

Model for Automated Generation of DTM with Hybrid Data Structure Using Point Clouds

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Abstract: In this paper, a model has been created for the automated generation of DTM (Digital Terrain Models) using a hybrid data structure based on LiDAR (Light Detection and Ranging) data. The automated process facilitates the creation and implementation of both simplified and complex DTMs using hybrid data structure. The classification of terrain into various classes is achieved through the application of the slope parameter. This model can be applied to the entire area or a specific area of interest by loading the boundaries and offers the optional capability to implement structural terrain lines in the form of watersheds. The proposed model addresses the challenge of generating DTMs in rapidly changing terrain and areas with complex landscapes, providing solutions to enhance DTM generation performance. Alongside the hybrid DTM structure, the developed model introduces a hierarchical grid with three different spatial resolutions, allowing users to adjust them based on specific requirements. The model is designed to adapt to the terrain, creating a hybrid data structure that combines the benefits of the GRID and TIN (Triangulated Irregular Network) approaches. The development and implementation of the model were carried out in ModelBuilder, within the ArcMap software environment.

Keywords: automatic process; DTM; grid; hybrid data structure; point clouds; slope; TIN

1 INTRODUCTION

The initial development of Digital Terrain Models (DTMs) took place at the Massachusetts Institute of Technology Laboratory [1]. Their primary objective was to establish a connection with reality and represent the spatial distribution of land features through digital maps using numerical data. Today, there are various procedures and methods for collecting geodata. Advancements in technology have introduced modern data collection techniques such as digital photogrammetry and laser scanning. Additionally, powerful software solutions have emerged to facilitate data processing and digital terrain modeling. DTMs serve the purpose of transforming collected information into modeled data that reflects different features, enabling various analyses in diverse applications. While different authors may define DTMs in varying ways, they essentially represent a collection of points in 3D space with accompanying geoinformation. These models can be utilized to represent elevation and can be displayed virtually in different formats or spatial representations.

The generation of Digital Terrain Models (DTMs) commonly involves two widely used structures: Triangle Irregular Networks (TIN) and regular Grid shapes. However, relying solely on TIN or Grid structures may be insufficient unless seam lines are introduced to enhance their adaptation to reality [2]. Creating a hybrid DTM combines the advantages of both approaches, providing more favorable conditions for the representation and analysis of the natural and spatial characteristics of the terrain.

Hybrid DTMs offer a distinct advantage in terms of visual perception, as they provide a more immersive experience of real space through visualization. By incorporating algorithmic analysis of morphometric parameters of the terrain, a hybrid DTM allows for a qualitatively new way of perceiving spatial relationships and characteristics of the relief. This facilitates more efficient, faster, and more comprehensive terrain analysis.

Furthermore, the quantitative analysis of the relief, which plays a vital role in geospatial assessment, benefits significantly from the use of a developed hybrid DTM. It enables faster, more complex, and highly accurate

observation of the topographic surface, enhancing the understanding of its properties.

The main goal of this paper is to present process of automated terrain modeling in a hybrid structure, based on raw LiDAR (Light Detection and Ranging) data. The aim of the research is to develop and implement a concept that will enable automated creation of DTM with a hybrid data structure for an arbitrarily selected area. The presented model should enable the generation of a simplified and complex DTM with a hybrid data structure. Simplified and complex hybrid models are formed from a raw point cloud. This research also presents possibility of producing characteristic terrain lines, such as watersheds.

1.1 Previous Works

Digital terrain modeling is a modern method of elevation representation of land and relief forms [3]. Digital terrain modeling includes activities related to the collection and processing of geospatial data, the development of appropriate mathematical models, as well as aspects of use in various fields of application [4]. Based on DTM, through algorithmic analysis of morphometric parameters of the relief, a qualitatively new way of perceiving spatial relations and terrain characteristics is enabled. They have great application in hydrology, ecology, agriculture, engineering and other jobs.

Depending on the modeling and organization of data, or the structure of geospatial data, there are three basic types of DMT [3, 5, 6]:

- Raster data structure (Grid);
- Irregular Triangles Network (TIN);
- Hybrid data structure.

The Grid-shaped model consists of a regular lattice structure (usually a square Grid) whose members are points of known heights (Fig. 1). The great disadvantage of this method is the impossibility of a quality display of surfaces with sudden changes in the terrain or twisting of the terrain such as karst landscapes or fortresses. In order to eliminate some of the imperfection of the Grid structure, data modification is performed, in order that the resolution of the content is adjusted depending on the location and the complexity of the terrain configuration [7].

The TIN model represents a network of irregular triangles (Fig. 1), which is composed of distributed lines

and nodes with 3D coordinates (X , Y and Z). Some of the advantages of TIN structure is that it includes geomorphological forms such as watersheds, ravines, peaks. For flat terrain, only a few triangles are needed. On the other hand, this type of data structure is difficult to combine and compare with other types of data. It can be concluded that the structures of data in the form of TIN or Grid, has certain advantages but also disadvantages. Both of them do not provide a sufficiently high-quality and universal way of application and modeling of the terrain [8]. The algorithms developed for the purpose of multiresolution model based on domain decomposition, and simplifying the TIN by preserving the critical net topology or by adjusting it in terms of keeping the characteristic points of the terrain are explained in the papers [9, 10].

The hybrid model uses different structures to represent the terrain. The hybrid data structure uses the advantages of both Grid and TIN data structures [2, 11]. Usually, the entire area covered by the DTM is divided into a hierarchical Grid of variable size, and within the individual elements of the Grid, if it is necessary, a local triangulation is created (Fig. 1). In this way, the data structure adapts more efficiently to the characteristics of the terrain, with very little data redundancy.

