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Accuracy Assessment of Unmanned Aircraft Systems for Volumetric Estimation in Quarries

Avaliação da precisão de Sistemas de Aeronaves Não Tripuladas aplicado à estimativa volumétrica em pedreiras

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Abstract: This study proposes a methodology using UAS-based surveys for volume calculations, applied to scenarios such as tailings stacking, landfills, road cuts, and other material disposal methods commonly used in engineering. It also compares this approach to a traditional method based on conventional topographic surveys. UAS have been increasingly adopted for volume calculations, offering potential benefits such as operational efficiency and reduced risks during data collection.
A case study was conducted at the Anápolis Quarry, employing two distinct survey methods: conventional topography and UAS-based photogrammetry. Metrics such as precision, error rates, and computational resources were evaluated, with Ground Control Points (GCPs) playing a key role in ensuring accuracy. The surfaces were modeled using QGIS and Surfer software, and the results were compared to assess the methodologies. This study provides insights into the applicability of UAS technology for volumetric analyses in engineering contexts.

Keywords: Volume calculation; Ground Control Points (GCP); Digital elevation model (MDE).

Resumo: Este estudo propõe uma metodologia utilizando levantamentos baseados em UAS para cálculos de volume, aplicada a cenários como empilhamento de rejeitos, aterros, cortes de estrada e outros métodos de disposição de materiais comumente utilizados na engenharia. Também compara essa abordagem com um método tradicional baseado em levantamentos topográficos convencionais. Os UAS têm sido cada vez mais adotados para cálculos de volume, oferecendo benefícios potenciais como eficiência operacional e redução de riscos durante a coleta de dados.
Um estudo de caso foi conduzido na Pedreira de Anápolis, empregando dois métodos distintos de levantamento: topografia convencional e fotogrametria baseada em UAS. Métricas como precisão, taxas de erro e recursos computacionais foram avaliadas, com os Pontos de Controle no Solo (GCPs) desempenhando um papel fundamental para garantir a precisão. As superfícies foram modeladas utilizando os softwares QGIS e Surfer, e os resultados foram comparados para avaliar as metodologias. Este estudo fornece informações sobre a aplicabilidade da tecnologia de UAS para análises volumétricas em contextos de engenharia.

Palavras-chave: Cálculo de volume; Pontos de Controle no Solo (GCP); Modelo digital de elevação (DEM).

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1. Introduction

This study proposes a methodology for volume calculation in several engineering applications, with emphasis on surveys conducted using Unmanned Aircraft Systems (UAS). The proposed approach may be applied to tailings stockpiles, embankments, road cuts, and other general engineering demands, which are essential practices for the planning, execution, and monitoring of construction works. These activities directly influence the efficiency, safety, and sustainability of engineering projects. Although conventional topography is widely established as a high-precision method, it faces logistical and safety challenges in dynamic and risk-prone environments, such as mining fronts and stockpiles in quarries. In this context, photogrammetry based on Unmanned Aircraft Systems (UAS/UAV) has emerged as a viable alternative, driven by the development of the Structure from Motion (SfM) algorithm. SfM enables high-resolution three-dimensional reconstruction from overlapping images, without strict dependence on predefined camera parameters (Deliry & Avdan, 2021).

Additionally, the density of information captured by UAS is substantially higher. While conventional surveying is based on the sampling of discrete points, aerial imaging generates dense point clouds and Digital Surface Models (DSMs) with high spatial resolution, which Zhang et al. (2023) characterize as a qualitative leap in terrain interpretation. As a result, the generation of orthomosaics and multispectral 3D models significantly expands the capacity for data visualization and analysis (Silva & Oliveira, 2024).

The increasing adoption of Unmanned Aircraft Systems (UAS) in topography and engineering has reinforced the need for robust methodologies to validate the accuracy of collected data, especially in dynamic environments such as active quarries, as noted by Thammaboribal (2026). Recent studies, such as that of Yiğit and Senol (2025), demonstrate the application of UAV photogrammetry and geospatial analysis to quantify surface changes and assess risk factors in quarries, highlighting the importance of rigorous validation to ensure the reliability of the results. However, the literature still lacks investigations that systematically compare the results obtained by conventional topography and UAS in active quarries, with irregular surfaces and real operational conditions, particularly regarding the absolute and relative accuracy of the generated models (Thammaboribal, 2026).

Therefore, while traditional methods using Total Stations remain essential for staking out and positioning activities that require millimetric precision, the use of UAS has become established as a highly efficient and disruptive tool, capable of meeting the demands for agility and level of detail in an increasingly dynamic and technology-driven engineering sector (Brown et al., 2025).

In this sense, the use of UAS for volume estimation has shown promising results in several studies. For example, Jiang et al. (2022) proposed an automated methodology for the management of construction and demolition waste, applied to construction sites, landfills, and illegal dumping areas. This approach integrated UAS-based SfM photogrammetry, deep learning, and Geographic Information Systems (GIS) for surveying, detection, measurement, and management of waste-related information. In that study, experiments conducted at illegal dumping sites demonstrated the effectiveness of the methodology for waste detection and quantification, highlighting benefits such as the acquisition of quantitative and geographic information to support municipal governments in the intelligent management of these disposal areas (Jiang et al., 2022).

Although previous studies have demonstrated the feasibility of UAS-SfM for volumetric estimation in controlled or small-scale environments, there is still a lack of investigations that systematically compare the results obtained through conventional topography and UAS in active quarries, with irregular surfaces and real operational conditions. Additionally, this study contributes by proposing a methodology that considers the reconstruction of original surfaces, whether pre-excavation or pre-filling, when original topographic data are not available. This is a frequent challenge in projects involving the recovery of mined areas or the calculation of environmental liabilities.

Addressing this gap is relevant because it validates, using real field data, whether the accuracy of UAS is sufficient for engineering purposes, such as mass balance closure. It also provides the technical community with a practical and accessible method for estimating historical volumes without relying on previous surveys. Furthermore, it contributes to the standardization of good practices in UAS-based photogrammetry for volumetric applications, an area that still lacks widely accepted protocols. Reinforcing this trend, the study developed by Jiang et al. (2022) presented significant advances in the automation of volumetric monitoring at construction sites and disposal areas. The authors integrated Structure from Motion (SfM)-based photogrammetry with deep learning algorithms and Geographic Information Systems (GIS) to manage construction and demolition waste. The methodology enabled not only accurate volumetric estimation, but also automated detection and geographic mapping of materials. The results showed that the combination of UAS and artificial intelligence overcomes the limitations of conventional visual inspection and manual topographic methods, offering intelligent and real-time management, which is essential for urban planning and environmental compliance (Jiang et al., 2022).

Furthermore, according to the study by Deliry and Avdan (2021), Accuracy of Unmanned Aerial Systems Photogrammetry and Structure from Motion in Surveying and Mapping: A Review, the use of SfM-based photogrammetry has gained prominence as a viable alternative for volumetric surveys due to its low cost and rapid generation of results. According to the aforementioned review, Hugenholtz et al. (2014) applied this technique to calculate the volume of a gravel stockpile using images with a resolution of 3.5 cm. The results were validated using RTK-GPS, indicating that the UAS method generated a Digital Elevation Model (DEM) with a vertical accuracy of 0.10 m. The volume difference between the models generated by UAS and DGPS was approximately 3.2%. These results indicate that the UAS-SfM technique can achieve levels of accuracy higher than airborne LiDAR, although still lower than those obtained with TLS, or Terrestrial Laser Scanning. In the same review, Cryderman et al. (2014) were also cited for investigating the accuracy of SfM photogrammetry in volumetric surveys. When comparing the results with GNSS survey data, the models generated using the UAS method showed accuracy equivalent to that obtained with GNSS RTK surveys, considering a 95% confidence level. According to the standards established by the American Society for Photogrammetry and Remote Sensing (ASPRS), the obtained accuracies, RMSEXY = 0.039 m and RMSEZ = 0.044 m, were classified as suitable for mapping at a scale of 1:200 (ASPRS, 2014).

