3D modelling of Slums based on UAV data

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June 2022

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Enschede, The Netherlands, June 2022

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

Specialization: Geoinformatics

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# ABSTRACT

Favelas are the most common type of informal settlements found in Brazil (Pedro & Queiroz, 2019). Considering the complexity of the built environment in favelas in São Paulo, mapping and assessing the information related to the morphology of the slums becomes a challenge. The Housing Secretariat, City Hall, São Paulo, has conducted surveys using Unmanned Aerial Vehicles (UAVs) for the favelas to visualize favelas in 3D, thus facilitating the slum upgrading projects. There is much research in developing a 3D city model for the urban environment, but limited research has been conducted on the 3D modelling of slums due to the irregular and unplanned houses. This study develops a methodological workflow for 3D building reconstructions in slums using Dense Image Matching (DIM) point clouds from UAVs and 2D cadastral data. This study also focuses on developing a workflow to create the 3D model and a Digital Twin (DT) of the slums by facilitating the data integration and updating the semantic information to provide additional information about individual buildings in the slums.

Prior to the development of this research, semi-structured interviews were conducted to understand the stakeholders' requirements and the challenges the experts are currently facing in working with the data for the slums. The point cloud was filtered into the ground and the non-ground (building) points. A noise filter algorithm was used to remove the noise or outliers in the point cloud, especially from the surface of the roofs. The automatic data-driven model approach for the 3D building reconstruction from point clouds and 2D cadastral data by Xiong et al. (2016) was selected as a baseline. The resulting 3D model was enriched with semantic information using an Extract, Transform, Load (ETL) platform. The result of the experiment showed irregular reconstructions in roof structures in some places in the 3D building models of the favela in the form of erroneous spikes. The errors found in the roof surface construction were due to the over-segmentation and the noise in the point cloud. A total of ten houses out of 2156 were not perfectly reconstructed as a result of occlusions due to the presence of vegetation. A qualitative evaluation of the developed workflow and the model was carried out using semi-structured interviews with the stakeholders to assess its feasibility in slum upgrading activities.

The assessments concluded that the proposed workflow is suitable for creating digital twins for slums based on the UAV and 2D cadastral data. However, the 3D slum model had a few limitations, which are discussed in this research. During the semi-structured interviews to evaluate the model, four out of five interviewees agreed that the workflow could be used to visualize the buildings in slums in 3D and obtain information about individual buildings and update it in the future. However, due to the unavailability of ground truth or the validation data, the 3D model could not be evaluated quantitively. For further research, it is recommended to conduct field surveys to aid the comparison of the resulting 3D model with the validation/ground truth data.

Keywords: Informal settlements/Slums, 3D building reconstruction/modelling, Digital Twins (DT), Unmanned Aerial Vehicles (UAV), Point Clouds

ACKNOWLEDGEMENTS

I am indebted to my supervisors, Dr Mila Koeva and Dr Caroline Gevaert, for supporting me throughout this research with their constant input, support and motivation and for helping me make my thesis come to reality. I would also like to thank Dr Sander Oude Elberink for helping me with the algorithm and Ms Alexandra Pedro for providing me with all the necessary data. Special mention to Luiz, Stefania, Aline and Jose from São Paulo for taking the time out of their busy schedules to answer my questions and give me feedback on my work. I also thank my chair Dr Richard Sluizas, for his detailed feedback on the proposal and midterm assessments.

I would like to thank my friends Nishita, Nilay, and Shruti for giving me the company and motivation to work in the library every day throughout the duration of my thesis. I want to thank my closest friends in the Netherlands for putting up with me, constantly checking on me and for the support, motivation, advice and weekend trips, which helped me recharge after a stressful week. Thank you for always making me feel at home. Last but not least, I am immensely grateful to my parents for their constant blessings and for their financial and moral support, without which I wouldn't have been where I am today.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLE

1. INTRODUCTION

1.1. Background and justification

According to the Sustainable Development Goals (SDGs) adopted by the United Nations (2015), Goal 11 emphasizes on "*making cities and human settlements inclusive, safe, resilient and sustainable*". Particularly, Goal 11.1 aims "*By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums*" (p.26). People migrate to cities in search of opportunities; however, due to the lack of available space or housing in the cities, some people tend the occupy the available land and settle with or without the legal aid, and this gives rise to an unplanned form of urbanization/the informal settlements (Salazar Miranda et al., 2021).

Favelas are the most common type of informal settlements found in Brazil. Pedro & Queiroz (2019) defined Favelas as "*public or private areas occupied by low-income and socially vulnerable families, without ownership of the land, living in self-constructed and precarious dwellings, in a disorderly layout, in breach of formal regulations, and lacking public services and infrastructure*" (p.31). In the 20th century, the government of Brazil attempted to eradicate the favelas to replace them with formal housing, but it had a lot of negative consequences (Duarte et al., 2021). Hence, in many cases, the slum upgrading projects were considered more appropriate than slum eradication as they focused more on improving the existing infrastructure than a physical intervention that might lead to relocation and cause the slum dwellers to lose their homes (Alliance, 2012; UN Habitat, 2018).

In order to proceed with the activities related to slum upgrading, the slums need to be mapped to access information related to the urban phenomena. However, favelas often remain neglected on the cadastral map (Temba, 2014) due to their complex built environment, lack of accessibility, unsafe living conditions and an unhealthy environment to undertake the conventional methods of cadastral survey (Duarte et al., 2021). Remote sensing data comes very handy and can tackle most of the challenges, as it can be used to obtain precise information about the current situation in the slums (Kuffer et al., 2016).

The Housing Secretariat in City Hall in São Paulo, Brazil, has conducted surveys using Unmanned Aerial Vehicles (UAVs) for the favelas to facilitate the slum upgrading projects and has taken the initiative to create a 3D model of the slum areas, which will be a valuable tool for slum upgrading projects. Visualization of the favelas in 3D started as a game within a miniature urban world called "Morrinho" (or "Little Hill") by the local teenagers a few years back. The 3D miniature model of Rio was made using bricks, wood, Lego and other recyclable materials (Projeto Morrinho, 2012). This model motivated the municipal urban development agencies to implement it in the formal property market and use the 3D models to develop the slum area (Angelini, 2013).

This research develops a methodological workflow using the photogrammetric point clouds obtained from the UAVs and the cadastral data to help reconstruct the 3D buildings in the slums in Jardim Colombo, São Paulo, Brazil. Figure 1 shows the image of the favelas in Jardim Colombo, São Paulo, Brazil. In addition, this research also focuses on data integration to provide additional information about the individual buildings in the slums with implementation to update semantic information in the future to help in the creation of a Digital Twin of the slum. The generated 3D building model will be of immense help to the stakeholders, especially the government officials and the urban planners, to visualize how the houses are perceived in real life and would be helpful for the activities concerning slum upgrading.

Figure 1: Favelas in Jardim Colombo, Brazil (Source: *Jardim Colombo*, n.d.)

1.2. Research problem

Geospatial information is needed to create a 3D model of the slum. Along with assessing the data, innovative methods are required to obtain the 3D model. Researchers have been using Very-High-Resolution (VHR) images to extract the geospatial information in slums (Kuffer et al., 2016), and UAVs have also been proven to be useful for slum mapping (Gevaert, 2018; Koeva et al., 2018; Nex & Remondino, 2014). In addition to orthogonal high-resolution images of the area, UAVs can take oblique images to capture information on the facades of the buildings. Methods have been developed for 3D building reconstruction based on 3D point clouds generated by dense multi-stereo image matching (Nex & Remondino, 2014; Xiong, 2014). However, most 3D building reconstruction algorithms using 3D point clouds have been extensively used and tested on the built environment for formal settlements. Its implementation has been lacking in the built environment for informal settlements since building houses in the slums lack planning and have irregular structures and patterns compared to the houses in the urban environment (Kuffer et al., 2016). Moreover, terrestrial laser scanning has been used to map the slums in 3D (Salazar Miranda et al., 2021). However, there is a gap in the knowledge in using the aerial photogrammetric point clouds to generate Digital twins of slums that incorporate 3D building models, including semantic information with possibilities for their dynamic updating.

1.3. Research objectives

1.3.1. Main Objective

The main objective of this research is to develop a method to automatically reconstruct a 3D slum model, including semantic information with possibilities for their dynamic updating using remotely sensed data in São Paulo, Brazil.

1.3.2. Sub-objectives and research questions

Sub-objective 1: Understanding the user requirements of the stakeholders
1.What are the main requirements for the 3D slum model and the workflow for the 3D reconstruction?

Sub-objective 2: To develop a methodology for 3D reconstruction of the buildings in the slum and update the model with semantic information.
1. How should the data be prepared for reconstructing the 3D model?
2. What weaknesses do the 3D slum models reconstructed with existing method show?

Sub-objective 3: To evaluate the quality of the generated model based on the interviews with the stakeholders from City Hall, São Paulo, Brazil
1. What are the strengths and the limitations of the model?
2. How useful is the generated model to the stakeholders?

1.4. Conceptual framework

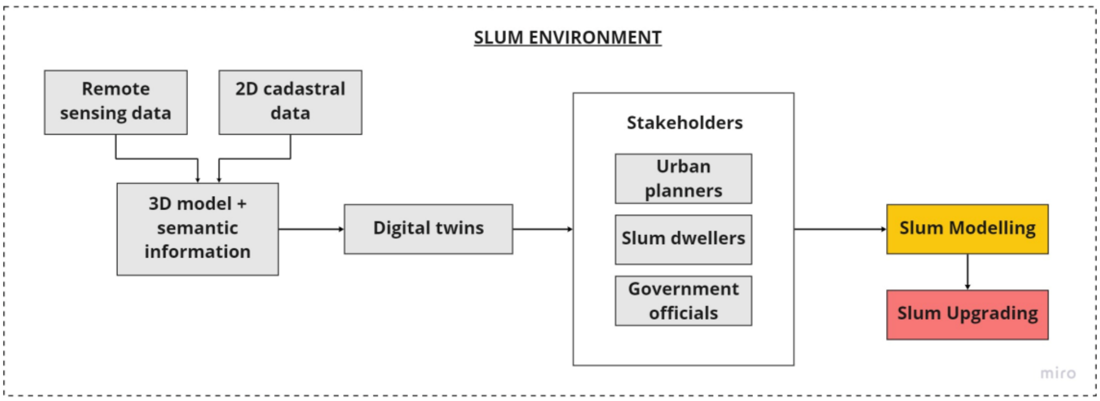

Figure 2: Conceptual framework

The relationship between concepts applied in this research is illustrated in Figure 2. Creating a workflow for 3D slum modelling, which would be a helpful tool for activities concerning slum upgrading in urban planning, is the main objective of this research. The input data for creating the 3D building model is the remotely sensed data obtained from the UAVs and the 2D cadastral data. This research aims to develop a 3D building model of slums that can input the semantic information related to each building in the slum to create a digital twin of the slum, which, could be used by the stakeholders for the projects related to upgrading the slums. Therefore this research combines the concepts of using 3D remote sensing data obtained from the UAVs and the 2D cadastral data to reconstruct a 3D model of the slum with semantic information related to the individual houses to help the stakeholders understand the morphology of the buildings in the slum area to carry out the slum upgrading activities.

1.5. Thesis structure

This thesis comprises of five sections and an Appendix:

Section 1: **Introduction**: contains the background and justification of the study, the research gap, research objectives, research questions and the conceptual framework.

Section 2: **Literature review**: gives an overview of the related work in 3D building reconstruction using the point clouds, 3D modelling of slums, creation of digital twins and the evaluation methods for the 3D model.

Section 3: **Methodology**: describes the methods used in this research. It also provides the description of the study area and the description of the dataset used in this study.