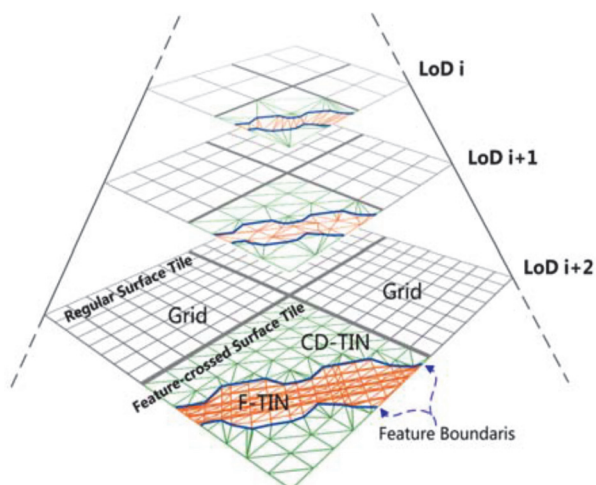


Figure 1 Hybrid surface structure integrating TINs and Grids [2]

The topic of DTM with a hybrid data structure is a relatively new and complex area of research. Compared to other areas of research in geodesy and geoinformatics, the number of papers dealing with automated terrain modeling in a hybrid structure is quite small. Some of the papers whose subject of research is DTM with a hybrid structure, are more concerned with creating a framework that allows the integration of techniques and methods with characteristics based on different types of data sets, such as irregular triangles, regular and irregular raster data structure [12, 13]. Some papers deal with the creation of a hybrid data structure, i.e., data models with multiple resolutions and levels of detail with the help of organizational methods for their seamless integration. This approach is characterized by a self-adaptive algorithm that retains terrain characteristics and efficiently combines Grid with different spatial resolutions and TIN data structures [2, 14].

Creating a DTM with a hybrid data structure is a concept of great potential for simultaneous cartographic and photogrammetry generation processes at different scales, where the main purpose is to feed different geographic information systems (GIS) with appropriate DTMs. Some studies suggest a semi-automatic DTM generalization process conditioned by a series of predefined parameters resulting in the generation of hybrid DTMs at different scales starting from a single cloud of points obtained through large-scale massive data acquisition processes [2]. The generalization results obtained, applied on different areas of different relief, offer specific application ranks for each parameter with great precision, in contrast with DEMs obtained directly in each spatial resolution [15].

Experiences and research dealing with digital height models, whose goal is to create raster DEM/DTM with improved raster values and the incorporation of certain details, can be of great importance for modeling and organizing a hybrid data structure [16]. Multiresolution terrain models provide a more efficient approach to 3D visualization, especially for the display and analysis of terrain in GIS, which is why the concepts of creating a high-resolution 3D terrain model are being improved. These models represent a space with multiple levels of detail using two main display methods: a regular Grid and TIN [17]. In some papers, there are data architectures for hybrid terrain representation that are based on the local convexification algorithm (conversion of non-convex parts into convex parts). This data structure enables the creation of additional triangles needed to connect the models and thus avoids discontinuities in the display [18].

Data sources, as well as DTM creation methods, have evolved significantly over the past few years, from the classic geodetic survey and digital topographic mapping to remote sensing, LiDAR, and radar imaging. With improved Lidar systems and the growing availability of Lidar data, research on Lidar-based DTM is receiving increasing attention. The advantage of laser scanning over other data collection techniques is the fact that this technology can collect a large number of points, with high precision and in a relatively short time [19, 20]. To develop algorithms for many other applications, one fundamental step is extracting DTM information from point clouds that contain both ground points and non-ground points [21]. This process is generally known as filtering. Aiming at realizing filtering effectively, lots of algorithms have been put forward in the past twenty years. These filtering algorithms can be categorized into four classes: slope-based, morphology-based, surface-based, and segmentation-based [19, 20].

In this research work, we proposed an automated process for the creation and implementation of a simplified and complex DTM with a hybrid data structure, using as input LiDAR data acquired by laser terrain scanning technique. Simplified DTM with a hybrid data structure involves the classification of terrain into 3 classes (Tab. 1), while a complex structure includes the classification of terrain into five classes (Tab. 2). During the creation of DTM, the parameter slope is used. Both models include a grid with variable resolution. Furthermore, we propose the possibility of the implementation of structural terrain lines in the form of watersheds.

1.2 Area of Research

The Petrovaradin fortress, located on the right bank of the Danube in Novi Sad (Serbia), at the location 45.252160°N, 19.862165°E, was chosen as the test area in this paper. The highest elevation of the Petrovaradin Fortress is 133 meters above sea level, while the lowest point is 75 meters above sea level. On the site of the previous medieval building, the current fortress was built by Austria in the period from 1692 to 1780 (Fig. 2). Because of its position and strategic importance, at that time it was named Gibraltar on the Danube. During the First and Second World Wars, as well as in the period between the two great wars, the fortress suffered some damage, and after the end of the Second World War, it was placed under the protection of the state, after which parts of the fortress were reconstructed and adapted to the needs of cultural and educational institution. The Petrovaradin fortress is one of the largest and best-preserved fortresses in Europe and covers more than 114 hectares. The fortress houses the Museum and Archive of Novi Sad, hotels and restaurants, studios and galleries of fine artists, an art academy, an astronomical observatory, a planetarium, and many other facilities. It is also home to numerous major cultural events including the EXIT festival. It is characterized by high and steep ramparts, and everything is surrounded by ditches and canals with drawbridges and control gates. For this reason, this area was chosen because it is characterized by both diverse terrain features and a very rich vegetation and forest cover.



Figure 2 Area of interest - Petrovaradin fortress

2 METHODOLOGY AND RESULTS

The process of terrain modeling involves the manipulation of an input dataset, typically consisting of a raw point cloud. In contrast to terrestrial surveying, where surveyors have control over the level of detail captured, airborne laser scanning treats the surveyed area as a single entity, with details defined by flight parameters and spatial constraints. It is important to note that the perceived "overmeasure" of information in airborne laser scanning is not redundant but can be utilized to isolate objects on the surface and provide additional insights into the research subject [22].