In light of this promising evidence and the increasing dissemination of UAS use, the incorporation of additional case studies can significantly contribute to the validation of the methodology by the scientific community. Moreover, such studies allow for a broader understanding of the behavior of different survey methods in several applications, such as road embankments, aggregate stockpiles, tailings stockpiles, and other forms of material disposal widely used in engineering.

The general objective of this study is to compare the accuracy and efficiency of volumetric surveys performed using conventional topography and UAS-based photogrammetry, taking as the object of analysis an active quarry located in Anápolis, Goiás, Brazil, with data collected in September 2024. To support this comparison, the research seeks to quantify volumetric discrepancies between both methods in stockpiles and excavated areas, validating the positional accuracy of the digital model generated by UAS against Ground Control Points (GCPs). Additionally, this study proposes and tests a methodological procedure for estimating original surfaces, whether pre-excavation or pre-filling, in scenarios where original topographic data are unavailable. Finally, it aims to document a replicable and integrated workflow, covering all stages from image acquisition to the final volume calculation, using Agisoft Metashape, QGIS, and Surfer software.

2. Methodology

The methodology adopted in this study was based on a volumetric comparison between two different surveys conducted at the Anápolis Quarry, located in Goiás, Brazil: a conventional topographic method and a photogrammetric survey performed using an Unmanned Aircraft System (UAS). Initially, the cadastral/topographic survey was carried out in June 2024, based on 11 cross sections spaced every 25 meters (Figure 1, Table 1), resulting in a calculated volume of 2,117,824.30 m³. Subsequently, in September 2024, the aerial survey was conducted at a flight height of 184 m, with a ground sampling distance (GSD) of 5.89 cm/px. To validate the accuracy of the model, the Reprojection Error and RMSE (Root Mean Square Error) metrics were adopted.

(Equation 1):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y_i})^2}$$

The reprojection error quantifies the geometric accuracy of image alignment (James et al., 2017), whereas RMSE assesses the discrepancy between estimated and reference coordinates (ASPRS, 2014). The operation covered an area of 1.23 km² through the acquisition of 420 images, presenting robust overlap, as indicated in the overlap map (Figure 1). Most of the central area was covered by more than nine images per point, ensuring longitudinal and lateral overlap rates greater than 70–80%, which are essential for redundancy in mining areas.

Data processing was performed using Agisoft Metashape Professional software, version 1.8.3. For the initial image alignment stage, based on Structure from Motion (SfM), medium accuracy was adopted, along with reference preselection based on source data. The processing parameters were set to 40,000 key points and 4,000 tie points. This process resulted in the generation of 313,907 tie points, with a reprojection error of 2.03 px, and was completed in approximately 24 minutes and 43 seconds. The processing was carried out on a workstation equipped with a Machinist PR9 motherboard, an Intel Xeon E5-2640 v3 processor, 48 GB of DDR4 RAM, an RX 550 graphics card with 4 GB of memory, and a 120 GB SSD. This hardware configuration, combined with the adopted processing parameters, ensured adequate performance for generating the Digital Elevation Models (DEMs), providing the accuracy required for the comparative volumetric analysis.

To ensure comparability between the methods, the same interpolation points used in the conventional survey were applied to the UAS-based survey in Surfer software. Both datasets were processed in QGIS, where Digital Elevation Models (DEMs) were generated. Subsequently, representative interpolated surfaces of the area surrounding the quarry were created using Surfer, in order to provide greater fidelity to the terrain model. These surfaces were considered an approximation of the terrain prior to excavation.

After generating the interpolated surfaces, the volumes corresponding to the areas of interest were calculated for each method. This approach enabled a comparative analysis between the two surveys, assessing their accuracy, efficiency, and potential discrepancies in the results.

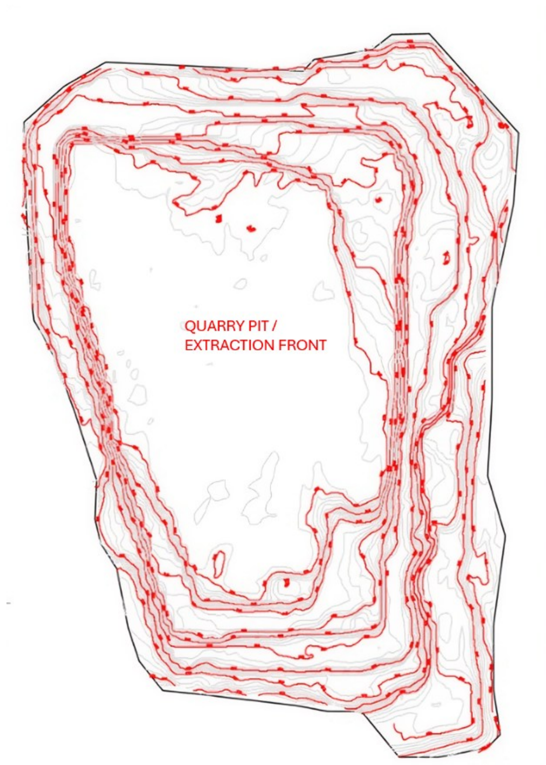

Figure 1 – Cadastral survey – June 2024.
Source: Authors (2024).

Table 1 – Extracted volumes from the cadastral survey – June 2024.

Volumes Extraídos			
Section	**Distance (m)**	**Spacing (m)**	**Volume of extracted material (m³)**
S1	45,561	0.000	0.0
S2	70,561	25,000	83,347.00
S3	95,561	25,000	283,624.20

S4	120,561	25,000	567,751.10
S5	145,561	25,000	883,778.60
S6	170,561	25,000	1,204,412.50
S7	195,561	25,000	1,522,154.90
S8	220,561	25,000	1,822,304.80
S9	245,561	25,000	2,024,012.20
S10	270,561	25,000	2,102,035.90
S11	295,561	25,000	2,117,824.30

Source: Authors (2024).

In the UAS survey, the SIRGAS 2000 / UTM Zone 22S coordinate reference system was used (EPSG: 31982). The initial point cloud contained 341,648 points, of which 313,907 were retained after processing, with an RMS reprojection error of 0.261921, corresponding to 2.02632 pixels. The generated dense point cloud consisted of 28,312,699 points, using 3.20 GB of memory and requiring a processing time of 15 minutes and 28 seconds in Agisoft Metashape Professional, version 1.8.3. The generated Digital Elevation Model (DEM) had dimensions of 10,645 × 8,671 pixels, with a file size of 6.09 GB, and was processed in 16 minutes and 35 seconds, using 1.04 GB of memory. Processing was performed on a system with 15.85 GB of RAM, an Intel Xeon E5-2640 v3 processor at 2.60 GHz, and a Radeon RX550/550 Series GPU (Figure 2).

Figure 2 – Orthomosaic of the Quarry under Study.
Source: Authors (2024).

For the data collection carried out on September 22, 2024, a DJI Mavic Pro UAS equipped with an FC220 camera, with a focal length of 4.73 mm, was used. The flights were conducted at an average height of 184 meters, resulting in the acquisition of 420 images (Figure 3) and covering an area of 1.23 km². To ensure survey accuracy and image georeferencing, a CHC NAV i50 GNSS receiver was used. This high-precision equipment is capable of providing real-time RTK data, thereby ensuring the quality of the ground control points and the accuracy of the geographic coordinates. The spatial resolution obtained was 5.89 cm/pixel, while the mean reprojection error of the generated models was 2.03

pixels. The model reconstruction errors were graphically represented by ellipses, in which the color of the ellipses indicates the errors associated with the Z coordinate, or elevation, and the shape of the ellipses represents the errors in the X and Y coordinates, corresponding to horizontal location. Additionally, the estimated camera positions during the survey were marked by black dots, allowing a visual analysis of the spatial distribution of errors and image capture positions in the generated model (Figure 3).