Section 4: **Results and discussions**: Presents the results and answers to the research questions.

Section 5: **Conclusions and recommendations**: Provides findings on the feasibility of 3D modelling of slums using the UAV data. This section also includes recommendations for further research in this area.

2. LITERATURE REVIEW

2.1. 3D building reconstruction

Extensive research has been done on 3D city modelling, and much focus has been given to developing the techniques for automatic building reconstruction (Haala & Kada, 2010). 3D data can be obtained from various sources. Some of the sources which produce 3D information are airborne laser scanning systems (ALS) (Dorninger & Pfeifer, 2008), also known as LiDAR (Light Detection and Ranging), or image matching using stereo photographs using UAVs (Nex & Remondino, 2014). 3D building reconstruction can be done from the point clouds obtained from both techniques (Dorninger & Pfeifer, 2008; Rebelo et al., 2015).

There are two types of methods for 3D model generation, data-driven and model-driven methods. "*Data-driven approach created 3D models without relating it to the library of primitives, and in model-driven approach, complex models are decomposed to simpler models*"(Malihi et al., 2016) (p.71). To generate a 3D model using the model-driven approach, the point clouds need to be segmented into a coarse polyhedral model using a robust linear regression algorithm (Schindler & Bauer, 2003). The most suitable template is selected for each detected feature. However, the model-based method cannot reconstruct the buildings if the detected features do not match the predefined templates in the library with the primitives.

The data-driven approach generates the 3D models based on the input data. One of the significant steps in the reconstruction using the data-driven approach includes grouping the unorganized point clouds into the planar surface groups of roof and walls. Algorithms like Random Sample Consensus (RANSAC) (Malihi et al., 2016), Hough transform (Vosselman & Dijkman, 2001) is used, and the roof segments can be generated by the process of surface growing.

A method for 3D building reconstruction, using LiDAR data and roof topology graphs, was proposed by Xiong (2014). It was later updated, integrating it with footprint map partitions so that it could work with the photogrammetric point clouds as well (Mwangangi, 2019; Xiong et al., 2014, 2016). The method used two map decomposition methods for the 3D building reconstruction using the point cloud and the existing 2D map. The first method was dependent on the LiDAR data and the contours from the roof layers, which were later cropped to footprint maps. The second method was more dependent on the footprint map and was used to detect step edges between the layers, as seen in Figure 3. The boundary of the roof segments was then projected to the ground as walls to get a 3D model.

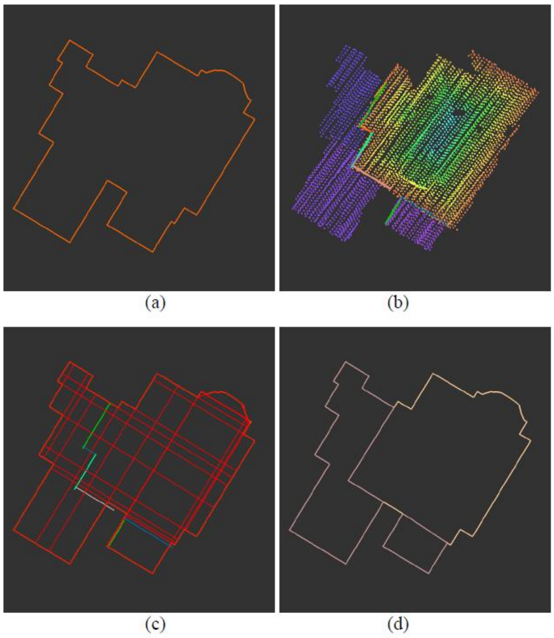

Figure 3: Footprint map decomposition (a) Footprint map (b) LiDAR points (c) Partition lines,(d) Final output (Source: (Xiong et al., 2016))

2.2. 3D modelling of informal settlements

The use of 3D models has been exponentially increasing and can be used for various applications other than just for visualisation (Biljecki et al., 2015). Much of the previous research on 3D modelling and its usage is mainly focused on the applications in the formal urban environment (Li et al., 2020), and limited research has been conducted on 3D models for informal settlements. The importance of a 3D cadastre for the informal settlements was emphasised in a study conducted by Temba (2014), which concluded that incorporating the third dimension into the cadastre leads to a better understanding of the problems and helps to formulate public policies. The 3D cadastre can store, manipulate, analyse information and visualise the buildings, thus helping in the process related to slum upgrading.

As a part of the slum upgrading process, the City of Rio de Janeiro and MIT's Senseable City Lab digitally mapped the Favelas in Rocinha using the terrestrial LiDAR, as seen in Figure 4 (Salazar Miranda et al., 2021). This recent study aimed at understanding the morphological properties of the streets and the facades of the buildings, which would be used to analyse accessibility to public services, improve already existing roads, have better knowledge of the buildings in the area, visualise the structures which obstruct the addition of new streets or which structures need to be removed to allow more air or sunlight in the regions (Duarte et al., 2021). The method automatically extracted the 3D morphology by considering building-scale attributes from LiDAR data (Salazar Miranda et al., 2021). The informal settlements were mapped to improve the area, formalise the slums and incorporate them into the city planning.

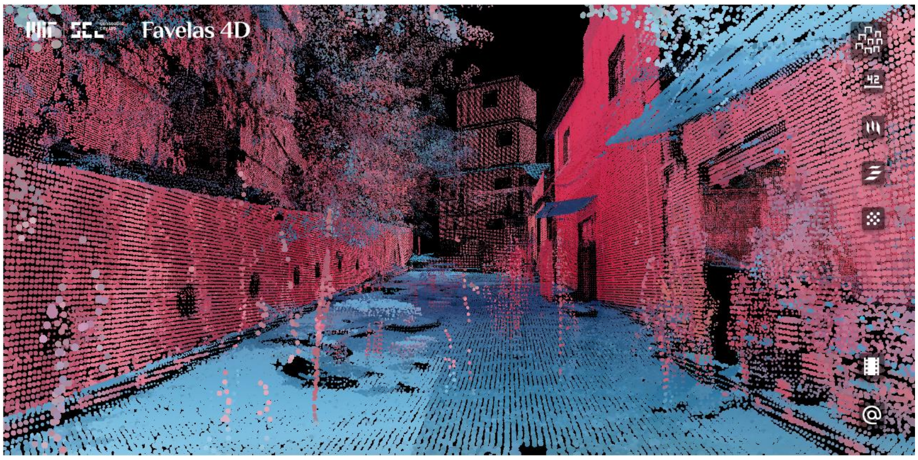

Figure 4: The web-viewer of the project Favelas 4D (Source: *Favelas 4D :: MIT Senseable City Lab*, n.d.)

Researchers in Brazil have conducted many studies to understand the complex morphology of the Favelas. The use of Lidar data has been tested in the informal settlements; to detect the horizontal and the vertical growth of the informal settlements in the favelas located in São Paulo, Brazil (Ribeiro et al., 2019) and also to develop a digital surface model (DSM) to delineate the building footprints in Favelas in Belo Horizonte (Temba et al., 2015). Another attempt to reconstruct favelas in Dona Marta in Brazil used the images from Google Earth to generate the 3D slum model of the area (Verniz et al., 2016). A recent study by Gianelli (2021) performed solar analysis on buildings in favelas in São Paulo using 3D building models generated using LiDAR data.

Few researchers have explored the applications of 3D modelling in slums with various tools and methods. These researches have sparked a motivation to test the use of multiple datasets to explore the techniques and the use of 3D modelling in slums. City Engine and Computer Generated Architecture (CGA) was used to create a 3D model of the informal settlements in Slovo Park, Johannesburg, South Africa, with Level of Details (LOD3) and the visualisation characteristics for the informal settlements models were defined (Rautenbach et al., 2015). Landsat, TerraSAR-X, Quickbird, and the data from the OpenStreetMap were used to generate a 3D model to classify the informal settlements by taking the building density, size and height into consideration in Santosh Nagar, Mumbai, India (Kraff & Taubenboch, 2014). The classified 3D model helped to distinguish the slums from the urban settlements. The low-cost method of Terrestrial image-based modelling (IBM) was used to generate the 3D model of the buildings in the slums of Nairobi and was used to delineate the 2D outlines of the building (Mwangi, 2016).

2.3. Creation of digital twin

The 3D reconstruction techniques from point clouds often lead to the loss of semantic information in the resulting 3D model. The semantic information of the model helps the users to use the 3D model for various applications apart from just visualisation (Yao et al., 2020). An implementation that allows the dynamic update of the semantic information in the model is beneficial in real-time monitoring, obtaining remote access, and planning activities (Singh et al., 2021). A Digital Twin (DT) can perform such a task efficiently. According to Bolton et al. (2018), a Digital Twin (DT) can be defined as *"A dynamic model of an asset, with the input of current performance data from the physical twin via live data flows from sensors; feedback into the physical twin via real-time control"* (p.10). To aid the creation of a digital twin, a direct link should be created between the 3D geometry and its metadata to exchange the information, which can be done using an ETL platform (Extract, Transform, Load) (Heaton & Parlikad, 2020). The national and regional government have started using the digital twin of the cities for urban planning. Hence a semantically-enriched 3D scene enables the users to use the model for various purposes other than just 3D visualisation (Singh et al., 2021; Yao et al., 2020). A semantically enriched 3D slum model would facilitate the creation of a Digital Twin of the slums, which would help the planners with the slum upgrading.

2.4. Methods for evaluation of the model

The 3D data quality is assessed in terms of its completeness, logical consistency, positional accuracy, thematic accuracy, temporal quality and usability (ISO, 2005). Many methods have been developed over the years to generate 3D models, but the methods for evaluating the 3D models are limited (Wong & Ellul, 2016). The geometric accuracy of a generated 3D model can be compared with the validation dataset by surface matching and evaluating the Euclidean distances between the two datasets(Akca et al., 2010). Ledoux (2013) implemented a prototype methodology to assess the quality of the 3D data using the International standards of geoinformation by taking the geometry and the topology of the 3D model. The prototype informed the user regarding the erroneous models and their nature.

Another way to assess the quality of the model is by doing qualitative analysis. When there is a lack in the availability of the 3D validation data, a convenient way to evaluate the 3D models is by understanding the user requirements of the model, identifying the 3D characteristics the users are interested in and designing methods to measure these characteristics like geometric fidelity and relative positional accuracy (Sargent et al., 2007). Involving stakeholders and users of the model in the evaluation process takes into account the interest of the stakeholder and gives clarity on whether the model can be of use to the stakeholders for the purpose it was intended (Jones & Preskill, 2009).

3. METHODOLOGY

This chapter discusses the study area of this research, describes the data used for this research, and gives a detailed background on the processes and the tools used in each phase of this research.

3.1. Study area

São Paulo, one of the wealthiest cities in Brazil, is also home to informal settlements, 'Favelas'. The slum area selected for this study is Jardim Colombo, located in the municipality of São Paulo, Bairro do Morumbi (District Villa Andrade), situated in the Paraisopolis Complex. Paraisopolis is the second largest favela community in São Paulo (Mion, 2018). This area was selected due to the availability of the data provided by the City Hall, São Paulo, Brazil. In one of the initial meetings with a representative from the City Hall, it was mentioned that the 3D slum models would play a significant role in various slum upgrading activities. Geographical coordinates of the area are Latitude (ф): 23°11'15.57 "S, Longitude (λ): 45°48'38.45 "W. The slum area is around 13.4 hectares, with 2158 houses. The study area in this research is shown in Figure 5.