This study utilizes a raw point cloud obtained through aerial laser scanning of the city of Novi Sad. The data collection was a collaborative effort between the Laboratory for Geoinformatics at the Faculty of Technical Sciences in Novi Sad and the Italian company GEOCART S.p.A. The scanning was conducted using a RIEGL LMS-Q680i scanner. Flight altitude, determined by the local topography and safety regulations, was maintained at approximately 200m above ground level, with a speed of around 45 km/h. The raw laser pulse density was approximately 40 points per square meter. The geodetic system employed for the survey was ETRS89-UTM34N. The chosen study area boasts diverse relief types with complex terrain configurations, which is advantageous for exploring the capabilities of generating a hybrid DTM using a combined data structure. The presence of different geomorphological forms, particularly steep slopes, and terrain fractures, necessitates more intricate data processing and modeling procedures, making this area an ideal choice for the study.

For the realization of the proposed process of automated terrain modeling in a hybrid structure, the ArcGIS software package was used. As part of our case study, the creation of diagrams and application schemas was performed in the ModelBuilder software environment, and then a DTM with a hybrid data structure was created.

Due to the complex structure of the main development model, data processing is explained in a simplified scheme (Fig. 3). The model concept is presented as a diagram that connects process sequences and geoprocessing tools, using the output of one process as the input for another process.

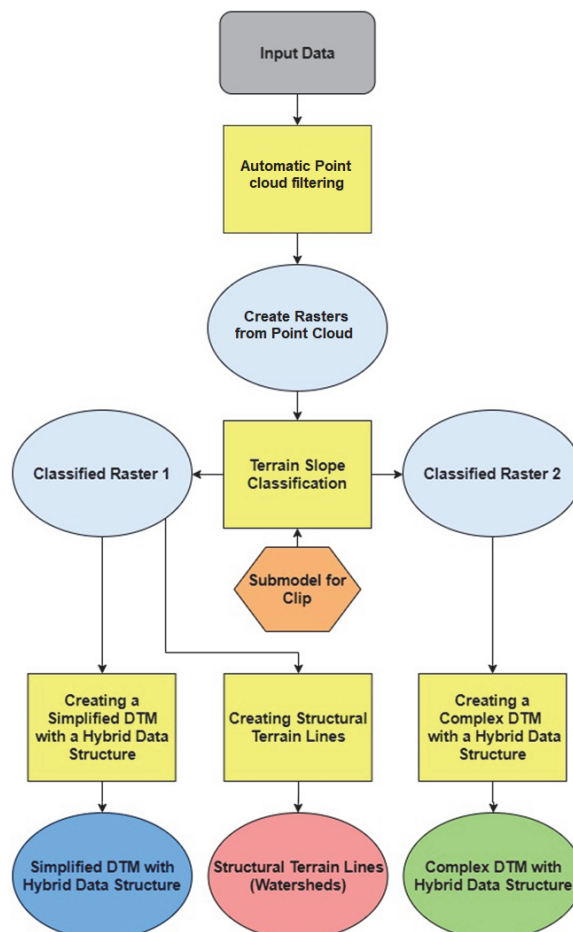


Figure 3 Simplified model for generating DTM with a hybrid data structure

To be suitable for the creation of different, simple, and complex DTM with hybrid data structure, our proposed model consists of two submodels: one for simple, and one for complex DTM, and also one separate submodel as a solution for choosing an area of interest "Submodel for Clip" (Fig. 5).

2.1 Rasters Generation from Raw Point Cloud

To generate a DTM with a hybrid data structure from the raw point cloud, first the points belonging to the ground are extracted, and then conversion of *.las data into the raster of appropriate resolutions is performed. Using the Classify LAS Ground tool, the points belonging to the terrain were extracted from the raw point cloud, while LAS Dataset to Raster was used for conversion to raster.

To create model for the creation of simple and complex DTM, we have added step for the creation of two raster's with two spatial resolutions (10 m and 8 m). These spatial resolutions were chosen as the border between high and very high spatial resolution. The horizontal distance of elevation points of 10 m belongs to high resolution, and 8 m belongs to very high spatial resolution [23]. From a raster with a spatial resolution of 10 m, simplified DTM with a hybrid data structure is created, and complex DTM with a hybrid data structure is created from a raster with a spatial resolution of 8 m (Fig. 4). The natural neighbor interpolation method is used to generate these rasters.

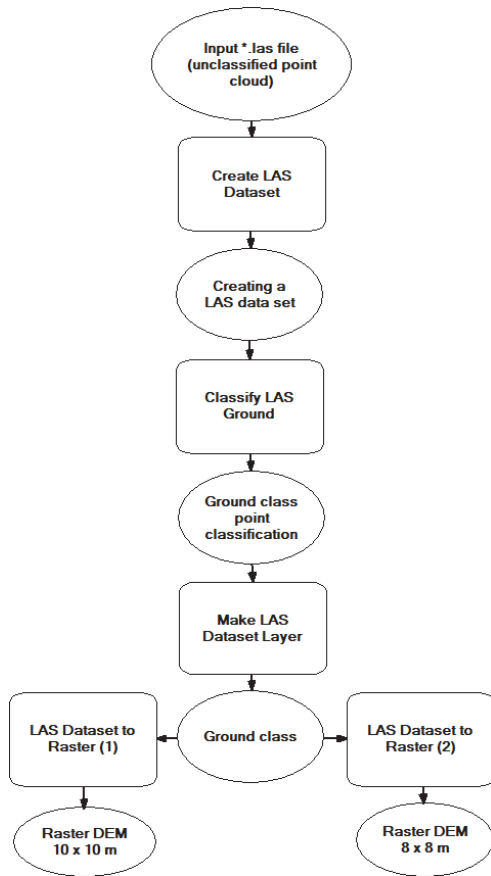


Figure 4 Rasters generation from raw point cloud

2.2 Classification of Terrain Slope Angles

The angle of inclination of the terrain is of great importance in perceiving geospace and monitoring various

processes in nature. For geomorphological analysis of the terrain, the slope angle is a key parameter. For easier relief analysis and consideration of potential opportunities for the development of a geographical area, several different classifications of terrain exist. The general classification of terrain according to slope and elevation range [21], is given in Tab. 1.