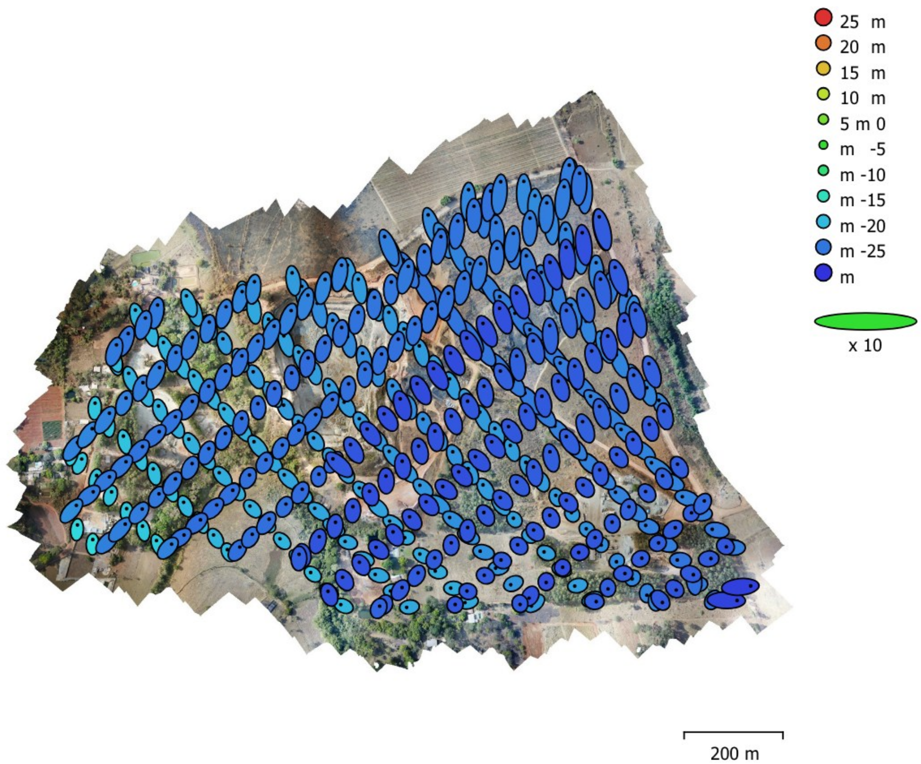

Figure 3 – Camera positions and estimated errors.
Source: Authors (2024).

Table 2 presents the mean camera location errors estimated during processing. The mean errors in the horizontal coordinates, X and Y, were 1.18819 m and 2.50389 m, respectively, resulting in a combined XY error of 2.7715 m. In contrast, the mean error in the Z coordinate, corresponding to altitude, was higher, reaching 19.5297 m, which contributed to a total error of 19.7253 m. These values highlight the difference in accuracy between the horizontal and vertical dimensions, reflecting the influence of factors such as the quality of the digital terrain model and sensor calibration during the survey.

Table 2 – Mean camera location error.

Mean camera location error				
X Error (m)	**Y Error (m)**	**Z Error (m)**	**XY Error (m)**	**Total error (m)**
1.18819	2.50389	19.5297	2.7715	19.7253

Source: Authors (2024).

Furthermore, it is important to highlight the role of Ground Control Points (GCPs) in this UAS survey for obtaining images with higher accuracy and precision. GCPs are widely used to correct positional information in images acquired by

UAS. For this purpose, they are distributed throughout the area of interest, and their coordinates (x, y, z) are measured using high-precision equipment, such as RTK-GNSS systems. Before image acquisition, visible markers are placed over the GCPs to facilitate their identification in the aerial photographs. Subsequently, the correct coordinates of these points are entered into the photogrammetry software, allowing the accurate adjustment of image positions through the bundle adjustment process (Taddia; Stecchi; Pellegrinelli, 2020).

In the survey conducted in this study, 20 Ground Control Points (GCPs) were used. Most of these points, approximately 15, were concentrated in the main area of interest, referred to as the quarry area. Additionally, three control points, numbered 16, 17, and 18, were distributed within the processing area, while two other points, numbered 19 and 20, were positioned in a more distant area, as shown in Figure 4. The errors associated with the Z coordinates are represented by the color of the ellipses, whereas the errors in the X and Y coordinates are indicated by the shape of the ellipses. Finally, the estimated locations of the GCPs are marked by points or crosses in the model.

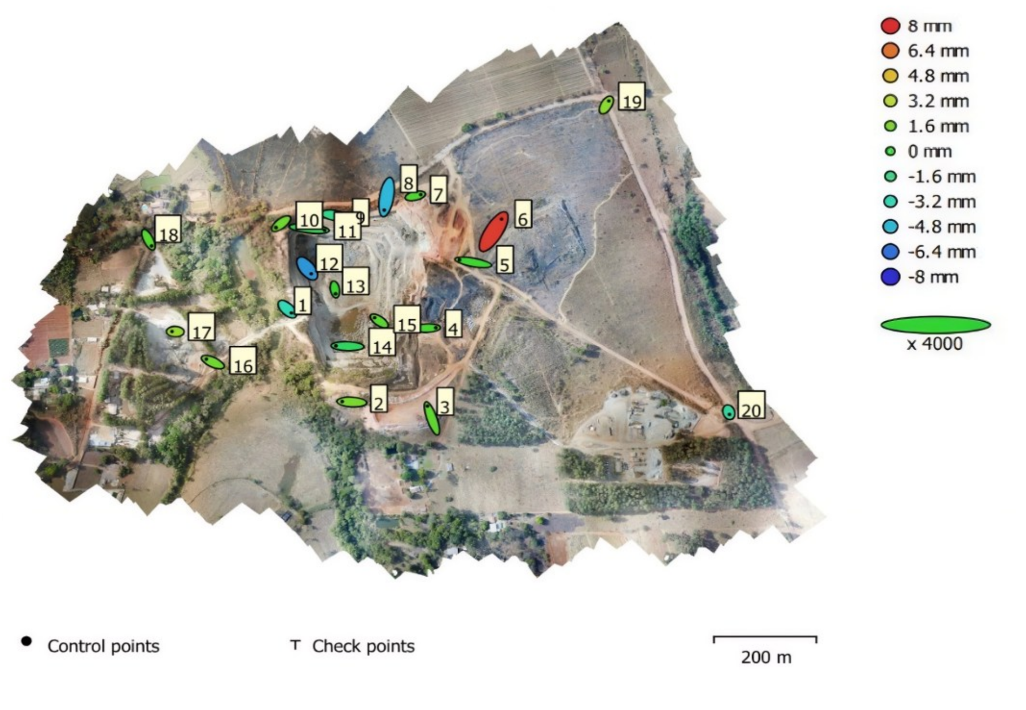

Figure 4 – Ground control point locations and estimated errors.
Source: Authors (2024).

Table 3 presents the Root Mean Square Error (RMSE) values for the ground control points used in the survey. The mean errors in the X and Y coordinates were 7.03 mm and 6.02 mm, respectively, resulting in a combined XY error of 9.26 mm. The error associated with the Z coordinate, corresponding to altitude, was 2.81 mm, indicating higher vertical accuracy compared with the horizontal coordinates. The total error, which integrates all dimensions, was 9.68 mm.