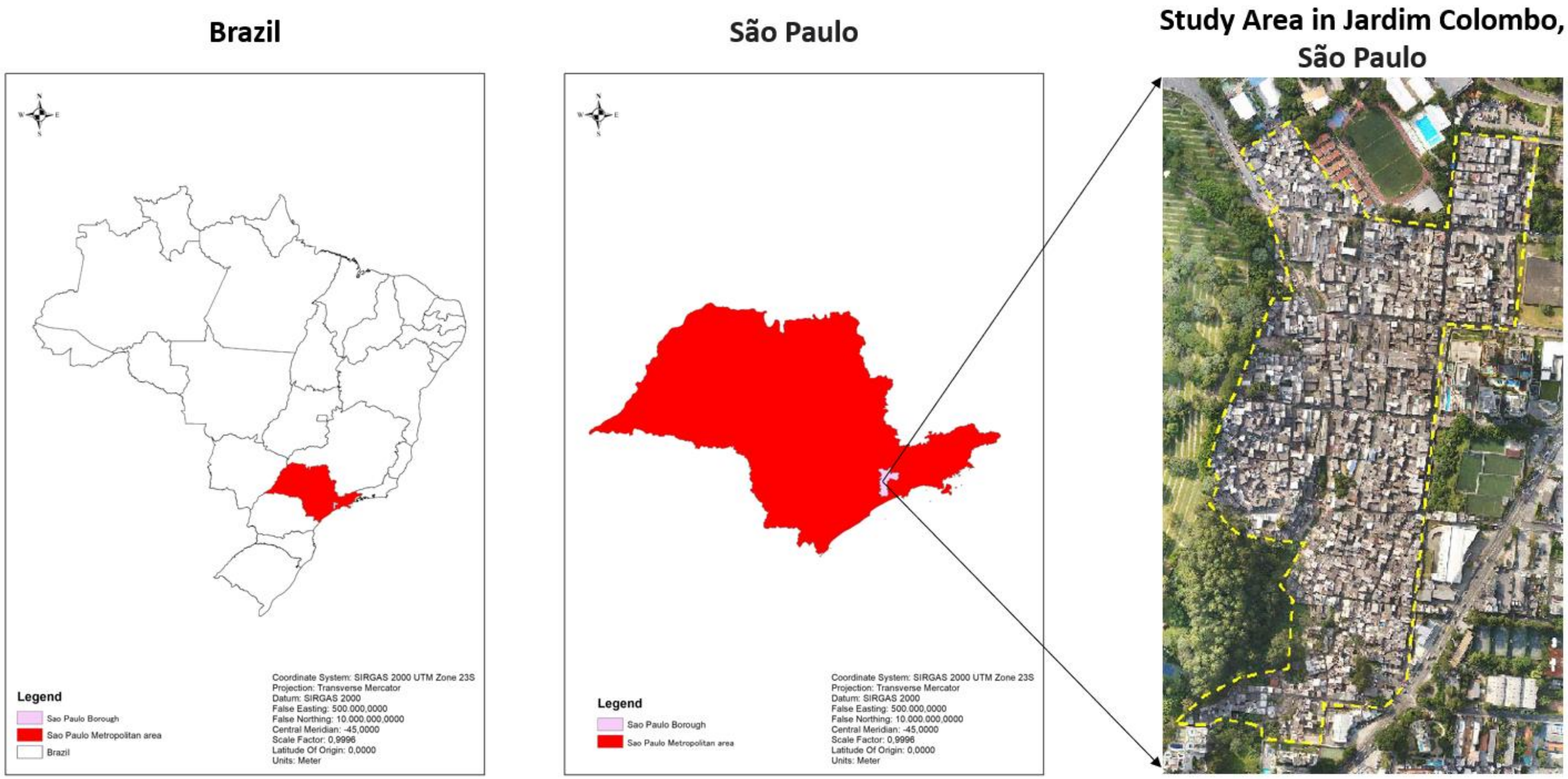

Figure 5: Study area

3.2. Overall Approach

The work in this research is organised into three phases, each focusing on one objective at a time. The first phase includes conducting semi-structured interviews with the stakeholders from the City hall, São Paulo, Brazil, identifying the research problem, data acquisition and conducting a literature review. The second phase includes data preparation and developing a methodology for the 3D reconstruction of buildings. The third and final phase includes an evaluation of the model. The overall research approach is presented in Table 1.

Research Phase	Sub-Objective	Tasks
Phase 1	Understanding the user-requirements of the stakeholders	Semi-Structured interviews
		Data Acquisition
		Literature review
Phase 2	To develop a methodology for 3D reconstruction of the buildings in the slums and update the model with semantic information	Data pre-processing
		3D building reconstruction
		Implementation of semantic information
		Data visualisation
Phase 3	To evaluate the quality of the generated model based on the interviews with the stakeholders from City Hall, Sao Paulo, Brazil	Semi-Structured interviews

Table 1: The overall research approach

3.3. Data description

All of the data needed for this research was provided by the City hall, São Paulo, Brazil.

Data	Data format	Data Source
UAV point cloud	.E57 (converted to .las)	City Hall, São Paulo, Brazil.
Orthophoto	.ecw (GSD =3.8cm)	
Building polygons	.shp (polygon)	
Contour lines	.shp (polyline)	

Table 2: Information on the available data

3.3.1. UAV data

The aerial orthophotos were captured by the experts from São Paulo (AmbGis) with the help of a drone Phantom 4 pro (version 1) with a 20 MP camera with a maximum image size (frame) of 5472*3648. The image acquisition was carried out from 13/05/2019 to 09/07/2019. Two flight plans were carried out to cover the entire area, one covering in the North-South direction and another in the east-west direction resulting in 408 photos. The flight path is shown in Figure 6. The images were captured at a flying height of 120m with 80% longitudinal and 70% lateral overlap. The images captured had a Ground Sampling Distance (GSD) of 3.8cm. The collected data were further processed to generate, a rectified orthomosaic and a Dense point cloud using Agisoft Metashape Professional software. The products were georeferenced to the SIRGAS 2000 coordinate system using the UTM projection for Zone 23 South.

Figure 6: Flight path (V1 is the flight path running North to South and V2 is the flight path running East to West) (Source: (AmbGis, 2019))

3.3.2. Vector data

Shapefiles: The Building footprints were mapped by the experts (AmbGis) from São Paulo and delineated on a scale of 1:500 to 1:200 in order to maintain the details using the generated orthomosaic with the help of GIS software. The generated shapefiles were validated by conducting field surveys by the surveyors in São Paulo. During the survey, information regarding the construction material used for the buildings in slums, the number of floors and identification of alleys was collected. Figure 7 shows an example of a sketch used in the field. After the field survey, the information was systematized, and the data was incorporated into the shapefiles using a GIS platform.

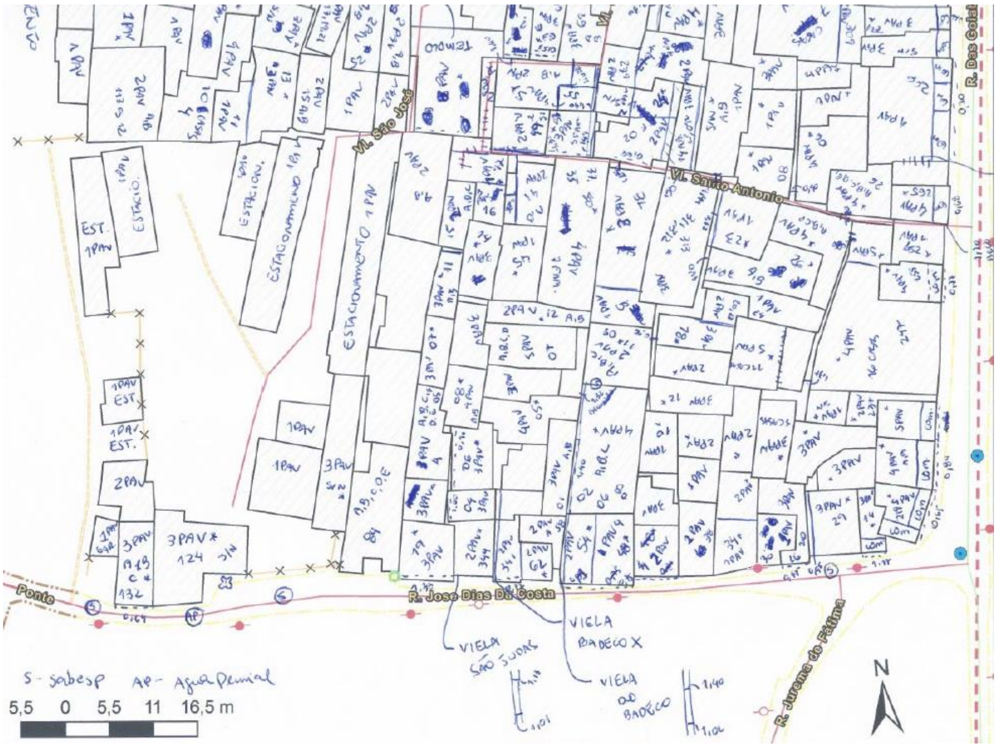

Figure 7: Example of sketch used for field work to gather detailed information which would be incorporated into the shapefiles (Source : (AmbGis, 2019))

Contours lines: Contour lines (Figure 8) were extracted by the experts (AmbGis) from São Paulo from the Digital terrain model (DTM). After removing the non-terrain elements, the voids were filled in by creating a 3D model from the interpolation between the altimetric dimensions. The best standard of terrain classification without any distortions in the DTM was adopted to generate the contour lines with 1m spacing using the Agisoft Metashape Professional software. The contours were later systematized and coded in a GIS environment, presented on a 1:500 scale, and provided as a shapefile by the officials.

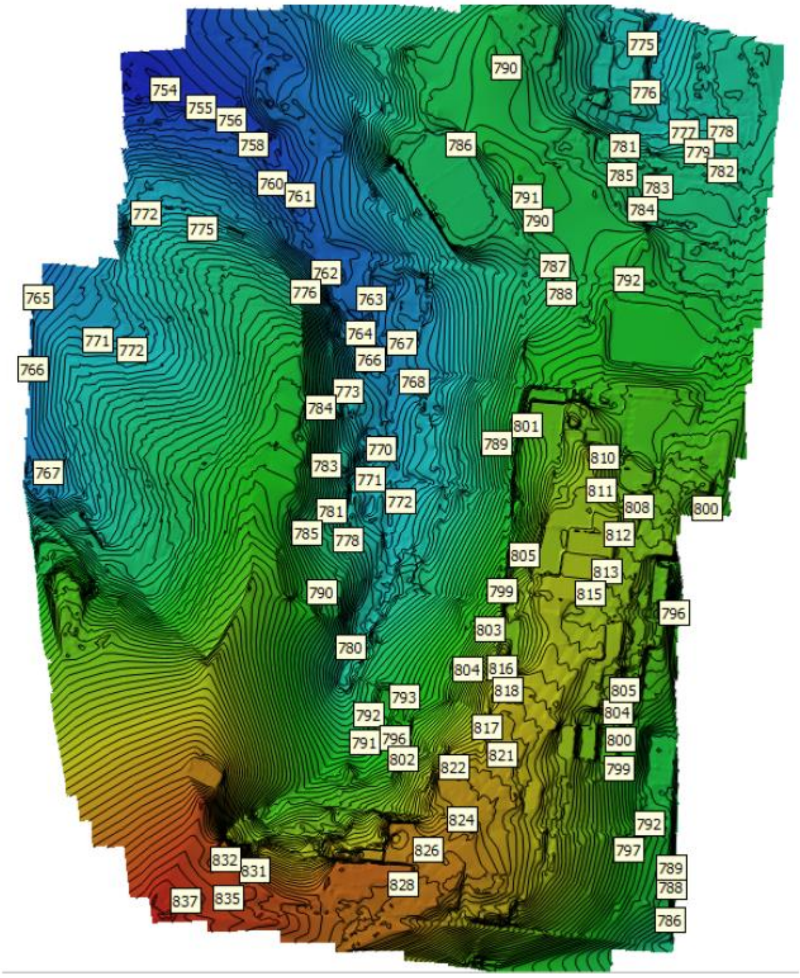

Figure 8: Contour lines (Source: (AmbGis, 2019))

3.4. Phase 1 : User Requirements for the model

3.4.1. Understanding the user requirements of the stakeholders

Understanding the user requirements of the stakeholders from the City Hall, São Paulo, Brazil, forms the basis of the commencement of this research. Semi-structured interviews were conducted as a part of qualitative research to understand the need to create a 3D slum model and its usefulness in the activities related to slum upgrading. Semi-structured interviews aim to generate interpretative data based on the interaction between the interviewer and interviewee using a predefined questionnaire used as an interview guide to gain insight into the interviewee's knowledge and interpretation (Lewis-Beck et al., 2011). Limited pre-existing knowledge about the currently adapted methods for 3D modelling of slums and the need for the 3D slum model was known. Hence semi-structured interviews were conducted as exploratory research to understand the user goals and requirements (Wilson, 2014).