Table 1 Terrain classification using slope and elevation range [21]

Landform type	Slope / °	Elevation range / m
Plain	< 2	< 80
Upland	2-6	80-300
Hill	6-25	300-600
Mountain	> 25	> 600

Having in mind the specifics of the terrain in the study area, it is necessary to classify the terrain according to the slope and relief. In the process of classification of terrain slope angles, we have added an optional submodel for those users who want to choose only the selected part of input point cloud data.

2.2.1 Submodel for the Area of Interest

To allow the users to focus on a desired AOI (Area of Interest), the first Submodel for Clip was created. With this submodel, users can load the *.shp file with a border of desired area to subset the input raster obtained from *.las data belonging to the Ground class. The input raster is a subset based on the *.shp file. Raster is then used in further classification processes in order to create a hybrid data structure on the area of interest (AOI). It should be noted that loading the desired *.shp file according to which the raster should be subset is optional and that if the AOI is not loaded, the output raster represents the area located at the input of the Submodel for Clip (Fig. 5). Then, on both raster's, the Slope function was applied in order to conduct an analysis of the slope angle (Fig. 5).

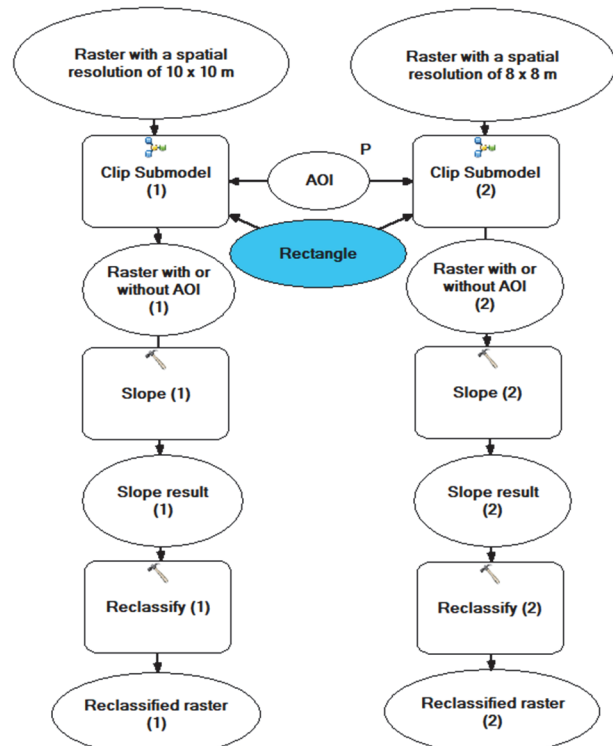


Figure 5 Classification of terrain slope angles

The next step in the process of forming a hybrid data structure is the reclassification of the slope angle, which was performed using the Reclassify function. Having in mind the specifics terrain of the selected area and the classification of the terrain according to the slope and relief (Tab. 1 and Tab. 2), new (reclassified) values of the terrain slope were created.

Table 2 Terrain classification using slope [24, 25]

Qualitative description of the slope	Slope / °
Plain	< 1
Very slightly sloping	1-3
Slightly bent	3-5
Fairly bent	5-8
Slanted	8-12
Very skewed	12-16
Moderately steep	16-20
Medium steep	20-30
Very steep	30-40
-	> 40

The proposed model enables the generation of both, simplified and complex DTM with a hybrid data structure.

Based on terrain classification by means of slope and elevation range (Tab. 1, Tab. 2), the authors suggest a simplified case with three classes, i.e., two classes for Grid and one class for TIN structure, and complex four classes for Grid and one class for TIN structure. For the simplified case (raster 1), the following class values are created:

- Class 1 - from 0° to 6°;
- Class 2 - from 6° to 25°;
- Class 3 - from 25° to 90°.

The value of 90° is taken as the limit value when it comes to the slope angle. For a more complex case (raster 2), with a hybrid data structure that has a larger number of classes, the following values were taken:

- Class 1 - from 0° to 3°;
- Class 2 - from 3° to 8°;
- Class 3 - from 8° to 16°;
- Class 4 - from 16° to 20°;
- Class 5 - from 20° to 90°.

The results of reclassification of the slope angle, for both cases, are presented in Fig. 6.

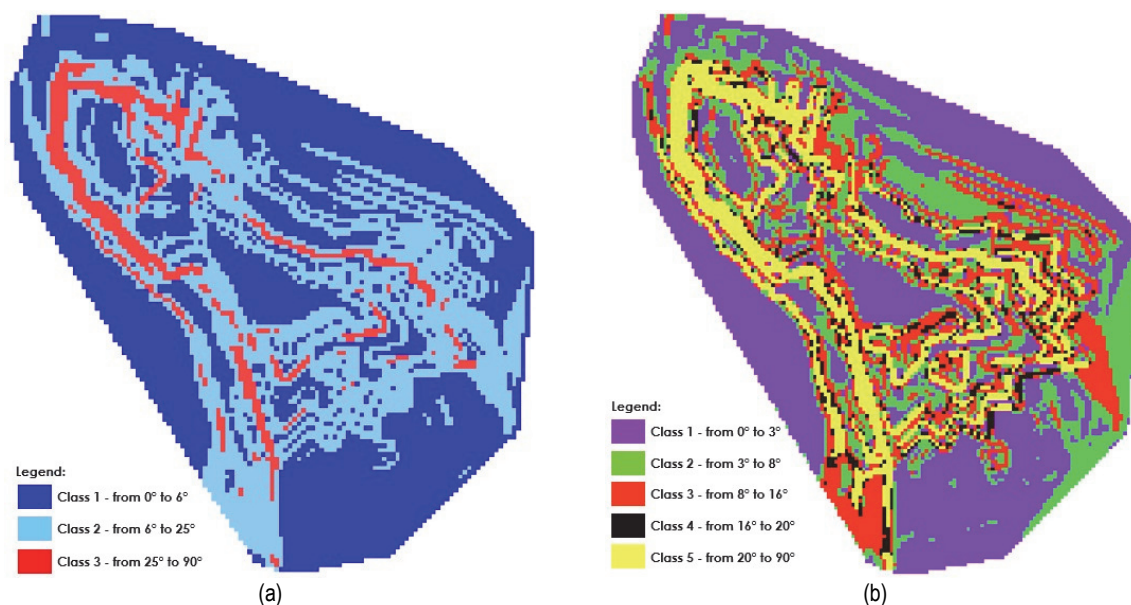


Figure 6 Reclassified terrain slope angle for raster 1 (a); Reclassified terrain slope angle for raster 2 (b)