Table 3 – RMSE values for the ground control points.

RMSE					
Count	**X Error (mm)**	**Y Error (mm)**	**Z Error (mm)**	**XY Error (mm)**	**Total (mm)**
20	7.0358	6.02461	2.81721	9.26274	9.68169

Source: Authors (2024).

The generated Digital Elevation Model (DEM) presented a spatial resolution of 23.6 cm/pixel (Figure 5). According to Mandlburger et al. (2016), resolutions of approximately 25 cm/pixel are considered suitable for engineering and urban planning applications. In addition, the point density achieved was 18 points per square meter. In this regard, as indicated by Vosselman et al. (2010), a minimum density of 10 points/m² is recommended for high-accuracy models. These values indicate that the DEM produced is within the standards recommended by the aforementioned bibliographic references.

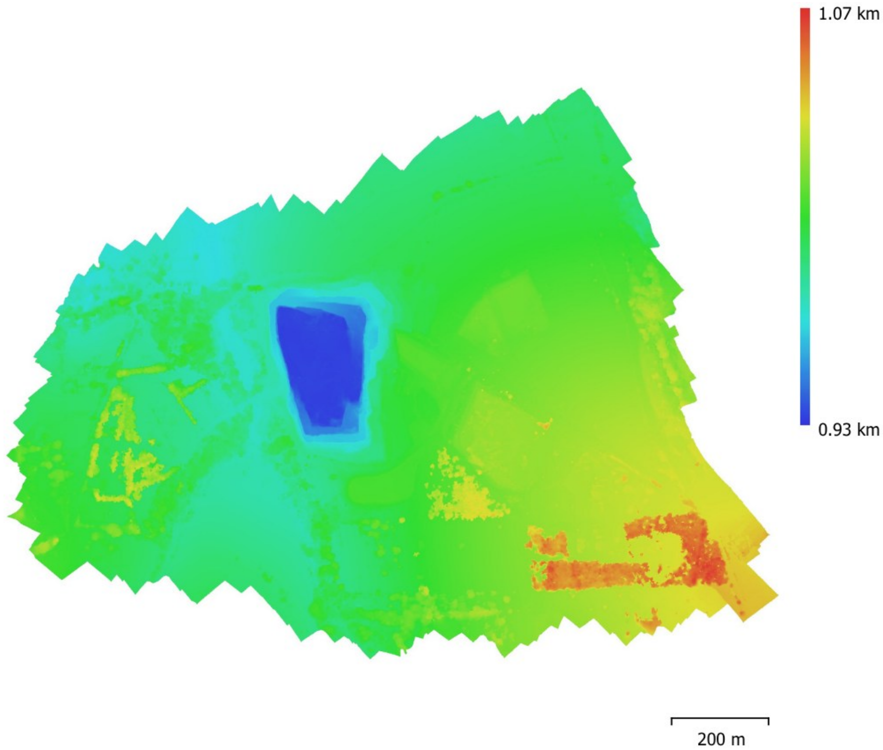

Figure 5 – Digital Elevation Model.
Source: Authors (2024).

To precisely delimit the quarry area, QGIS software was used, allowing the analysis of georeferenced data and a detailed assessment of the topographic characteristics of the region. Figure 6 shows the delimitation of the study area, which covered approximately 25 hectares.

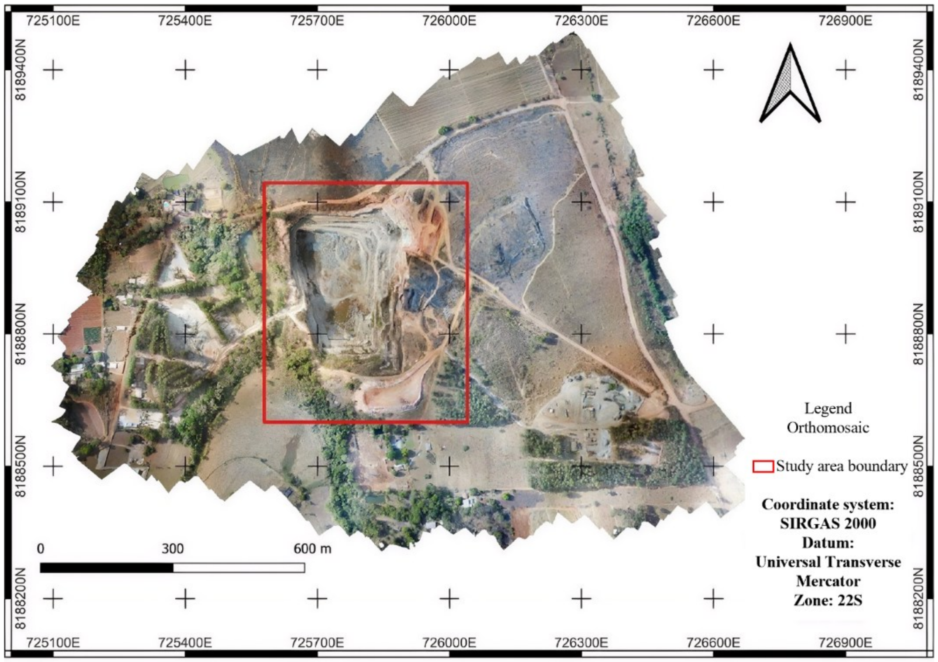

Figure 6 – Delimitation of the study area using QGIS software.
Source: Authors (2024).

Using the data acquired by the UAS, QGIS software was used to generate the points corresponding to the coordinates of the area of interest, namely the quarry area. Subsequently, these points, together with those obtained from the conventional topographic survey, were used in Surfer software to model the terrain surface.

The choice of Kriging interpolation for reconstructing the original surface, instead of other interpolators such as Triangulated Irregular Network (TIN), was based on the need to model the terrain trend in areas where sample data were restricted to the boundaries. Although TIN is effective for representing local features and is frequently used with dense point clouds generated by photogrammetry, it produces a faceted surface that may not be ideal for estimating a continuous and smooth original morphology in areas that were not directly sampled (Cheng et al.). Kriging, in turn, is a geostatistical method that models the spatial autocorrelation of the data and, importantly, provides an estimate of the error associated with prediction, known as Kriging variance. This is essential when reconstructing an unsampled original surface. This approach is consistent with reference studies such as Zarychta et al. (2020), who validated the use of Kriging to reconstruct pre-extraction morphologies in quarries. Although the high point density generated by photogrammetric surveys may enable other strategies, such as the direct generation of Digital Elevation Models (DEMs) through triangulation, Kriging proved to be more suitable for the specific objective of estimating the original surface from sparse data restricted to the preserved perimeter.

For the calculation of the excavated volume, it was necessary to determine the original surface of the area of interest. In this context, the methodology adopted in Surfer consisted of selecting points along the boundary of the study area and applying Kriging interpolation using 30 random points located around the area of interest. The number of 30 points was established after preliminary analyses indicated that using fewer or more points resulted in the generation of outliers.

The selection of the 30 points was performed in QGIS based on visual analysis of the orthomosaic and the current Digital Elevation Model (DEM). Points were manually selected along the external perimeter of the pit, in locations where there was no evidence of excavation or deposition of mining tailings and/or waste rock, assuming that the original topography had been preserved. The points were distributed approximately equidistantly around the entire quarry area, ensuring angular coverage. The X, Y, and Z coordinates of these points were extracted from the DEM generated from the UAS survey. In Surfer, Kriging interpolation was configured using a linear semivariogram model. After tests with exponential and spherical models, the linear model showed the best fit to the data. No anisotropy was considered, and the maximum number of neighboring points was set to 12. The same set of points and the same interpolation parameters were applied to both the conventional topographic survey data and the UAS survey data, ensuring the comparability of the results.