Three experts in the City hall of São Paulo dealt with 3D modelling of slums, of which two had working experience with slum modelling. The three experts, all with a background as Urban planners/Architects, were approached for participation in the interviews, which were held using an online video conferencing platform. The questionnaire was shared with the interviewees prior to the interviews, and the interview was recorded and transcribed. The detailed questionnaire and the answers are presented in the Appendix.

The interviewees were questioned on:

1. Their background of work to understand the background knowledge of the interviewees, which could influence their answers.
2. Information on the available data, to understand the quality of the provided data.
3. The methods for the 3D reconstruction, to understand the 3D reconstruction methods currently used within the organisation and their expectation related to developing an algorithm for automatic building reconstruction.
4. Expectations on the generated 3D slum model.

3.5. Phase 2 : 3D building reconstruction

Phase 2 of this research focuses on obtaining the 3D slum model. It consists of data pre-processing, 3D building reconstruction and implementation of the semantic information and data visualisation. A detailed methodology flowchart of phase 2 is shown in Figure 9.

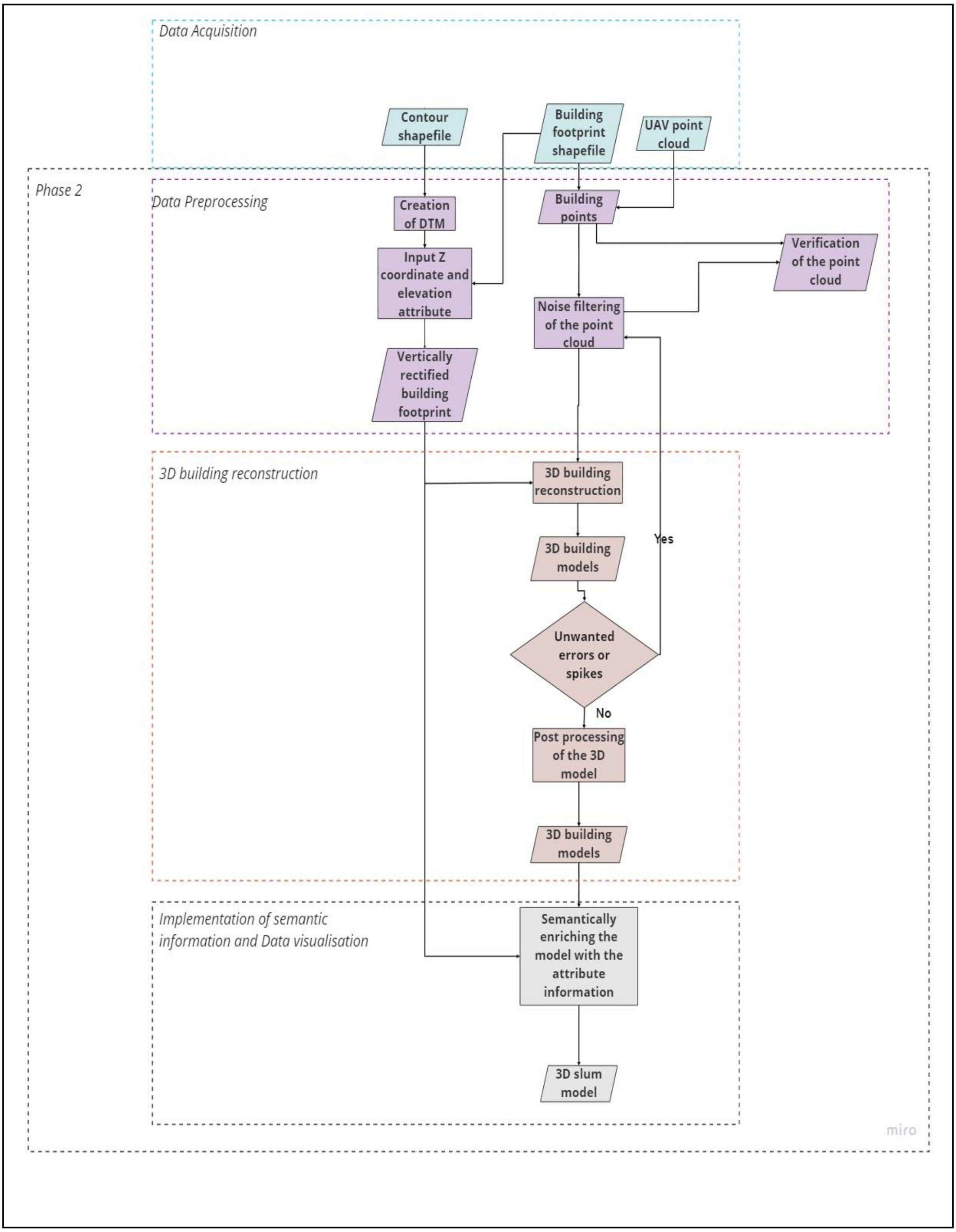

Figure 9: Detailed Methodology for phase 2

3.5.1. Pre-processing of the data

The building footprint shapefile did not have the vertical coordinate/ Z coordinate. Hence, the building footprint shapefile was vertically rectified to the ground elevation to facilitate the 3D building reconstruction process. The shapefile with contours was used to create a DEM raster using a local interpolation method using a GIS platform. The mean values of the pixels in the DEM lying inside the building the footprint shapefile were used as an attribute to define the Z value to rectify the shapefile vertically.

Since this research focuses on 3D building reconstruction, only building points in the point cloud are needed. The building points in the point cloud were obtained by clipping the whole point cloud with the building footprint shapefile using an ETL (Extract, Transform and Load) platform, FME (Feature Manipulation Engine). Traces of vegetation in the filtered point cloud were segmented manually. Dense Image Matching (DIM) point cloud is subjected to a lot of noise or outliers, which could take place due to ambiguities during the image matching. Due to this, the filtered point cloud was further cleaned using the noise filter. The point cloud was filtered by defining a radius for the nearest neighbours, and a plane fitted. The algorithm removes the points if it is too far from the fitted plane (CloudCompare Version 2.6.1. User Manual, 2015). This process was used to eliminate most of the irregularities on the roof of the buildings, such as vegetation, water tanks etc., which could give rise to errors in the surface construction of roofs.

3.5.2. Verification of the quality of the point cloud

The original and the filtered point cloud were statistically analysed based on the Point Spacing, Point Density and Internal accuracy. According to (LAS Dataset Statistics—ArcGIS Pro | Documentation, n.d.), "*Point spacing is defined as linear units per point, and Point density is defined as points per square unit area*". An Internal accuracy assessment of both the filtered and the original point cloud was done by least square plane fitting (CloudCompare Version 2.6.1. User Manual, 2015), and an output Root Mean Square (RMS) was used to assess two point clouds. Five building roof sections were selected randomly to assess the internal accuracy of the two point clouds.

3.5.3. 3D building reconstruction

3D building reconstruction with the point clouds is the most crucial step in this research. The 3D model was generated using the algorithm by Xiong et al. (2016), which used the 3D point cloud and the building footprints (2D cadastral data) to reconstruct the buildings as 3D polygons. The point density of the input point cloud was expected to be above 5 points/m^2. Furthermore, the algorithm worked with a maximum of 7 million points at a time. Hence, the entire area was divided into three zones with zone 1, zone 2 and zone 3, each having 10, 5 and 11 sub-zones, respectively (see Figure 10), and the algorithm was applied to one sub-zone at a time to assist the process of 3D reconstruction.

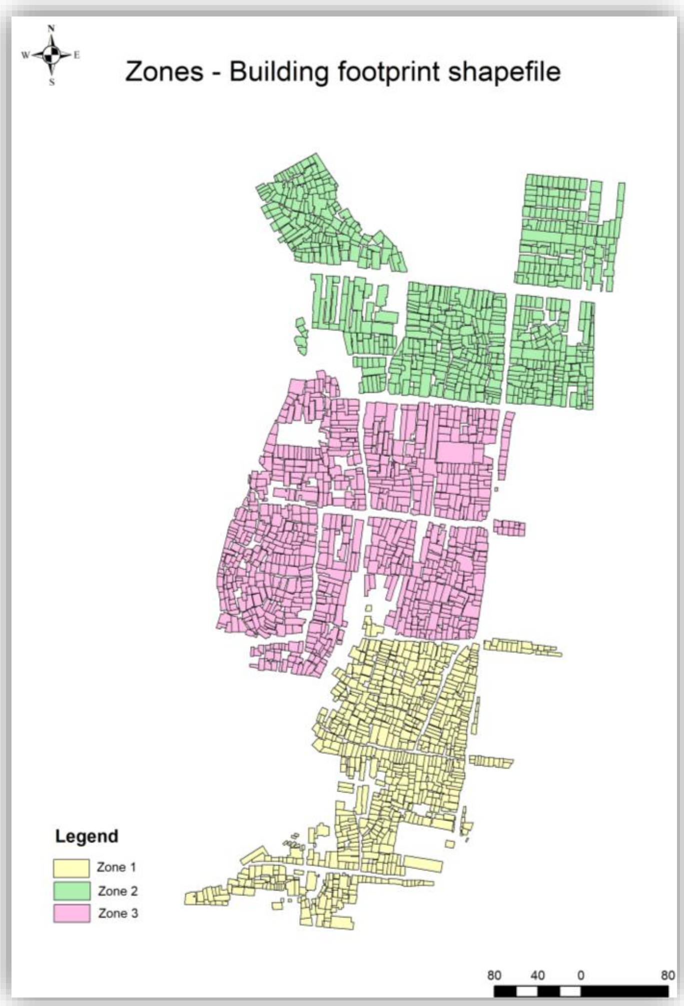

Figure 10: Demarcation of the zones

The steps followed in the algorithm for the 3D reconstruction of buildings in the slums are as follows:

1. Point cloud segmentation: Point cloud segmentation is one of the important steps in defining the roof structure of the buildings by clustering the points that lie in the same planar face into one segment. The roof was segmented using the surface growing method, which uses a 3D Hough Transform to detect the planar seed surfaces in a 3D point cloud (Elberink & Vosselman, 2009; Vosselman et al., 2004). The surface growing method of segmentation has two stages; the determination of seed surfaces and the growing of the detected surfaces which lie in the same plane. A small set of nearby points that forms a planar surface is selected as a seed surface. The Hough Transform determines whether the points within the defined radius fit in the same plane. Then, the surface growing stage begins. Figure 11 shows the surface growing segmentation method in a pictorial representation, demonstrating that red points belong to the same plane and green points belong to a different plane. As a result, the green dots will form a different cluster. The segmentation parameters; seed neighbourhood radius, a

growing search radius, maximum distance from the point to the surface, and a minimum number of points in a segment were defined to help segment the roofs.