2.3 Creating a Simplified DTM with a Hybrid Data Structure

The basic idea when creating a simplified case of DTM lies in the fact that the simplified hybrid data structure should contain less information, i.e. to have fewer classes belonging to the Grid data structure. Accordingly, at the input of this part of the proposed model, there is a reclassified raster 1 with 3 classes, and the output is a DTM with a hybrid data structure in a vector notation (*.shp file). To be suitable for further processing, the proposed model for creating a simplified DTM with a hybrid data structure was created.

The basic function of this submodel is to create a network (Grid) for two types of input raster data. For input raster data 1 (Class 1 - from 0° to 6°), a Grid with a cell size of 10 × 10 m is created, and for input raster data 2 (Class 2 - from 6° to 25°), a Grid with a cell size of 5 × 5 m is created. To properly fit the Class 1 and Class 2 Grid data structures, the Class 2 spatial resolution values are twice the Class 1 spatial resolution values.

To obtain a hybrid model, in addition to the raster, a TIN data structure is required (Class 3 - from 25° to 90°). When converting a raster to a TIN structure, the value of the Z tolerance parameter should also be considered (Fig. 7).



Figure 7 Z tolerance display [12]

The description of the procedure and process of creating a simplified DTM with a hybrid data structure is shown in Fig. 8. Also, a part that automatically calculates the maximum allowable value of Z tolerance is integrated within it.

From the results of the first reclassification of the slope angle, the extraction by attributes is performed using the function Extract by Attributes. From attribute 1, attribute 2, and attribute 3, the function Raster to Polygon is used to create polygon 1, polygon 2, and polygon 3. In order to

create a Grid within polygon 1 and polygon 2, the function Create Fishnet (1/2) is applied. This submodel is used to form Grids with a cell size of 10 × 10 m and a cell size of 5 × 5 m for the entire area of the input raster.

