of detail and accuracy for the model. In addition, while digital twins with 3D city models have been increasingly common, this solution provides the information model that is able to be integrated into 3D city models, especially for mining towns as they are some of the important parts of the real world.

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Використання стандарту CityGML для 3D ГІС підземних і відкритих гірничих виробок

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Мета. Дослідження спрямоване на вирішення проблем, пов'язаних з інтеграцією різних методів, з акцентом на методах збору даних і рівні деталізації (LoD), що полегшує створення детальних 3D-моделей. Стандарт CityGML використовується завдяки його здатності відображати складні міські об'єкти, адаптовані до умов гірничодобувної галузі.

Методика. Поєднання технологій безпілотних літальних апаратів (БПЛА) і технологій наземного лазерного сканування (TLS) для збору даних про відкриті та підземні вугільні виробки. Ці дані обробляються для створення хмар точок, що потім використовуються для створення 3D-моделей гірничих споруд за допомогою Sketchup та REVIT. Зрештою, ці моделі будуть перетворюватись у стандарт CityGML за допомогою програмного забезпечення FME SAFE.

Результати. Завдяки використанню безпілотних літальних апаратів і технологій наземного лазерного сканування отримані точні дані хмари точок для відкритих і підземних споруд. CityGML слугує зручним середовищем для цифрового представлення виробок, пропонуючи стандартизовану організацію даних та обмін ними. Запропонована методологія оптимізує процедури збору та обробки даних, забезпечуючи точність і ефективність створення моделей. Зокрема, у дослідженні представлено детальний підхід до вибору LoD,ураховуючи складність і специфічні вимоги різних гірничодобувних структур.

Наукова новизна. Робота інноваційно поєднує технології БПЛА та TLS зі стандартом CityGML для створення комплексних 3D ГІС-моделей вугільних виробок, що працюють як відкритим, так і підземним способами, вирішуючи унікальні проблеми моделювання різноманітних гірничих структур і особливостей рельєфу місцевості.

Практична значимість. Полягає в наданні системного підходу з використанням технологій БПЛА і TLS у поєднанні зі стандартом CityGML для створення точних 3D ГІС-моделей вугільних виробок. Ця методологія підвищує ефективність управління шахтами й кар'єрами, точність оцінки ресурсів і можливості оцінки безпеки.

Ключові слова: *кар'єр, шахта, CityGML, 3D ГІС, БПЛА, TLS*

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