The choice of Kriging, instead of other interpolators such as TIN, was based on the nature of the proposed objective: reconstructing the trend surface of the pre-excavation terrain from sample data restricted to the boundaries. TIN interpolation is a deterministic method that connects sample points through straight edges, generating a faceted surface. Although effective for representing local features, this approach may present limitations when the objective is to estimate a continuous surface in areas without well-consolidated sample data.

As discussed by Raza et al. (2023), Kriging is a family of geostatistical methods that, unlike deterministic interpolators, models the spatial autocorrelation of the data and, crucially, provides an estimate of the error associated with prediction, known as Kriging variance. This characteristic was a determining factor in the choice of Kriging in this study, since, when reconstructing an unsampled original surface, it is essential to have a measure of the uncertainty of the estimate, especially in areas farther from the boundary points.

The methodological choice adopted in this study is aligned with reference studies in the field, such as Zarychta et al. (2020), who used Kriging to reconstruct the pre-extraction morphology of the Liban Quarry in Poland based on topographic map data, validating the method through cross-validation and error maps. Other interpolators, such as Inverse Distance Weighting (IDW), were not adopted because they may generate circular artifacts, known as the bull's-eye effect, and do not provide an associated estimate of prediction error (Raza et al., 2023). For these reasons, Kriging was considered the most suitable interpolator for estimating the original surface in this study.

It should be noted that the photogrammetric survey generated a dense point cloud with approximately 28 million points, which would allow the use of other modeling strategies, such as the direct generation of a Digital Elevation Model (DEM) through TIN triangulation from the dense cloud, or even the application of local interpolators such as natural neighbor, which, according to Raza et al. (2023), showed good performance for datasets with high sampling density. However, for the specific objective of reconstructing the original pre-excavation surface, which was not directly sampled, a selection of points exclusively along the preserved perimeter of the quarry area was adopted. In this context of sparse data restricted to the boundaries, Kriging proved to be more suitable than methods that depend on high sampling density or that produce faceted surfaces.

These points were interpolated to create a surface that approximately represented the terrain conditions prior to excavation. To ensure uniformity and consistency in the calculations, the same interpolated points were applied to both the conventional topographic survey and the UAS-based survey. Based on the generated surfaces, it was possible to calculate the volumes from the difference between the original surface and the current surface, allowing a comparison between the results obtained by the two methods. Based on the data acquired, the flowchart presented in Figure 7 summarizes the methodology used in this study, detailing the stages of data collection, processing, and analysis of the surveys performed using UAS and conventional topographic methods.

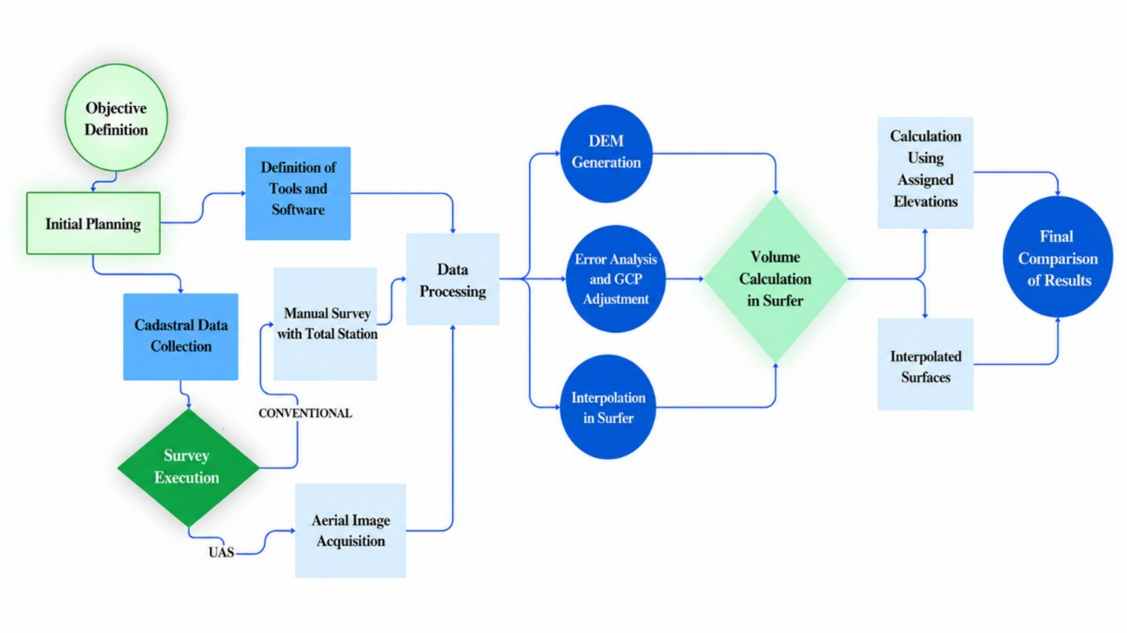

Figure 7 – Flowchart of the methodological steps adopted in the study.
Source: Authors (2024).

3. Results

After processing the digital terrain models, shown in Figures 8 and 9, a slight difference can be observed in the arrangement of the contour lines between the conventional topographic survey and the UAS-based survey. These discrepancies are minimal, indicating a close agreement between the two surveying methods.

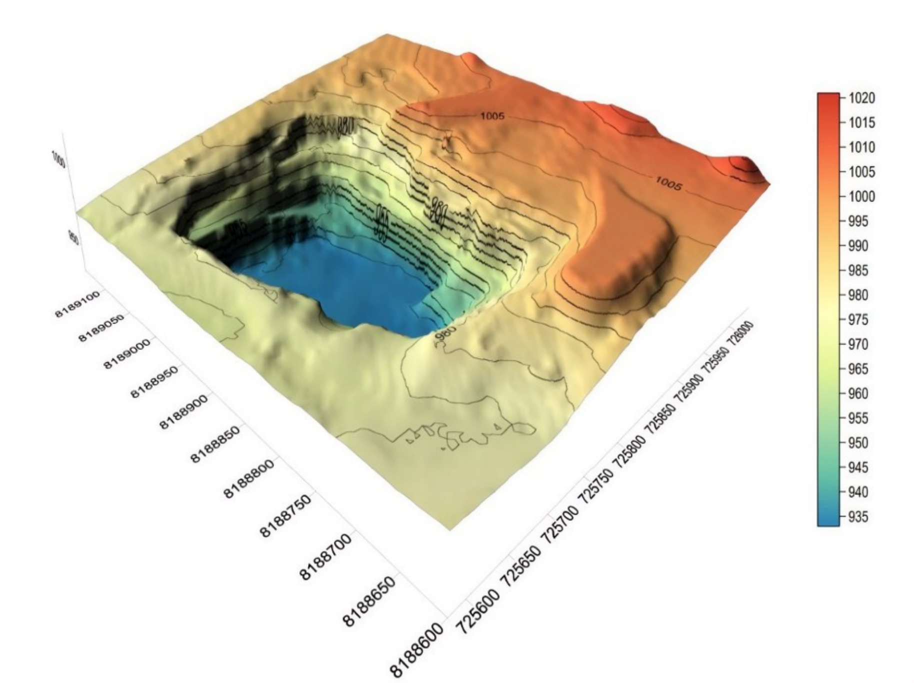

Figure 8 – Digital Terrain Model from conventional topography in Surfer.
Source: Authors (2024).