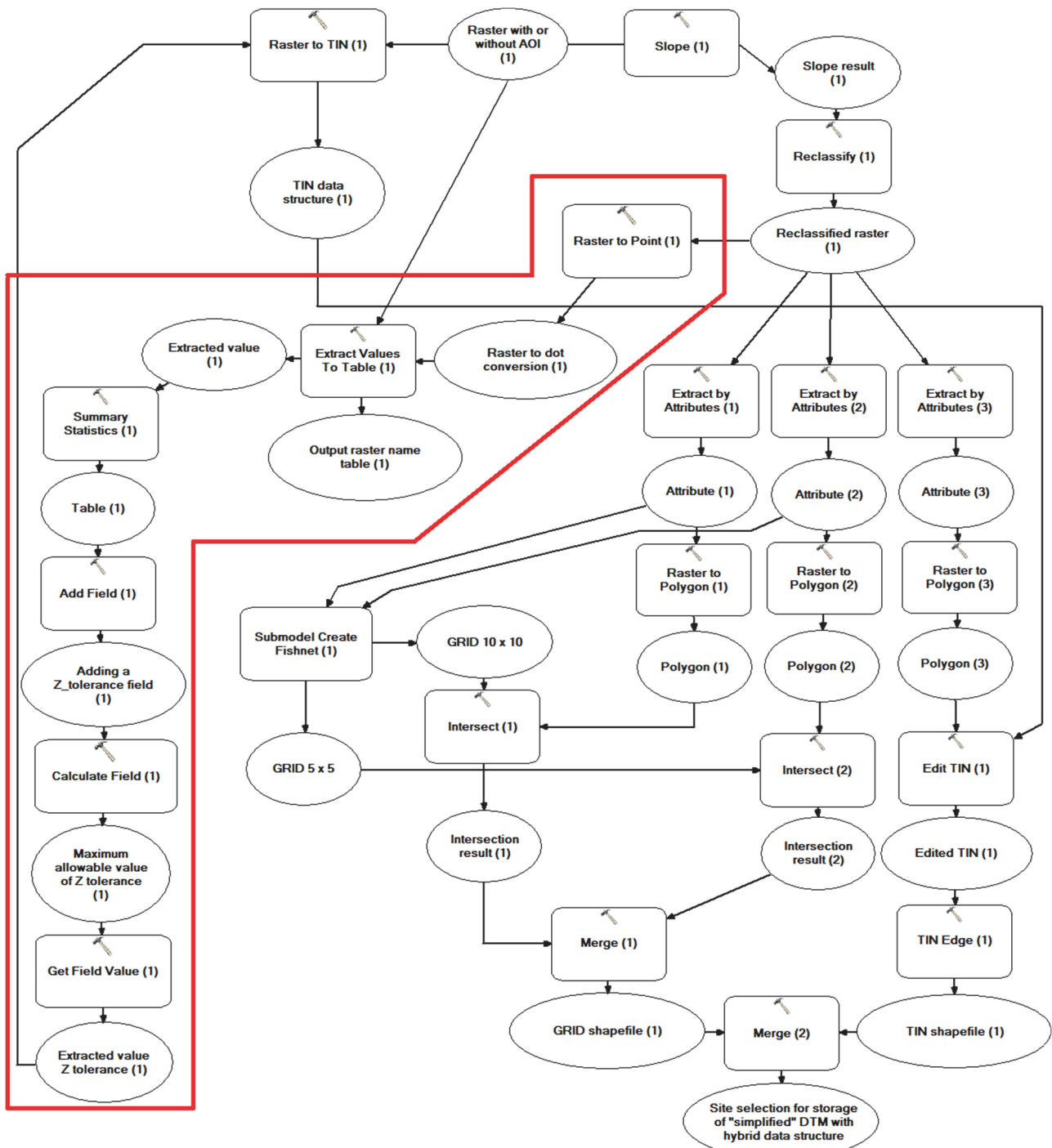


Figure 8 Submodel - creating a simplified DTM with a hybrid data structure

In order to keep the created Grids with such cell size within polygon 1 and polygon 2, the Intersect function intersects polygon 1 and the created network with a cell size of 10 × 10 m, as well as polygon 2 with a cell network size of 5 × 5 m. The results of this function are files "Intersect (1)" and "Intersect (2)", after which they are joined using the Merge function.

To obtain a simplified DTM with a hybrid data structure, it is necessary to merge the Grid and TIN data

structures. The TIN data structure within polygon 3 is obtained by converting the entire input raster 1 into a TIN data structure. In this conversion, as mentioned earlier, it is necessary to take into account the maximum allowable value of Z tolerance. The maximum permissible value of Z tolerance is calculated by the formula:

$$Z_tolerance = \frac{1}{10}(\max Z - \min Z) \quad (1)$$

The value of the maximum allowed Z tolerance must be entered manually each time the raster is converted into a TIN data structure. To automate this process, it is necessary to find the maximum and minimum height in the area of the entire input classified raster 1. This is achieved first with the Raster to Point function, where points are created for the entire reclassified input raster 1. In this case, each raster pixel is converted to one point. After that, with the Extract Values to Table function, the assignment of heights from raster 1 to the points that remained as a result of the previous step is performed. The assigned height values are then stored in the attribute table. In the further procedure of data processing with the help of the Summary Statistics function, points that have the maximum and minimum height from the mentioned points that are saved in the attribute table are extracted.

After the calculation of the Z tolerance value and creating a TIN data structure for the entire input raster 1, it

is truncated with the TIN data structure within polygon 3, using the Edit TIN function.

The final integration (merge, Fig. 8) of the GRID and TIN data structure yields a simplified DTM with a hybrid data structure. The obtained model is shown in Fig. 9.

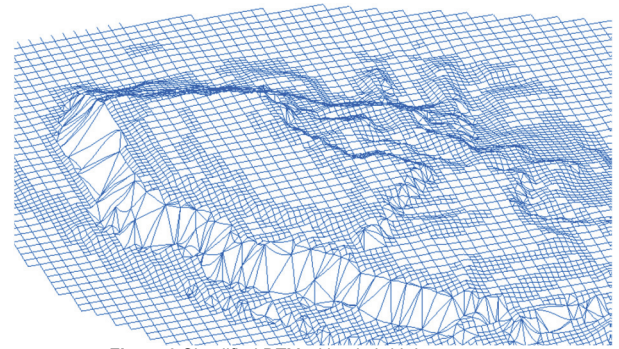


Figure 9 Simplified DTM with a hybrid data structure



Figure 10 Submodel - complex DTM with a hybrid data structure

2.4 Creating a Complex DTM with a Hybrid Data Structure

The formation of complex DTM with a hybrid data structure is done, so that some parts of the terrain that are in simplified DTM with TIN data structure, here in a complex model could be presented with GRID data structure characterized by much smaller cell size than was the case with simplified view. In this way, details are gained, and the terrain that the GRID structure would not be able to adequately display, only those parts will be with the TIN data structure. All steps for creating complex DTM with a hybrid structure are shown in Fig. 10.

The same functions that are used in creating a simplified DTM, are used in the process of creating a complex DTM with a hybrid data structure. The only difference is that instead of three attributes in this part of the proposed model, there are five attributes. In this way, the GRID data structure is formed from the first four attributes, and when it comes to the TIN data structure, local triangulation is formed within the polygon of the fifth attribute. The basic function of the Create Fishnet (1/2/3/4) is to create a network with four different slope angles, which will better represent the complex structure of the terrain (Tab. 3).

Table 3 Pixel dimensions in grid model based on terrain slope

Slope / °	GRID size / m
0-3°	8 × 8
3-8°	4 × 4
8-16°	2 × 2
16-20°	1 × 1

In the final integration of the Grid and TIN structure (Class 5 - from 20° to 90°), a complex DTM with a hybrid data structure is obtained (Fig. 11).

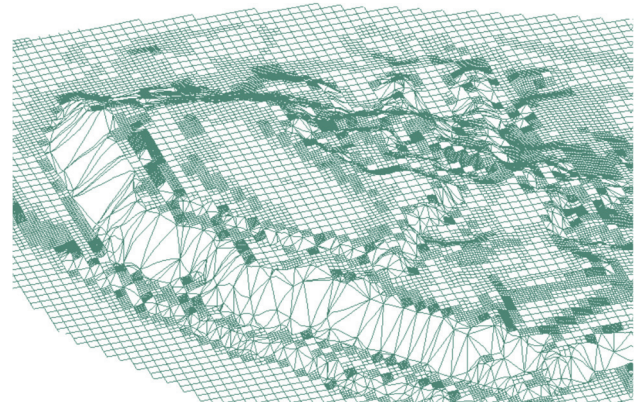


Figure 11 Complex DTM with a hybrid data structure

2.5 Subsection

To complete the concept of simplified and complex DTM with a hybrid data structure, the part that creates structural terrain lines in the form of watersheds is integrated within the developed model. Creating structural terrain lines is optional. The input to the part of the model is a raster obtained by converting *.las points belonging to the Ground class into a raster, and the output is watersheds in vector *.shp format (Fig. 12).