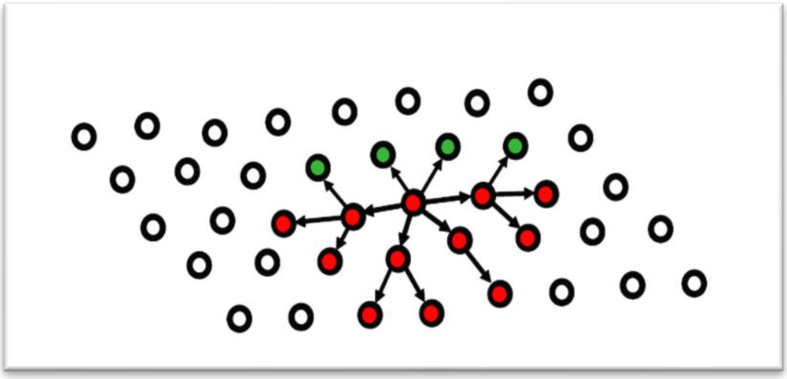

Figure 11: Surface Growing (Source : Point Cloud Segmentation: Laser Scanning (2020-2B), n.d.)

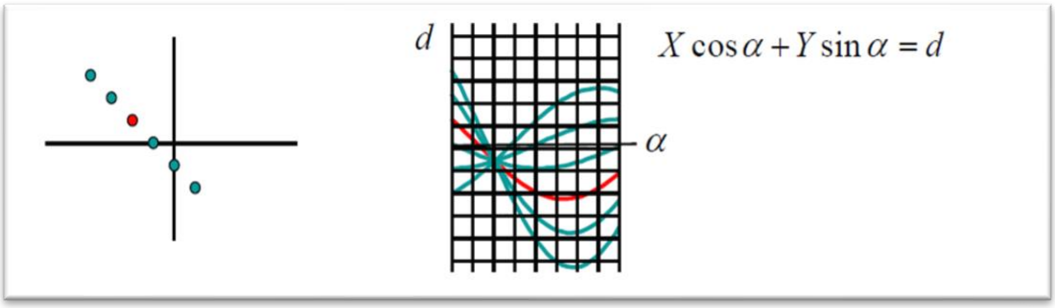

Figure 12: Hough Transform (Source : Point Cloud Segmentation: Laser Scanning (2020-2B), n.d.)

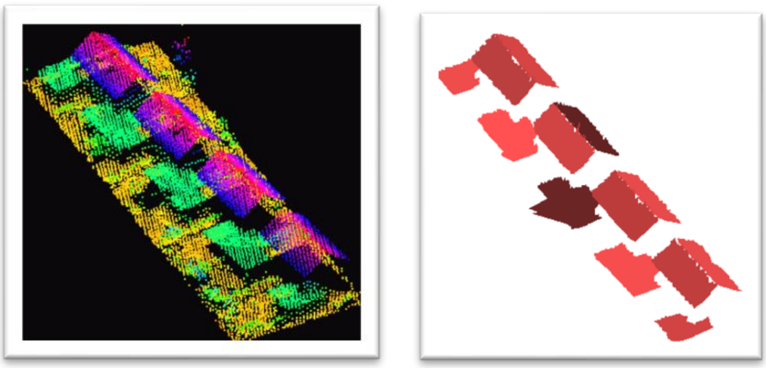

Figure 13: Roof surfaces- Plane detection (Source : Point Cloud Segmentation: Laser Scanning (2020-2B), n.d.)

Figure 12 shows the graphical representation of the Hough transform, where 'alpha' is the angle between the line and the Y-axis and d is the distance between the line and the origin. "*The Hough transform, therefore, detects lines in the object space by determining locations in the parameter space with a high number of crossing curves*"(George & Hans-Gerd, 2010) (p.64). Figure 13 shows the detected roof planes from the point clouds after a successful roof segmentation.

3D building reconstruction: The 3D building model was reconstructed from the point clouds and the building footprint. Points connecting the planar patches are grouped as structuring points and boundaries, which provide the inner corners and the boundaries (see Figure 14), while the 2D building footprints define the outer boundaries (see Figure 15). The outer boundaries of the roof model thus obtained are thus projected onto the ground as walls (Xiong et al., 2016).

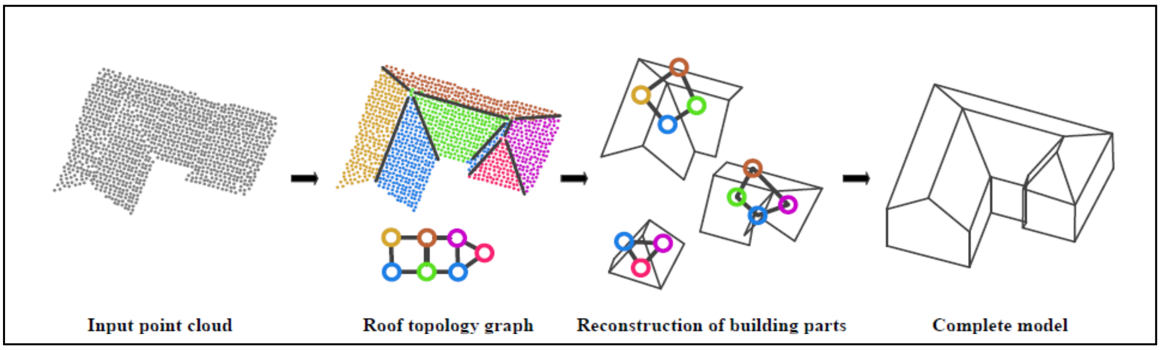

Figure 14: Workflow of the building model reconstruction from point cloud (Source : (Xiong, 2014))

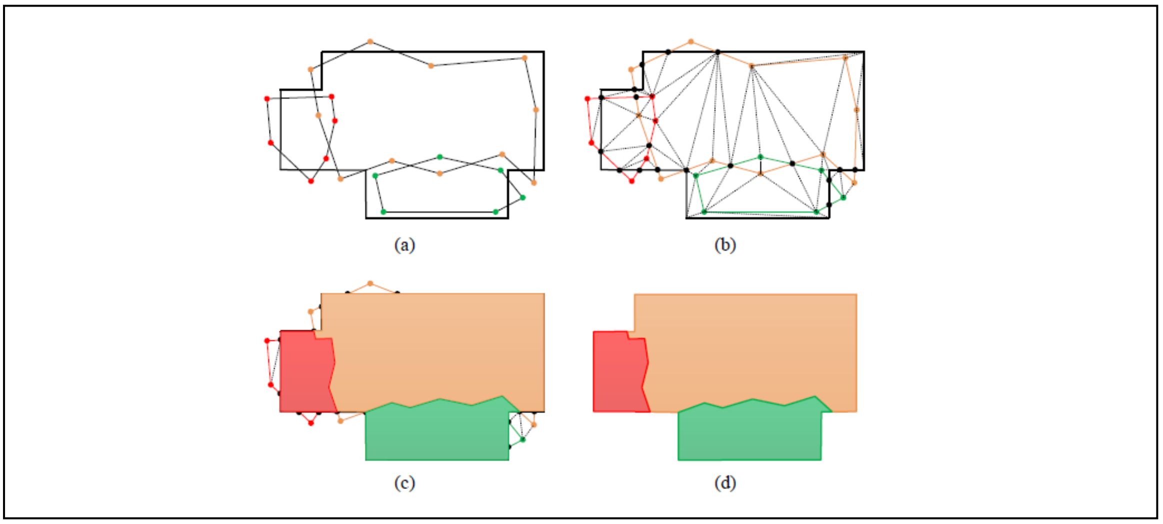

Figure 15: Snapping of roof layer contours (a) Footprint map and the roof layer contours (b) The derived constrained Delaunay Triangulations (c) The tagged roof regions (d) The output of the snapped contours (Source :(Xiong et al., 2016)

The 3D slum model was obtained as a 3D polygon shapefile. To eliminate the unwanted spikes in the model, a noise filter was applied again, and the process of 3D building reconstruction was repeated. Post-processing of the model was done manually to eliminate minor spikes in the model using a GIS platform.

3.5.4. Implementation of the semantic information in the 3D model and Visualisation of the model

The generated 3D model was populated with the semantic attribute information using the Extract, Transform and Load platform (ETL) to create a digital twin of the slum. The information related to the individual buildings in the slum environment was extracted from the attributes of the building footprint shapefile. Implementation was also created to facilitate updating the new semantic information for the future. The individual 3D slum buildings were populated with information related to the construction material used, the area in m^2, number of floors, house number, building height values, and terrain elevation values. A workflow was created to add new information about individual houses that could be updated if the house number was known. The model was exported as a KML (Keyhole Markup language) file and was visualised in Google Earth Pro along with the semantic information of the individual house. Visualising the results in Google Earth Pro was preferred as it is free, can be easily shared with the stakeholders, and provides a perception for any project which is location-based (Google Earth ProTM - Atlas Networking, 2022).

3.6. Phase 3 : Evaluation of the model

A qualitative approach was used to evaluate the generated 3D model. The generated 3D slum model was evaluated by conducting semi-structured interviews with the stakeholders. Five interviewees were questioned on the feasibility of the methodology, usability and fitness of the model, and satisfaction with the method used for visualisation. The interviews were conducted on an online video conferencing platform, and interviewees were given a presentation on the methodology used and the research before starting the evaluation procedure. The results were measured based on defined qualitative factors like algorithm, usability and fitness of the model, visualisation and overall satisfaction using an evaluation scale from 1 to 5 (1- Strongly agree, 2- agree, 3- Neither agree nor disagree, 4- disagree, 5- strongly disagree). The interview was then followed by a few questions related to the strengths and limitations of the model. The interview session was recorded and transcribed. The detailed questionnaire and the answers are presented in Appendix.

3.7. Summary

In overview, this research took place in three phases; 1. Understanding the user requirements of the model, 2. 3D building reconstruction, 3. Evaluation of the model. Semi-structured interviews were conducted to know the user requirements of the model. The insights obtained from the literature review were applied to the pre-processing steps. The 3D model was generated using point cloud and the building footprints as the input data. The 3D model was enriched with semantic information using the cadastral information from the building footprints to create a digital twin of the slum. The generated 3D model was evaluated based on semi-structured interviews with the stakeholders.

4. RESULTS AND DISCUSSIONS

4.1. User requirements

Semi-structured interviews were conducted among three experts from São Paulo to get an insight into their background of work, information on the available data, comments on the model usage, comments on the method for the 3D reconstruction and comments on the 3D models. Given below is the summary of the results:

According to the experts, the 3D slum model is needed:
1. To improve project planning and development activities related to slum upgrading.
2. To reduce the time and effort of going to the location and conducting field surveys.
3. To monitor the growth of the slums and help visualise the area in 3D.

The expectation of the method for the 3D reconstruction of slums:
1. The algorithm should be open source or cost-effective.
2. The input data would be the point cloud, and the building footprint and the output would be the 3D model with semantic information related to the individual houses in the slums.
3. The workflow should allow the future update of any new semantic information in the model.
4. A possibility of extracting the building footprints from the orthophoto.

The expectation of the 3D model
1. Individual houses should be correctly recognised and visualised as solid blocks.
2. The model should have semantic information related to the individual buildings.

The results from phase 1 formed the basis of this research. The expectations related to the 3D building reconstruction method were in-line with the existing state-of-the-art method. This research phase also provided some insight into using the 3D slum model in the activities related to slum upgrading. A major emphasis was that the 3D model should have semantic information related to the individual buildings, and an implementation should be made to update it in the future. Most of the user requirements were considered for building the model, except one which required the generation of the building footprints from the orthophotos as it was out of the scope of this research and is a research topic on its own.