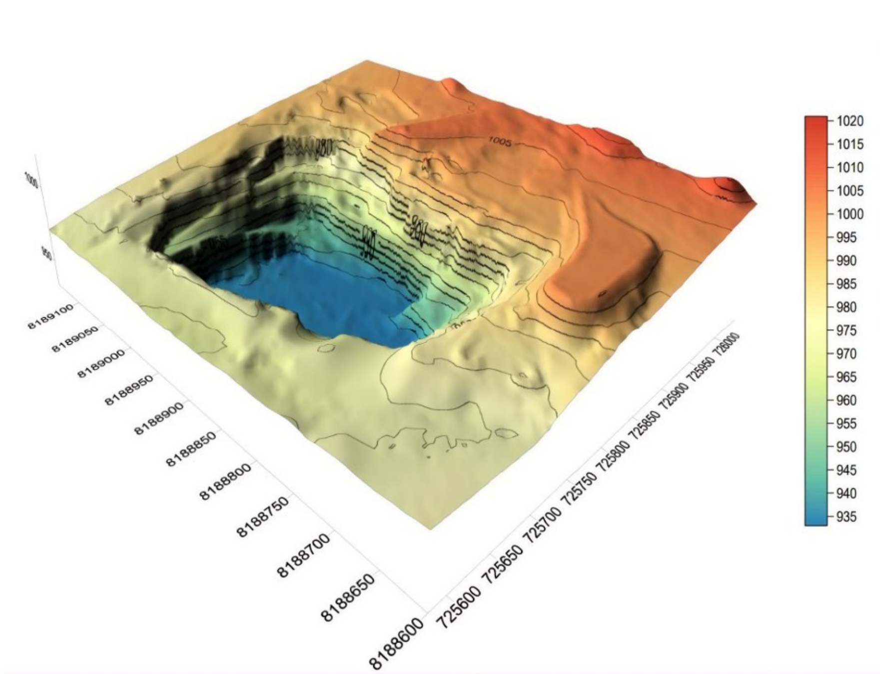

Figure 9 – Digital Elevation Model from the UAS survey using Surfer software.
Source: Authors (2024).

Subsequently, after interpolation, surfaces with adequate smoothing were generated, without the presence of outliers. These surfaces showed evidence of representing elevation trends, with the highest points highlighted in red and the lowest points in blue, emphasizing the altimetric variations of the quarry terrain. This result can be considered a positive aspect of the proposed modeling approach, demonstrating its ability to rapidly capture the general characteristics of the relief (Figures 10 and 11).

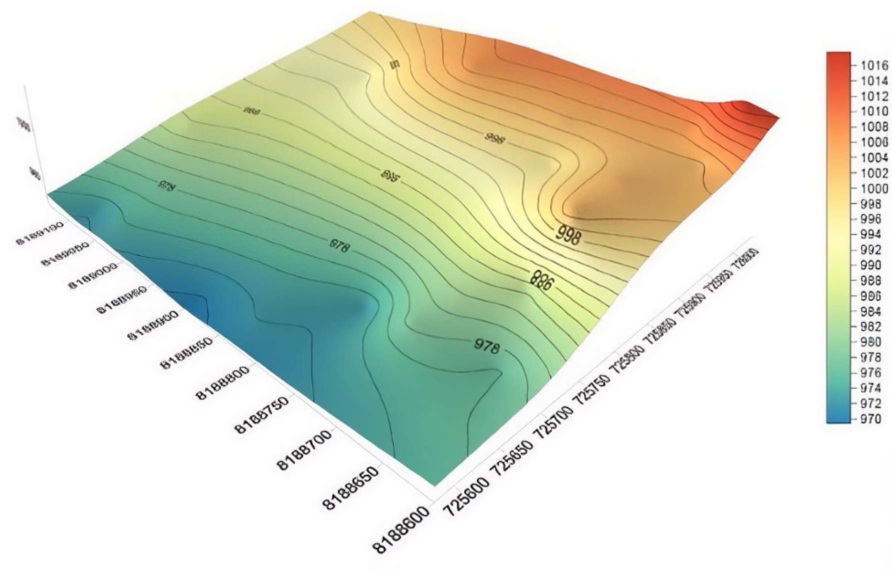

Figure 10 – Interpolated surface generated using Surfer software.
Source: Authors (2024).

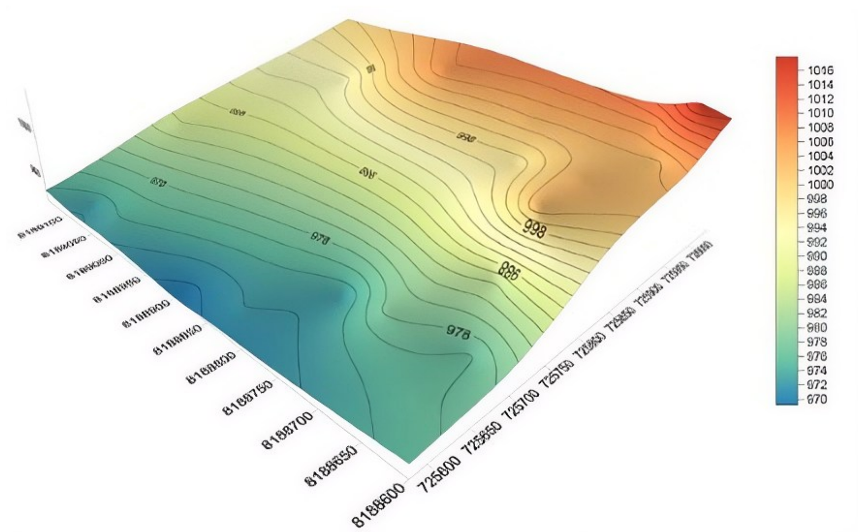

Figure 11 – Interpolated surface from the UAS survey using Surfer software.
Source: Authors (2024).

After analyzing the aforementioned surfaces, an overlay between the digital terrain model and the interpolated surface was performed in order to identify possible discrepancies. As expected, the interpolation produced contours that differed from the original surface (Figures 8 and 9), which became evident in some protruding elevations, as illustrated below (Figures 12 and 13). This result highlights that the proposed interpolation model presents some imperfections inherent to its nature, since its objective is to approximately represent the terrain conditions prior to excavation. However, these limitations do not compromise its effectiveness as a tool for preliminary analyses and approximate estimates.

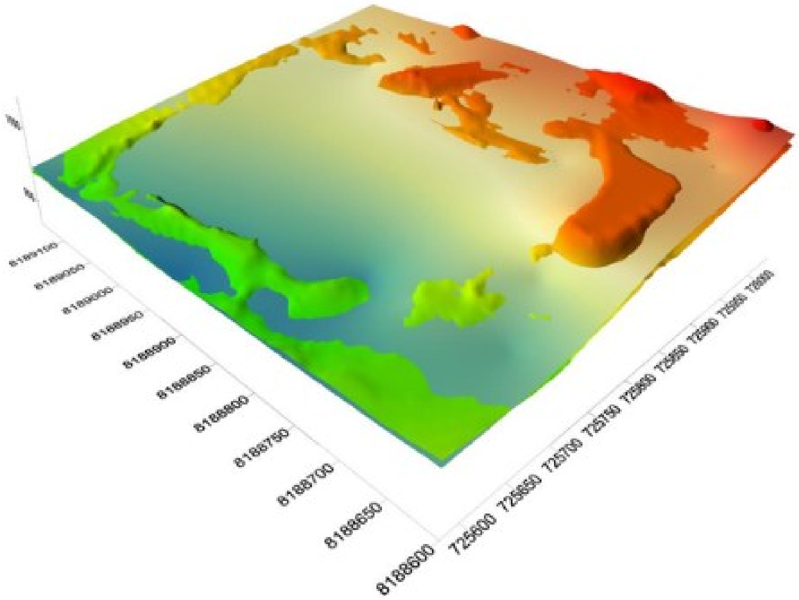

Figure 12 – Overlay between the interpolated surface and the DEM from the conventional topographic survey in Surfer. Source: Authors (2024).