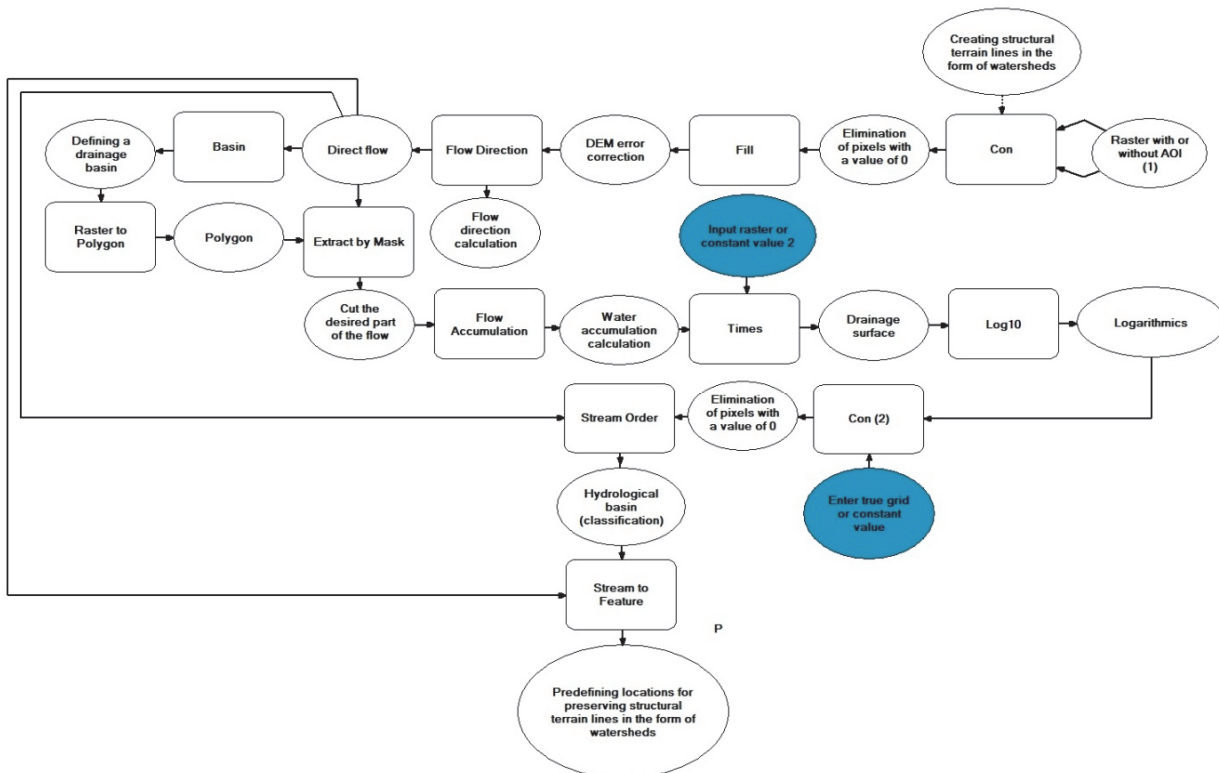


Figure 12 Creating structural terrain lines in course lines

The proposed model takes a raster 1 as input, which has a spatial resolution of 10 m. However, the same procedure and outcome would apply if a raster 2 with a spatial resolution of 8 m were used instead. The Con function is utilized to remove input pixel values that are

equal to 0, and subsequently, the Fill function is employed to correct errors present in the raster.

The correction using the Fill function is necessary because most rasters cannot be directly used for hydrological network modeling. Namely, rasters intended

for hydrological network modeling often contain peaks and depressions that disrupt the natural flow of water within the network [26]. Hence, the Fill function is employed to rectify these irregularities and ensure a more accurate representation of the hydrological network.

Using the Flow Direction function, a value is assigned to each raster cell that shows the direction of flow leaving the cell [27, 28]. This function uses the method of the steepest fall to determine in which direction the water flows. Then the drainage basins are defined with the Basin function, where the terrain areas from which water flows into the same stream have been defined.

The next step, for further analysis, is to isolate the basins using the Raster to Polygon tool. With the help of functions Flow Direction with the Extract by Mask, the calculation of water accumulation was performed. Results are in the raster format, where pixels with higher values indicate areas with higher water accumulation.

From the results of the calculation of water accumulation using the Times function, a drainage area is obtained. Due to the exponential increase in the value of pixels in the drainage area, the values of cells in the resulting Grid are large, so the Log10 function is used. With the Con function, the minimum drainage area formed by the river flow is obtained, and the identification and classification of flows based on the number of their tributaries is created using the Stream Order function. With the help of the Stream to Feature function, we finally get the structural lines of the terrain in the form of watersheds (Fig. 13).

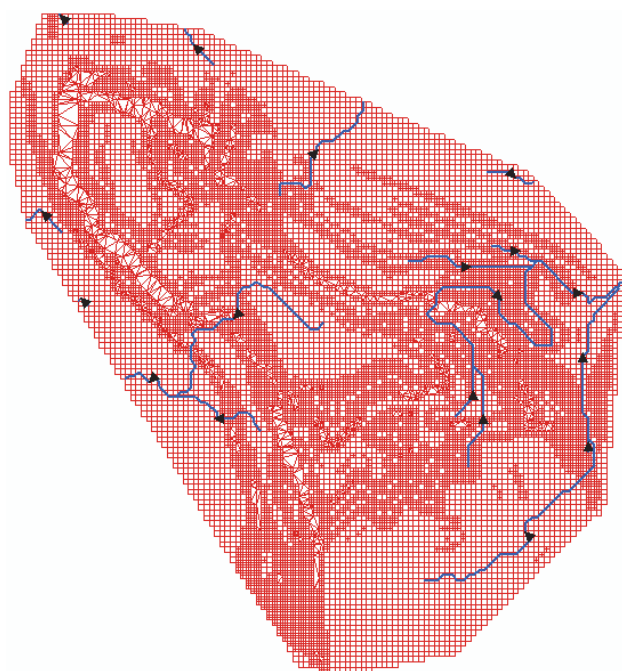


Figure 13 Structural terrain lines in the form of watersheds and simple hybrid data structure

3 DISCUSSION

The presented results show that the developed models integrate the Grid and TIN data structures well and that the different data structures fit together well (Fig. 14).