4.2. Results of the Pre-processing of the data

4.2.1. Filtering of the point cloud

The workflow to filter the ground and building points was developed in FME (Figure 18). The workflow successfully filtered the point cloud into building points (non-ground) points (Figure 16). Since this research required only the building points, the effects of shadows and vegetation in the 3D reconstruction were minimised. The noise filter was applied to the entire point cloud by defining a spherical neighbourhood with a radius of approximately 0.485 m (a system-generated default value taking into account the point density in that area (CloudCompare Version 2.6.1. User Manual, 2015)) and fitting a plane (around each point of the cloud). The noise filter aided in decreasing the noise in the point cloud, as seen in Figure 17 and Table 3 (see internal accuracy), and this facilitated the segmentation and roof mapping process. The filtering also removed the unwanted roof furniture like water tanks and vegetation on the roof (Figure 17). However, filtering of vegetation in between the dense buildings caused occlusions within the building points, which was unavoidable, but its effect on the 3D building reconstruction was minimal.

Figure 16: Left: Point cloud covering entire area, Right: Filtered point cloud only with building footprints

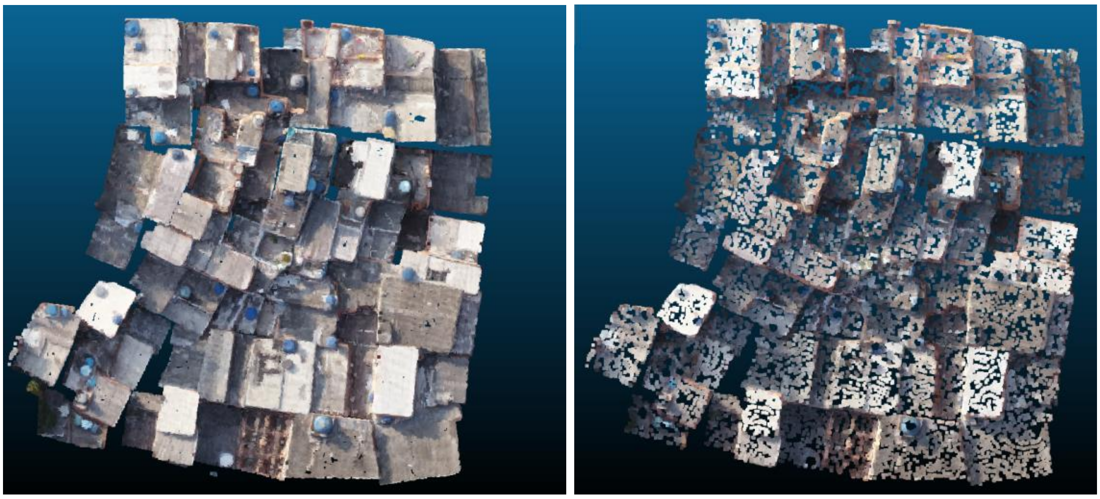

Figure 17: Left: Original point cloud with water tanks and roof furniture, Right: Filtered point cloud eliminated the waters tanks and outliers from the roof

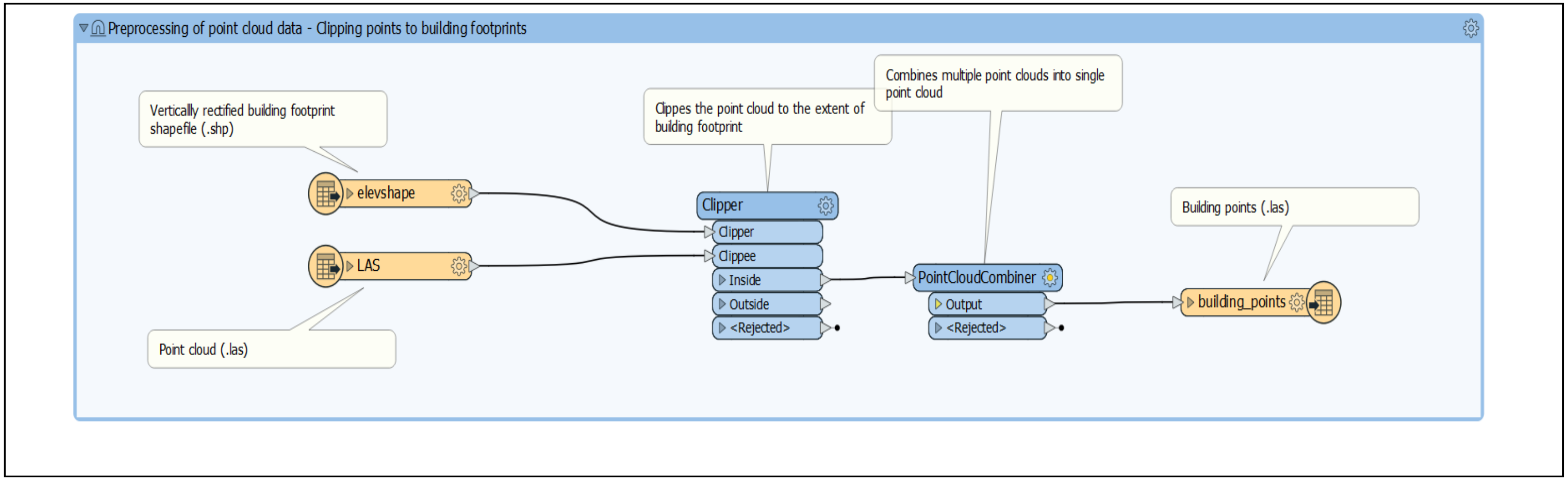

Figure 18: FME workflow for filtering the point into ground and non-ground (building points)

4.2.2. Verification of the point cloud

Points		Point spacing (m)		Point density (m2)		Internal accuracy (RMS)	
Original Point cloud	Cleaned Point cloud	Original Point cloud	Cleaned Point cloud	Original Point cloud	Cleaned Point cloud	Original Point cloud	Cleaned Point cloud
4,652,938	1,695,544	0.16	0.26	38.49	14.31	0.0108	0.0083
						0.0293	0.021
						0.0541	0.037
						0.0338	0.0245
						0.0270	0.0228
Average Internal accuracy (RMS)						0.0310	0.0227

Table 3: Verification of the point cloud

The point clouds were analysed before and after filtering based on the number of points, point spacing, point density and internal accuracy. It showed that the number of points and the point density decreased after applying the noise filter and the point spacing increased, as seen in Table 3. The Root Mean Square (RMS)/the standard deviation also decreased in the filtered point cloud compared to the original point cloud, suggesting that filtering helped increase the internal accuracy of the point cloud. There was an increase in the internal accuracy of the filtered point cloud as the unwanted noise over the roof structures was minimised, giving rise to a smoother surface, causing it easier to fit a plane.

4.2.3. Segmentation of the point cloud

Segmentation is one of the first and most important steps in roof surface modelling. To facilitate the process of segmentation, several parameters have to be set, and these parameters depend on the spatial appearance of the objects in the laser data, such as the minimum size of the object to be detected, the point density of the point cloud etc. The segmentation parameters were set referring to the manual designed for the project '3D4EM' (Xiong et al., 2015) and the MSc thesis of Mwangangi (2019), who had applied the same algorithm. The seed neighbourhood radius was set to 2. The growing search radius was set to 1 since the average point spacing of the resulting filtered point cloud was around 0.2-1m. The maximum distance of a point to the surface was set to a default of 0.3. The minimum segment size was set to 30 as the minimum segment size was dependent on the point density, which had an average value of (15-20 points/m^2).

The segmentation parameters used in Figure 19 were selected as the optimal parameters but still showed over-segmentation, which could be attributed to the fact that the roof structures in the building in the slums were highly irregular, and the irregularities in the point cloud affected the segmentation. The segmentation result with the parameters used in Figures 20 and 21 resulted in erroneous structure boundaries, which might have occurred due to the selection of the seed radius as 1. The selection of seed radius as 1m restricted the neighbourhood to a radius of 1m. This gave rise to unwanted errors in areas where no points were within a search radius of 1m. In Figure 21, when the maximum grow radius was restricted to 1m, it gave rise to a highly over-segmented result. The segment size defines the minimum number of points in a segment. Small segments were obtained when the minimum segment size was given a value less than the point density, which gave rise to over-segmentation or loss of segments (white segments), as seen in Figure 22.

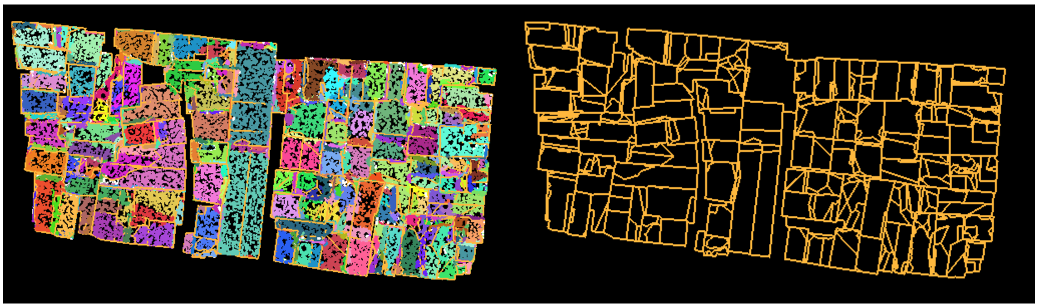

Figure 19: Segmentation results with Seed radius :2 , maximum grow radius : 1 , Maximum growing distance : 0.3 , Minimum segment size : 30 (Optimal result)

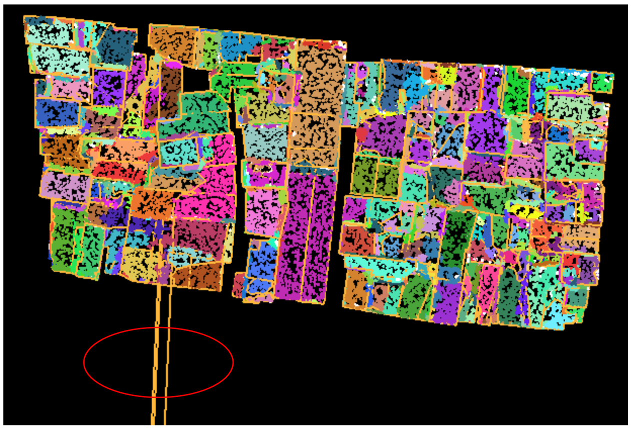

Figure 20: Segmentation results with Seed radius : 1, maximum grow radius : 1 , Maximum growing distance : 0.3 , Minimum segment size : 30 (The structure boundaries weren't defined well and lead to an erroneous 3D model)

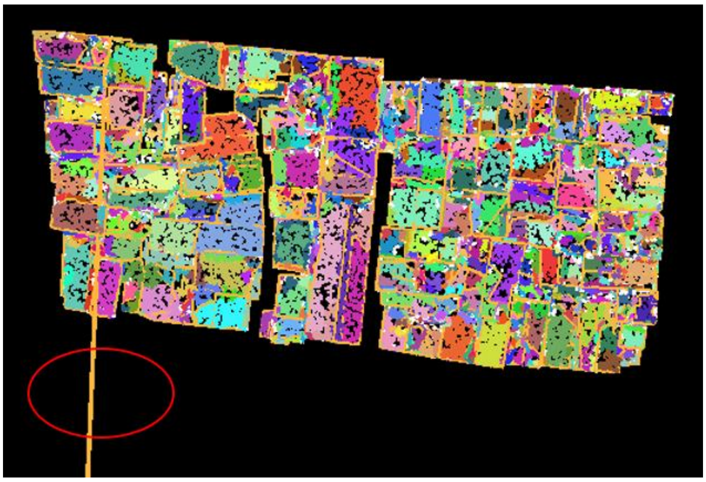

Figure 21: Segmentation results with Seed radius : 1, maximum grow radius : 1 , Maximum growing distance : 0.3 , Minimum segment size : 30 (Highly over-segmented, the structure boundaries weren't defined well and lead to an erroneous 3D model)