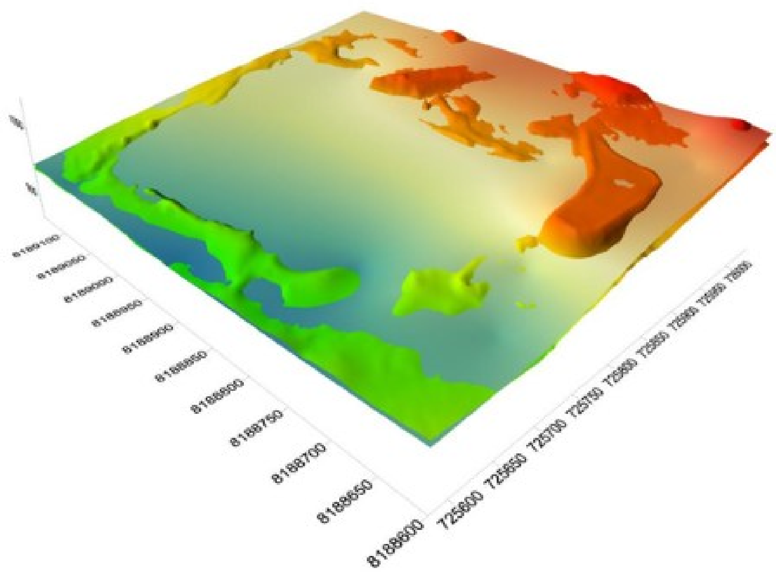

Figure 13 – Overlay between the interpolated surface and the DEM from the UAS survey in Surfer. Source: Authors (2024).

3.1 Comparative Volume Analysis

The reports generated by Surfer software (Appendix I) enabled the comparison of volumes, showing the close agreement between the results obtained from the conventional topographic survey and those generated from the UAS survey. This analysis reinforces the reliability and accuracy of the UAS survey as a viable and effective alternative.

Initially, the fill volumes were calculated using an assigned elevation of 1000. It should be noted that this assigned elevation was used as a methodological resource to standardize the calculation surface in Surfer, allowing a direct comparison between the two models.

In a second comparative analysis, interpolated surfaces were used, representing models that are closer to the original terrain conditions. This approach produced more practical results compared with the methodology based on the assigned elevation, as shown in Table 4.

Table 4 – Comparison of volumes obtained from conventional topography and UAS-based surveying.

Comparison of Estimated Volumes				
Comparative Analysis	**Conventional Topographic Survey**	**UAS Survey**	**Absolute Difference (m³)**	**Relative Percentage (%)**
Fill volume (m³)	5,269,099.27	5,275,239.31	6,140.00	0.10%
Volume using interpolated surfaces (m³)	2,593,055.26	2,598,952.42	5,897.16	0.22%
Cut volume - Cadastral plan (m³)	2,117,824.30	-	-	-

Source: Authors (2024).

The relative difference of 0.22% between the volumes calculated using conventional topography and the UAS survey falls within the range of compatible results reported in the literature for open-pit mining environments. For comparison, Mora et al. (2020) found differences of less than 2% when comparing UAS and TLS data for small-area stockpiles (345 m²). Ajayi and Ajulo (2021) reported an error of 2.3% between the volume estimated by UAS and the actual processed volume, while Kokamägi et al. (2020) obtained variations ranging from 1% to 6%, depending on the number of ground control points used. In contrast, Kuinkel et al. (2023) found errors of approximately 11.9% for very small stockpiles (0.14 m³) and in the absence of GCPs, which reinforces the importance of the control strategy adopted in this study, based on 20 well-distributed GCPs. Table 5 summarizes these comparative results.

Table 5 – Comparative volumetric results.

Comparative results			
Study	**Compared method**	**Volumetric error**	**Area/context**
Present study	UAS vs. topography	0.22%	Quarry (25 ha)
Mora et al. (2020)	UAS vs. TLS	< 2%	3 stockpiles (345 m²)
Ajayi & Ajulo (2021)	UAS vs. weighed material	2.3%	Stockpile
Kokamägi et al. (2020)	UAS vs. TLS/GNSS	1% – 6%	Various stockpiles
Kuinkel et al. (2023)	UAS vs.weighed material	11.9%	Very small stockpile

Source: Authors (2024).

It is worth noting that, when using the cadastral plan from June 2024 as a reference, a cut volume of 2,117,824.30 m³ was measured. When compared with the volumes of approximately 2.6 million cubic meters obtained from the analyzed surveys, these values can be considered reasonably consistent with field conditions, considering that additional extraction likely occurred in the quarry area during the three months following the cadastral survey. This would have resulted in an increase in the total existing cut volume.

Therefore, the proposed methodology shows significant potential for the periodic monitoring of the quarry, enabling continuous tracking of the extracted volumes. In addition, it stands out as a promising initial solution for approximating the original terrain surface, especially in situations where the actual original surface is unavailable or when no topographic survey was conducted at the time.

Unlike the study conducted by Molnar and Domizi (2016), this study did not include the acquisition of the original terrain surface of the quarry, which prevented direct validation and precise comparison with the reported results. In this context, obtaining this surface is identified as an essential next step for improving this study, as it would allow a more detailed comparative analysis consistent with the approach adopted by Molnar and Domizi, as illustrated in the figure below.

Table 6 – Molnar and Domizi (2016, p. 158).

TABLE MOLNAR; DOMOZI, [2016]

-	VOLUME
Original mine model	~32,200 m³
With covering surface moved to the left	~31,500 m³
With covering surface moved to the right	~37,200 m³
Rotated covering surface 1.	~36,100 m³
Rotated covering surface 1.	~41,300 m³

Source: Molnar and Domizi (2016, p. 158).

The table presented highlights discrepancies in some of the models proposed by the authors. In this sense, it can be observed that the model based on the Delaunay algorithm may still be improved. The approach proposed in this study could help address this gap, considering that Surfer software provides smoother surfaces, as demonstrated in Figures 10 and 11.

Additionally, it is important to emphasize an issue pointed out by Molnar and Domizi, related to errors caused by the overlapping and intersection of "faces/triangles." This limitation, in theory, may be mitigated by the methodology proposed in this study, which seeks to overcome such challenges and provide more accurate results.

3.2 Ground Control Points

Before the use of Ground Control Points (GCPs), the estimated errors in the model presented significantly high values, especially in the horizontal and vertical coordinates, compromising the accuracy of the survey. With the inclusion of GCPs and the subsequent bundle adjustment process, the errors were substantially reduced. After processing, the mean errors in the horizontal coordinates, X and Y, were 1.18819 m and 2.50389 m, respectively, resulting in a combined XY error of 2.7715 m. In the Z coordinate, corresponding to altitude, the mean error remained higher, reaching 19.5297 m and contributing to a total error of 19.7253 m.

After processing with ground control points, the survey results demonstrated good overall accuracy, with a total Root Mean Square Error (RMSE) of 9.68 mm. The mean error was 7.04 mm in X, 6.02 mm in Y, and 2.82 mm in Z. The distribution of the GCPs revealed a higher concentration in the central area, which coincided with the lowest error values. In contrast, points located in areas with greater topographic variation, such as points 6, 8, and 12, positioned on the periphery of the quarry area, presented higher errors, especially in the Z coordinate. This variation may be associated with the influence of topography on model accuracy. Nevertheless, the errors obtained are within acceptable limits reported in the literature. According to Deliry and Avdan (2021), quantitative analyses indicate that the predominant vertical RMSE ranges from 0.04 to 0.06 m, meeting the Class 3 mapping standard of the ASPRS, American Society for Photogrammetry and Remote Sensing (2014). The authors emphasize that these accuracy levels are suitable for several engineering and GIS applications, reinforcing the quality of the survey conducted. These results also highlight the importance of GCPs in improving the overall accuracy of the model.