When creating a DTM with a hybrid data structure from a raw point cloud, the option to select an area of interest can be used, as well as to create structural terrain

lines in the form of watersheds, which complements the concept of created DTM with a hybrid data structure.

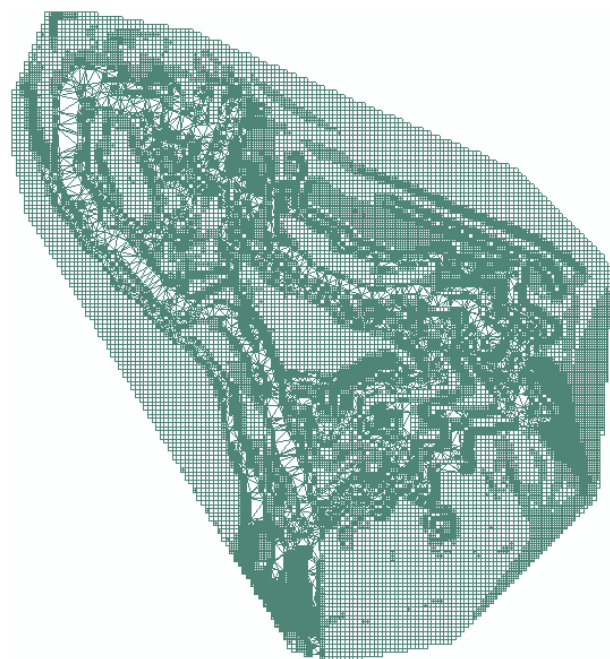


Figure 14 Complex DTM with a hybrid data structure

The fact of existence of Grid and TIN data structures in the generated hybrid models allows to use the good features of both data structures in the interconnection and display of terrain. In order to show parts of the terrain with a smaller slope, a Grid data structure with different spatial resolutions was applied. In this way, we have achieved that flatter parts of the terrain are shown with a smaller spatial resolution, without large and elongated triangles. The presentation of steeper parts of the terrain, such as parts with more complex geomorphology, is presented in the TIN data structure, thus retaining the characteristic features of the relief of the area that was analyzed. In this way, hybrid data structures were very efficiently adapted to different morphological types of terrain and, with this proposed model the imperfection of both mentioned data structures was eliminated.

This paper presents a new approach to modeling and managing geospatial data such as relief with an extremely complex geomorphological structure.

4 CONCLUSIONS

In this research it is aimed to explore the potential of utilizing automated generation of a DTM with a hybrid data structure using point clouds. As this approach represents a novel method for obtaining a DTM, it has been demonstrated that the developed model possesses the capability to generate a hybrid data structure, particularly in areas characterized by complex relief. The key contributions of the developed model are summarized as follows:

1. Integration of Hybrid Data Structure: The model successfully combines and integrates the Grid and TIN data structures, creating a hybrid data structure that leverages the advantages of both approaches. This integration enables a more comprehensive and accurate representation of the terrain.

2. Adaptation to Complex Relief: The model has demonstrated its effectiveness in handling complex relief areas. It can effectively process and model terrains with varying geomorphological features, including steep slopes, fractures, and other intricate terrain configurations.
3. Automation and Efficiency: The developed model automates the process of DTM generation, reducing the need for manual intervention and enabling faster and more efficient data processing. This automation streamlines the workflow and enhances productivity.
4. Enhanced Spatial Analysis: The hybrid DTM generated by the model allows for improved spatial analysis. It provides a solid foundation for further analysis and exploration of the topographic surface, enabling advanced quantitative assessments and supporting various applications.
5. The generated hybrid model adapts quite well to any set of input data (any unclassified point cloud in las format).
6. The user has the optional ability to focus on the desired area of interest and thus generate a DTM with a hybrid data structure only for the selected area.
7. It is possible to create a hybrid data structure with both simplified and complex DTM data structure with different spatial resolutions, as well as automated export of created models to vector data type.
8. In the developed model additional option is offered. The automated creation of structural terrain lines in the form of watersheds, as well as their export in the vector data type.

Overall, the main contribution is the automated process of creating more complex terrain models, and standardization and specification of geometric and attributive modeling that allow easier and more successful development of models with a hybrid data structure, completely subordinate to the user. Also, the geoinformatics functionally oriented approach used in this case study enables an easier process of transformation of one structure, in this case the input raw point cloud (*.las file) into the desired hybrid structure in accordance with the relief shape. Due to the advantages of DTM with a hybrid data structure, which are reflected in the fact that they represent geomorphological forms (all types of relief), it should be expected that they will be increasingly developed and applied in the future. The developed model has many advantages mentioned earlier; however, in the implemented version, the authors restricted it to work with five classes based on the terrain slope, which represents one of the model's limitations. In the future, the authors will explore the possibility of a more detailed division of the terrain according to the slope and will adapt the model accordingly. Additionally, a theoretical problem in applying the developed model may arise in the case of lateral recesses of the relief, such as galleries, where the terrain slope is over 90°. This aspect requires further investigation.

Acknowledgements

This research has been financially supported by the Ministry of Science, Technological Development and Innovation of Republic of Serbia (Contract No: 451-03-

47/2023-01/200026 and Grants No. 451-03-47/2023-01/200156 "Innovative scientific and artistic research from the FTS (activity) domain"). The authors wish to express their deepest gratitude and warmest appreciation to the Laboratory for Geoinformatics of the Faculty of Technical Sciences in Novi Sad. Further, many thanks go to the staff of the above institutions for giving their supply of materials and equipment for this study.

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