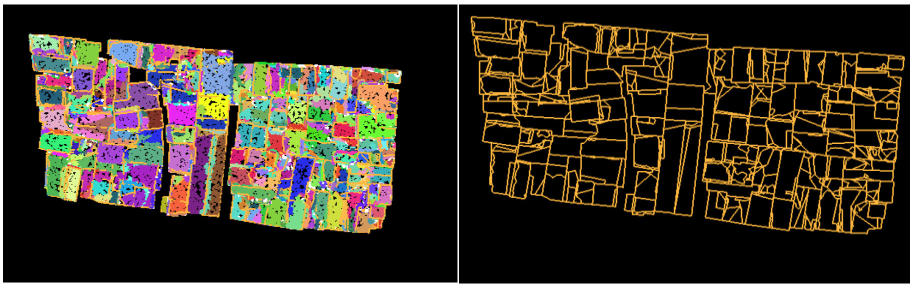

Figure 22: Segmentation results with Seed radius : 1, maximum grow radius : 1 , Maximum growing distance : 0.3, Minimum segment size : 10 (Over-segmented)

4.2.4. Result of 3D model

The main objective of this research focuses on creating a methodological workflow to create a 3D model for the buildings in the slums. The final 3D model obtained is shown in Figure 23. Out of the total of 2156 buildings, 2146 buildings were correctly modelled. Around ten houses were not modelled due to noise filtering errors or due to the occlusions created because of the removal of vegetation covering the roofs of the houses. The model was generated in the format of a 3D polygon shapefile. The three zones were processed separately and merged as one 3D slum model.

Figure 23: The generated 3D slum model

4.3. Limitations of the 3D model

Due to the noise in the UAV point cloud, some erroneous spikes were observed, as seen in Figure 24. Few areas displayed more errors than others and needed to be filtered again by increasing the neighbourhood radius to approximately 1m. In this case, the process of 3D reconstruction was repeated. The generated model still required post-processing using GIS software which needed manual editing. The errors in the 3D models were seen around the edges of the model. This could be due to the errors in the image matching. The presence of vegetation between the dense houses also affected the 3D model creation. In such a condition, the buildings were wrongly modelled, or some buildings (a total of ten buildings) were not modelled. The irregular roof structures in most buildings in the slums gave rise to non-smooth surfaces during the creation of the models, which is due to the errors in segmentation (over-segmentation).

(a)

(b)

(c)

Figure 24: Errors in the 3D reconstruction of buildings in the slums : a) Erroneous spikes on the edges of the building, b) Error in the 3D building generation due to presence of vegetation c) Irregular roof structures

4.4. Final results after the implementation of semantic information

The generated 3D model was successfully updated with the semantic information. Implementation was made to facilitate the update of the new attribute information within the model in the future with a workflow developed using an ETL platform (Figures 25 and 26). The following steps were taken to implement the semantic information in the 3D model.

1. All the buildings from each sub-zone were combined and aggregated into a single zone.
2. A counter was used to create a unique ID for the 3D buildings.
3. The 3D geometries of the buildings were transformed into 2D geometry polygons.
4. The 2D building footprints were converted into points.
5. A transformer was used to pass the attributes from points (obtained from the 2D shapefile) to polygons (obtained from the 3D shapefile).
6. The resulting attributes were then merged into the original 3D geometries using the unique ID which was set for the 3D buildings.
7. The three zones were processed separately and merged as an entire area.

8. A conditional clause was applied to facilitate the future update of new semantic information.

The information related to construction materials, area of the house (m^2), house number, and the number of floors was used from the building footprint shapefile and was updated in the model. The model was visualised in Google Earth. Implementation was made to update any semantic information related to any individual house in the future based on the details of the house number. Figure 27 shows the final results of the model.
The results of the research are demonstrated in this video; https://youtu.be/mZgxcO7HCso.

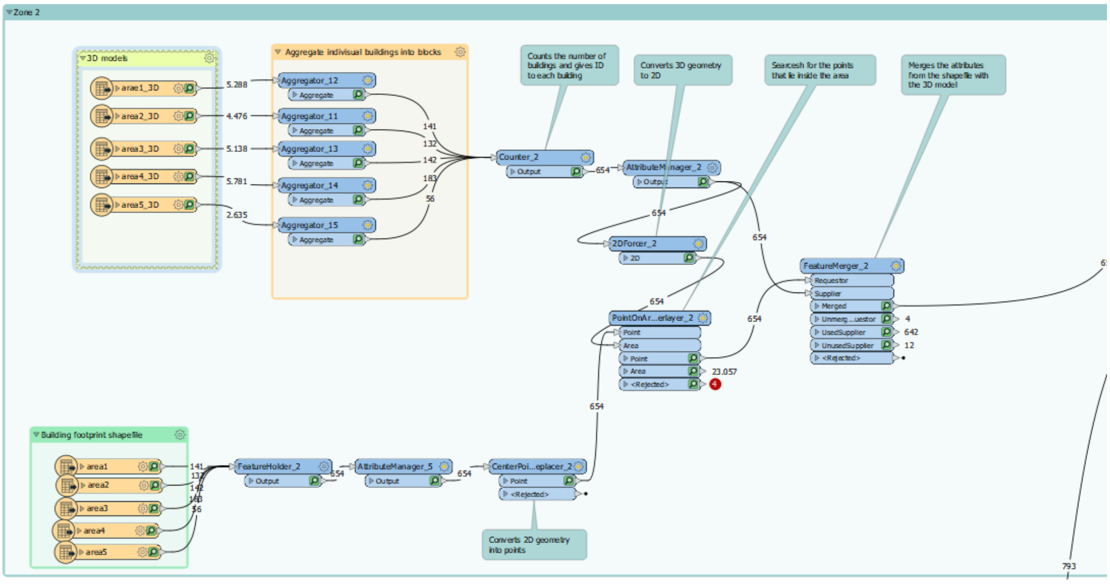

Figure 25: FME workflow for implementation of the semantic information into the model

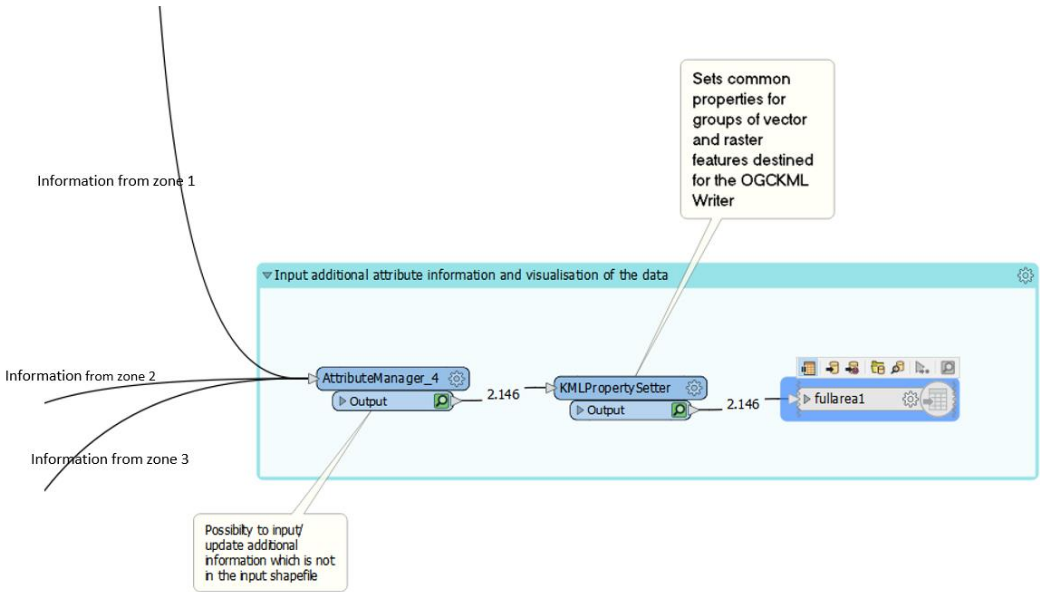

Figure 26: FME workflow to facilitate the input additional attribute information and visualise the data

Figure 27: The final 3D model of the buildings in the slums updated with the semantic information

4.5. Evaluation of the 3D model

Five interviewees from São Paulo involved in the projects related to slums were interviewed to evaluate the quality of the generated 3D slum model. The interviewees were asked to comment on the algorithm, usability and fitness of the model and visualisation on the evaluation scale from 1 to 5 (1- Strongly agree, 2- agree, 3- Neither agree nor disagree, 4- disagree, 5- strongly disagree). The results of the evaluation matrix are displayed in Table 4.

<table>
<tr><td colspan="2"></td><td colspan="5">Scale</td></tr>
<tr><td>Criteria</td><td>Description of the Criteria</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td rowspan="3">Algorithm</td><td>The algorithm used for the 3D reconstruction of slums aligned with the stakeholders' expectations.</td><td>|</td><td>|</td><td>|||</td><td></td><td></td></tr>
<tr><td>Software used are open source or cost effective</td><td>|</td><td>|||</td><td></td><td>|</td><td></td></tr>
<tr><td>The methodology used is feasible</td><td></td><td>|</td><td>||||</td><td></td><td></td></tr>
<tr><td>Usability and fitness of the model</td><td>The presented level of details of the 3D model is sufficient for the buildings in the slum</td><td>||||</td><td>|</td><td></td><td></td><td></td></tr>
</table>

<table>
<tr><td></td><td>Geometry of the building models is satisfactory</td><td></td><td>|</td><td>||</td><td>||</td><td></td></tr>
<tr><td></td><td>Input of semantic information into the model and implementation to update the attribute information is possible</td><td>||</td><td>||</td><td>|</td><td></td><td></td></tr>
<tr><td>Visualization</td><td>The method used for visualizing the buildings in the slum conveys the required information.</td><td>|||</td><td>|</td><td>|</td><td></td><td></td></tr>
<tr><td></td><td>Overall satisfaction with the results</td><td></td><td>||||</td><td>|</td><td></td><td></td></tr>
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Table 4: Evaluation matrix for interviews with the stakeholders

The interview results are summarised below:

1. Four out of five participants remained neutral regarding the algorithm's feasibility for practical applications, and three out of five participants agreed that the software was open source and cost-effective.
2. Four out of five participants strongly agreed that the presented level of details of the 3D model is sufficient for the buildings in the slum.
3. The comment on the geometry of the building model was debatable as two participants disagreed, two remained neutral, and one agreed that it was satisfactory.
4. All the four agreed on the possibility of inputting the semantic information into the model and were satisfied with the method used for visualising the model.

All the participants were asked whether "The presented 3D slum model can be used for applications related to slum upgrading activities (Yes/No)". Three participants responded affirmatively as, *"The 3D slum model could be used to visualise the existing buildings and gather information, which would be helpful for the urban planners for slum upgrading and would help to share the data easily with the slum dwellers*". Two participants responded negatively as "*The cartographic accuracy of the model was not guaranteed and hence could not be used for land regularisation*". According to the interviewees, the model could be improved for higher geometric precision and have clean-looking buildings. An overview of the detailed evaluation matrix used in the research can be found in the appendix.