However, a methodological limitation of this study must be acknowledged: all 20 Ground Control Points (GCPs) were used in the photogrammetric model adjustment, or bundle adjustment, and no independent check points were reserved to validate the actual accuracy of the model. As demonstrated by Sanz-Ablanedo et al. (2018), assessing accuracy only through the residuals of the GCPs themselves may overestimate the quality of the final product, since the model is deformed to fit these points. This may mask errors such as the formation of a dome-shaped surface, known as the dome effect, in areas farther from the control points. The authors show that, when only a limited number of GCPs is used, between 10 and 20 points, the RMSE calculated at check points may be up to five times higher than that indicated by the GCP residuals. In the present study, the RMSE values obtained for the GCPs were on the order of millimeters (Table 3), which reflects the quality of the internal adjustment, but not necessarily the absolute accuracy of the model across the entire quarry area.

The decision not to reserve independent check points was due to operational constraints in the field, including the active mining environment, risks to the survey team, and limited available time. In addition, the main objective of this study was the relative comparison between the two methods, conventional topography and UAS, applying the same interpolation points and the same volume calculation methodology. For this purpose, the consistency between the methods, evidenced by the difference of only 0.22% in the volumes calculated using interpolated surfaces, is not invalidated by the absence of independent check points, since both surveys share the same reference system and the same control points.

Future studies should incorporate a set of independent check points measured using GNSS RTK in order to quantify the actual accuracy of the model generated by UAS, following the recommendations of Sanz-Ablanedo et al. (2018).

4. Discussion

4.1 Methodological limitations and sources of error

The accuracy assessment methodology adopted in this study, which used all GCPs in the model adjustment and did not include independent check points, presents an inherent limitation. As highlighted by Thammaboribal (2026), the absence of independent check points may lead to an overestimation of the absolute accuracy of the model, since the reported errors, such as the RMSE of the GCPs, reflect the internal consistency of the adjustment, but not necessarily the accuracy in relation to a fully independent reference dataset. Although this methodological choice does not invalidate the relative comparison between the survey methods, UAS and conventional topography, it is crucial to acknowledge that the absolute accuracy of the model across the entire study area may be lower than that indicated by the GCP RMSE values. Future studies could mitigate this limitation by implementing a strategy based on independent check points, in accordance with cartographic accuracy assessment guidelines.

The comparative volume analysis revealed a relative difference of 0.22% between the conventional topography and UAS methods, a result that is consistent with the literature for open-pit mining environments. For example, Yiğit and Senol (2025) quantified volumetric changes in active quarries, demonstrating the capability of UAV photogrammetry for accurate monitoring. However, it is essential to discuss the possible sources of error and methodological limitations that may influence these results. The subjectivity involved in selecting the 30 points used for interpolating the original surface, as well as the choice of the semivariogram model in Kriging, linear in this case, may introduce variations in the estimation of the original terrain surface. In addition, the absence of independent check points, as previously discussed, prevents a robust validation of the absolute accuracy, which should be considered when interpreting the calculated volumes. Future investigations could explore the integration of complementary technologies, such as UAV-based LiDAR systems, which, despite having different accuracy characteristics (Urban et al., 2025), may offer advantages in specific scenarios, such as areas with dense vegetation or for advanced point cloud segmentation in stepped terrain. Additionally, the use of more advanced approaches for reconstructing original terrain surfaces, such as machine learning techniques and neural radiance fields, represents a promising path for improving accuracy and automation.

4.2 Comparison with studies from the literature

The results obtained in this study are aligned with the conclusions of Raza et al. (2023), who compared multiple interpolators for terrain modeling in mining areas. The authors observed that the choice of interpolator directly affects the final DEM and that, for datasets with high sampling density, the natural neighbor method showed the best performance (R = 0.969). In the present study, although the point density of the photogrammetric cloud was high, with approximately 28 million points, the reconstruction of the original surface required the use of only 30 sample points, which justified the choice of Kriging.

Zarychta et al. (2020), in a study on the reconstruction of the pre-extraction morphology of the Liban Quarry in Poland, used Ordinary Kriging based on topographic map data and obtained estimation errors (SDOK) lower than 0.51 m. Although the magnitude of the error differs due to the different scales and data sources, the methodological approach is analogous to that adopted in this study, supporting the use of Kriging for the reconstruction of original terrain surfaces.

Regarding positional accuracy, Deliry and Avdan (2021) compiled several studies and reported that the predominant vertical RMSE in UAS surveys ranges from 0.04 to 0.06 m, meeting the ASPRS Class 3 standard. The values obtained for the GCPs in this study (RMSE Z = 2.81 mm) are lower than this range, indicating good internal adjustment quality. However, as previously discussed, the absence of check points prevents a direct comparison with literature values for absolute accuracy.

The study by Molnar and Domizi (2016), although it proposed the reconstruction of surfaces from UAS images, presented limitations related to the overlapping and intersection of triangular faces. The methodology proposed in the present study, based on Kriging and smoothed surfaces, as shown in Figures 10 and 11, may contribute to reducing such limitations and improving the consistency of volumetric estimates.

4.3. Improvements and perspectives for future studies

In the present study, the manual insertion of points for interpolation, aimed at estimating the original surface, was performed using Surfer software. Although functional, this approach represents a bottleneck in the process, especially when greater efficiency and reduced processing time are desired. In this sense, it would be interesting to develop algorithms capable of automatically recognizing the boundaries of these areas in fills and cuts, identifying the areas of interest in an automated manner.

It is important to highlight that the study by Jiang et al. (2022) demonstrated the automated identification of stockpiles and solid waste, indicating a promising direction. However, it is understood that the challenges are greater in cases involving homogeneous materials, such as fills and cuts, where boundaries may be less evident for tools based on machine learning.

Therefore, one suggestion for improving the proposed methodology is to investigate automated techniques using machine learning algorithms to identify boundaries and areas of interest in fills, stockpiles, and cuts. Such algorithms could be developed to handle homogeneous materials, contributing to greater accuracy and efficiency in volume calculation.

Another possible improvement would be to obtain, from the Anápolis Quarry, the original terrain surface before any excavation, enabling a direct comparison with the interpolated model in terms of its realistic approximation of the terrain. In addition, it would be relevant to test the proposed methodology in different scenarios, as well as to vary the interpolation parameters or apply other models. This procedure would allow a more precise calibration, bringing the results even closer to the actual topographic conditions of the original terrain.

5. Conclusions

This study presented a methodology for volume calculation using UAS, together with QGIS and Surfer software, and compared it with the traditional method based on topographic surveys. The results demonstrated that the use of UAS can provide significant benefits, such as greater practicality, reduced execution time, and higher data density, allowing more detailed analyses. The integration with software such as QGIS and Agisoft Metashape further reinforced the efficiency of the process, highlighting the capability of UAS to meet the demands of engineering projects.

Although the proposed methodology showed satisfactory accuracy, especially with the use of Ground Control Points (GCPs), challenges such as the automatic identification of boundaries and the modeling of original surfaces for homogeneous materials still need to be overcome. Future studies should explore the development of machine learning and deep learning algorithms to automate these steps, further optimizing the process and expanding its range of applications.

Therefore, UAS-based surveying stands out as a modern and efficient tool for volumetric surveys in engineering projects, contributing to safer, faster, and more accurate practices when compared with traditional methods.

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