The results of phase 3 can be linked back to the results of phase 1, as the stakeholders agreed that the 3D model generated and the methodology used was satisfactory and met the expectation of the stakeholders. The methodological workflow developed in this research automates the 3D slum model generation. It also automated the input and update of the semantic information into the model, saving a lot of time and manual effort. The results of this study show that it fills the gap in the knowledge in generating the 3D model of slums using the UAV data. However, the generated model requires further improvements on roof details.

5. CONCLUSIONS AND RECOMMENDATIONS

The main goal of the current study was to develop a methodological workflow to automatically reconstruct a 3D slum model using the data from the UAV and the 2D footprint in São Paulo, Brazil. The study also aimed at developing a method to input and update the attribute information in the generated 3D model to facilitate the creation of a digital twin of the slum. The results of this study indicated that the suggested semi-automatic method could be used to efficiently create a semantically-enriched 3D slum model. However, the overall quality of the roof geometry was not satisfactory and needed manual post-processing to obtain spike-free models. Due to a lack of validation data, the quantitative evaluation of the model could not be carried out; hence the qualitative evaluation was carried out by conducting interviews with the stakeholders.

The semi-structured interviews with the stakeholders from São Paulo, Brazil, were valuable in giving insight into the information on the available data, geometric requirements of the model, the potential applications of the 3D slum model and the expectation of the algorithm. Semi-structured interviews were a useful resource for qualitative research to get interpretive data and give a direction to shape the research, even though the study was based on a small sample of participants.

The methodology by (Xiong et al., 2014, 2016) could successfully generate the 3D buildings in the slums but showed some limitations. Over-segmentation of the roofs was observed due to irregular roof structures, which gave rise to erroneous spikes in some regions near the edges of the buildings due to the noise in the point cloud. It was seen that some areas in the point cloud had more noise and needed to be filtered more, possibly due to the errors in image matching. Most areas needed manual post-processing to eliminate the spikes and get a clean model. It was also observed that the algorithm could not handle processing a large area at once, so the area had to be clipped into smaller areas for better results of 3D reconstruction. Around ten houses were not modelled due to vegetation between the houses or canopy over the roofs.

This research used a qualitative evaluation method for the generated 3D slum model due to the lack of available validation data. The semi-structured interviews were carried out with the stakeholders to evaluate the model. The interviews helped gain insight into how the generated 3D model is useful to the stakeholders for practical use. From the interviews, it can be concluded that the resulting 3D model of the favela could be used in meetings with the slum dwellers to aid in exchanging information between the planners and the residents, as the model can be easily visualised and shared using Google Earth Pro.

5.1. Limitations

The main limitation of this study is the lack of ground truth data for the validation of the model. Due to the absence of the ground truth/validation data, a quantitative model evaluation could not be carried out. The methodology used in this study was tested only with one dataset and one study area. Hence the results were specific to the selected study area and the data. Another major limitation in the 3D model was the presence of spikes that needed to be manually eliminated.

5.2. Recommendations for further studies

For future work, more robust methods of 3D reconstruction can also be explored so that it works on the entire area at once. More in-depth research should be conducted to find a reasonable approach to tackle unwanted spikes automatically. The automatic detection and removal of the unwanted spikes in the model will save much time in obtaining a spike-free model. Furthermore, future researchers can also work on developing methods for automatic extraction of the rooflines to generate the building footprints from the orthophotos. Future researchers working on developing a 3D slum model can conduct fieldwork and use the field data to validate the results. Therefore, the methodology used in this study is recommended to be tested with other study areas and other datasets (such as point clouds obtained from ALS) to understand its interoperability.

6. ETHICAL CONSIDERATIONS, RISKS AND CONTINGENCIES

The City Hall, São Paulo, Brazil, provided all the data required for this study. However, since the data includes high-resolution UAV images over the settlements, there is a concern regarding privacy and the misuse of the data. The situation was dealt with by making responsible use of the given data for the sole purpose of this research. The data was not and will not be shared with anyone without prior written permission from the authorities from the City Hall, São Paulo. I have not collected any data during this research concerning any privacy issues. The video interviews were recorded and transcribed with the prior permission of the interviewees.

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APPENDIX

Appendix 1: Questionnaire and answers to the semi-structured interviews with the stakeholders

Criteria	Description of the criteria	Questionnaire	Interviewee 1	Interviewee 2	Interviewee 3
Background of work	To understand the background knowledge of the interviewees, which could influence their answers.	1.What is your work domain ? 2.How is your experience working with the 3D data and for which applications are you using the 3D data for? 3.Have you used 3D data for slum mapping? 4.If yes, for what applications?	1. Urban Planner/ Architect 2. Working with 3D data for the architectural projects (houses/buildings) , introducing BIM for social housing. 3. Yes, it is in a trial phase. 4. For visualization and to understand the morphology better.	1. Urban Planner/ Architect 2. Worked with 3D data for the architectural projects (houses/buildings) 3. No experience with modelling slums in 3D. 4. Not applicable.	1. BIM specialist 2.Working with BIM for social housing with software like ArchiCAD, Revit, and Civil3D, Trimble connect, BIM collab zoom, Solibri, etc. 3. Yes, slums were mapped using UAVs to produce a 3D point cloud. 4. For visualization, produce a building footprint map link to a database with the names of the individual houses.
Information on the available data	To understand the quality of the data which is provided (UAV point cloud in Jardim Colombo and shapefiles).	1.Could you please comment on the quality of the point cloud data provided for the research? 2. What are the shortcomings of the data? 3. Did you face any challenges in the past when working with this data ?	1. Documentation related to the generation of the point cloud was provided to me, and shapefiles were generated manually using the orthophotos with some ground verification. 2. During the early phases, the point cloud was generated only with the orthogonal images captured with the UAVs. Later another project was initiated to get the oblique images to get a better point cloud. 3. The only challenge faced is the complexity of	1. Documentation related to the generation of the point cloud has been provided to me. The interviewee can't say much about the quality of the shapefiles as it has been manually generated using orthophotos. 2. The shapefiles provided do not have the vertical coordinates defined since they are very new to working with the 3D GIS data in their department.	1. __NA__ 2. __NA__ 3. UAVs do not produce a detailed image of the façade. It also doesn't provide information on the building material used for houses. A field survey is highly needed to get complete information on the actual extent of the building, the building material used, and the number of people and families living in those houses.

			the houses in the slums—none with the data as such.		
Comments on the usage of the model	To understand the demand for establishing a 3D model for slums.	1.Why do you need a 3D model for slums? 2. Who is the user of the model? 3.For which practical applications will the model be used?	1. 3D model of slums will be helpful in the visualization where individual houses will be represented as a solid geometry and will therefore ensure better quality in the upcoming projects related to the slums. 2. The urban planners in the city hall, São Paulo. The plan is to make the models available on the (http://geosampa.prefeitura.sp.gov.br/) an open website for data from São Paulo to be available for researchers all over the world to conduct scientific analysis on the data. 3. The model will monitor the growth of the slums, classify the risky regions, and planning other development activities.	(Ps: The interviewee is not directly involved with the projects related to the 3D reconstruction of the slums.) 1. The 3D models will save time and effort of going to the location and conducting a survey and will be helpful in the visualization of the houses located in the slums. 2. The urban planners in the city hall, São Paulo 3. The model will monitor the growth of the slums for easy visualization.	1. To improve project planning, produce a database linked to the geospatial data. 2. For now, nobody is the user, as the work is mostly experimental, but the potential users could be urban designers, the residents in the favelas, and the city dwellers. 3. BIM technologies and other processes.
Comments on the method used for the 3D reconstruction	To understand the methods /applications to reconstruct the 3D models from point clouds	1. What method of 3D reconstruction are you using? 2.What are the drawbacks of the currently used method for the 3D reconstruction of slums?	1. Currently, a model is being made for slums in the Panorama region, São Paulo, Brazil. The model is constructed using Autodesk Infraworks, where the data is imported from	1.Not involved in the current project on 3D reconstruction of slums. 2. Not applicable 3. Could preferably involve point clouds as the only input data	1. Directly visualizing the point cloud using 3D modelling software. 2. Heavy files, more processing time, software require a lot of manual work.

		3.What are your expectations with the algorithm for the 3D reconstruction of slums from the UAVs?	Bing maps, point clouds orthophotos, and shapefiles. 2. The major drawback is that Autodesk Infraworks is licensed software, and it works on predefined rules, mainly for urban areas. Since the slums do not work on any specific rules, it becomes difficult to model using Infraworks. It requires a lot of manual work and adjustments to align the shapefiles to the orthophoto and consumes time. 3. The algorithm should be open source or use open source or less expensive software. Preferably involve point clouds as the only input data. The result should be the 3D model as shapefiles need to be constantly updated due to the changing morphology of the slums.		3. Expectation is low as slums have a lot of complexity under the roof. We need an algorithm for creating solids from individual houses from the point cloud and the shapefile with local data as attributes. One should be able to input new information related to the local data in the model if any further field studies are conducted.
Comments on the 3D model					
Geometric fidelity	The "trueness" of the features in data to the shapes and alignment of the real world features they represent i.e. any real-world alignment or	1.To what extent of accuracy do you wish to obtain the model depending on the application you need to use it for?	1. The individual houses should be correctly recognized, visualized, and colour-coded based on their heights and construction materials. The	1.The individual houses should be correctly recognized and visualized.	1. Each solid must be separated and represented as an individual block, and each block should have information regarding the building material.

	shape must be accurately reflected in the data to the required specification		streets can also be visualized. The model should be suiTable enough to use as a reference for the planning purpose.		
Adaptability	To determine the number of applications the model can be used for	1.Depending on the number of applications the model is going to be used for, which is the format which is widely used?	1. Solid geometry model preferable as a shapefile.	1. A solid geometry model.	1. All solids in IFC format (Industry Foundation Classes)

Appendix 2: Evaluation of the model

General comments on Usability of the 3D slum model	
The presented 3D slum model can be used for applications related to slum upgrading activities. (yes/no)	Yes, because it allows you to record activities in a more practical way, with an easy-to-understand visualization. The 3D slum model can be used to improve the visualization of existing buildings, assisting urban planners and possibility to the data with slum dwellers. No, the 3D slum model cannot be used for land regularization because the cartographic accuracy is not guaranteed. The 3D slum model cannot be used for supervision of works.
Please list and explain what can be further improved and modified in the 3D slum model.	- Representation of how many families live in each houses (maybe as an attribute); - Higher geometric and cartographic precision. - To enable the land tenure regularization, the modelling of residences could have a better definition (number of floors, delimitation by the masonry and less noise). - For the production of urban and architectural projects, the 3D model could have a better definition in terms of access to buildings (location of the doors and level to access for each family). -The representation of the buildings does not include the division by floors as represented in the shape -Each building must be represented on a divided solid.

	One possibility: uniting the solids that represent a single building; Another possibility: The representation of the below the roof must contemplate the floors as indicated in the shapes Perhaps it would be interesting defining the buildings contours using the aerial orthophoto, which has guaranteed cartographic accuracy, and not the information from the roof point cloud. -expensive software Considering that São Paulo has 12 million inhabitants and the software cost will be over USD 25,000, this cost would be unfeasible. Considering the software price, the Infraworks Autodesk Software still presents best cost-effective (around USD 1,500 per year), even not using the data from dense cloud for best precision of building heights.
Please list and explain the benefits of the 3D slum model.	- An accurate means of visualization for professionals and the community, favouring the processes for necessary interventions. - 3D historical mapping for modifications. - Possibility of alterations and insertion of parameters, constituting a database. - Speed to produce the 3D model. - Cost effective. - As it allows the opening with Google Earth, the 3D model facilitates the access to the general public. -This 3D model of the favela is interesting to be used in meetings with slum residents. It can be an important material for exchanging information between designers and residents.