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# Inconsistencies in Cadastral Boundary Data—Digitisation and Maintenance

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**Abstract:** Most cadastral systems today are coordinate-based and contain only a weak or no reference to measurements or the origin of the information. In some contexts, this is largely due to the transition of land data management and maintenance from an analogue to a digital environment. This study focuses on analysing the importance of the measurement-based cadastre and the digitisation process in North Macedonia and Slovenia. The survey-based boundary data and their integration into the digital environment were not considered in either case study. The positional differences between the survey-based boundary coordinates and the graphical coordinates of the boundaries are significant. The RMSE(2D) for Trebosh was 48 cm, and the RMSE(2D) for Ivanjševci was 56 cm. Consequently, the differences in location affected the areas of the cadastral parcels, resulting in an RMSE of 26 $m^2$ and 23 $m^2$ for Trebosh and Ivanjševci, respectively. These differences can be considered as differences within the cadastral boundary data. Therefore, before harmonising the data between the cadastre and the land register, the inconsistencies within the cadastral data should be eliminated first. The differences in the location of cadastral boundaries and parcel area create new challenges in cadastral procedures (formatting of parcels), conflicts in the relocation of boundaries, and impacts on the land market. The solution lies in the way data is maintained, avoiding duplication of attributes or eliminating inconsistencies (after duplication). Both solutions require further modifications of the legal framework for cadastral procedures related to boundary adjustments and data compliance. This study provides a basis for evaluating inconsistencies in cadastral data and highlights the importance of proper source data selection in the digitization process.

**Keywords:** land; cadastre; cadastral map; surveying; measurement-based, cadastral triangular model

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## 1. Introduction

The land administration system (LAS) includes two main functions: the cadastre and land registration [1,2]. The cadastre is usually defined as a public inventory of surveyed land boundaries. Land registration defines the associated land rights and the parties involved [3,4]. In recent decades, much attention has been paid to the establishment of a LAS but not to its maintenance [5]. That is, once the relationship between people, rights, and the land was recorded, the procedures for capturing changes to these entities were poorly defined and ill-conceived [6]. Efforts to build LAS focused primarily on countries with low cadastral coverage [7]. However, not much attention was paid to maintaining the system and updating land data, for instance, in countries with complete cadastre [8].

Surveying and mapping techniques have been and are still used differently in different cases. For example, advanced and innovative techniques are being tested and applied mainly in developing countries with low cadastral coverage to establish a LAS [9,10]. These are generally indirect techniques, such as delineating visible land boundaries using remote sensing data, including satellite imagery, and, increasingly, imagery from unmanned aerial vehicles (UAVs) [11–14]. In developed contexts, when countries have full cadastral coverage and registered land rights, there are few case studies reporting on the ability of UAV-based cadastral mapping to update land data and meet accuracy requirements compared to ground-based methods [15–20]. However, image-based cadastral mapping is not new in these countries. In the 20th century, particularly from 1930 onwards, aerial surveys and photogrammetric mapping methods were used to collect cadastral data in many countries [21,22].

In countries with a long tradition of the so-called parcel-oriented cadastre and a complete cadastre, conventional surveying (e.g., theodolites) and mapping techniques were used, which required high positional accuracy, and cadastral outputs were produced in analogue form. In these cases, the digitization process was initiated in the 1990s and at the beginning of the new century with the digitisation of existing analogue cadastral maps and the computerisation of land records [23]. The digitisation process was followed by the conversion and integration of cadastral data, change of the environment—for example, from computer-aided design (CAD) to geographic information systems (GIS), and harmonisation of cadastral data. Today's cadastral surveying is still ground-based but more advanced, including total stations and receivers of global navigation satellite systems.

The conversion of the cadastre from paper-based to digital data made it possible to better identify inconsistencies between the cadastral data and the land register [24,25]. These discrepancies usually concerned the common attributes of the cadastre and the land register, such as the parcel numbers (updated in the cadastral map but not in the land register, or vice versa) and the differences in the area (the area calculated from the cadastral map differs from the area in the land register document) [24,26]. After digitisation, a harmonisation process was initiated in many countries to eliminate inconsistencies [24]. This process is highly dependent on the cadastral data on boundaries, which was used as input to compare and identify inconsistencies in the land records.

Digitisation also led to a change from a measurement-based cadastre to a coordinate-based cadastre in some countries [27]. The processing of measurement data and the storage of the resulting coordinates corresponds to a coordinate-based cadastre. The measurement-based cadastre uses measurement data as a carrier of metric information [28]. To implement a digital measurement-based cadastre and manage survey data digitally, supporting tools and improving the design of the traditional environment GIS are required [29].

In most cases, the digital ownership layer was created by scanning and vectorising analogue cadastral maps. This raises the question of whether the digitization process was properly carried out in regions where measurement-based cadastral data from fieldwork existed alongside analogue cadastral maps. To get a clear idea of the complexity and quality of cadastral data [30], especially land boundaries, it is necessary to take into account the historical development of the country under consideration [31,32].

This study explores the challenges posed by the digitization process and the complexity of boundary definition in countries with traditional parcel-oriented cadastre. The objective is to identify the inconsistencies in cadastral boundary data, which are mainly caused by the way they are maintained, and to reconsider the process of digitisation. We used the cadastral triangulation model (CTM) [30] as a framework to present and clarify these challenges. It was also used to evaluate the cadastral boundaries and the digitising process. The CTM distinguishes three types of land boundaries, namely physical boundaries, documentary boundaries, and digital spatial boundaries, and which of these should be treated as cadastral or legal boundaries.

The paper is organised as follows: after a description of the research context (Section 1), an overview of the CTM and the selected case studies, including the dataset on land boundaries, and the methodological approach are described (Section 2). The results are then presented and discussed (Section 3). Finally, general statements are made about the CTM and variations, the revised digitization process, the importance of measurement-based data, and inconsistencies in land boundary data (Section 4).

## 2. Materials and Methods

### *2.1. Cadastral Triangular Model*

The cadastral triangular model (CTM) was formulated and proposed by Grant et al. [33] and can be applied to analyse cadastral systems using cadastral data for land boundaries.

The model consists of four elements: physical boundary, documentary boundary, digital spatial boundary, and legal boundary. The last element is a conceptual element used to clarify and determine which of the previous three elements should be considered formal or cadastral when determining the boundary position in the field.

Physical boundaries are clues to the land boundary in the real physical world. Physical features may be natural features (e.g., land cover), including movable boundaries such as riverbanks, or man-made features such as walls and fences visible on remote sensing imagery. This group also includes boundary markers that may be visible on satellite or aerial imagery. The arrows pointing to the physical boundary (Figure 1) represent the use of information from the documentary records or the digital spatial boundary to either place boundary markers at boundary locations or record and locate existing physical features that represent boundaries (natural boundaries, fences, walls, markers).

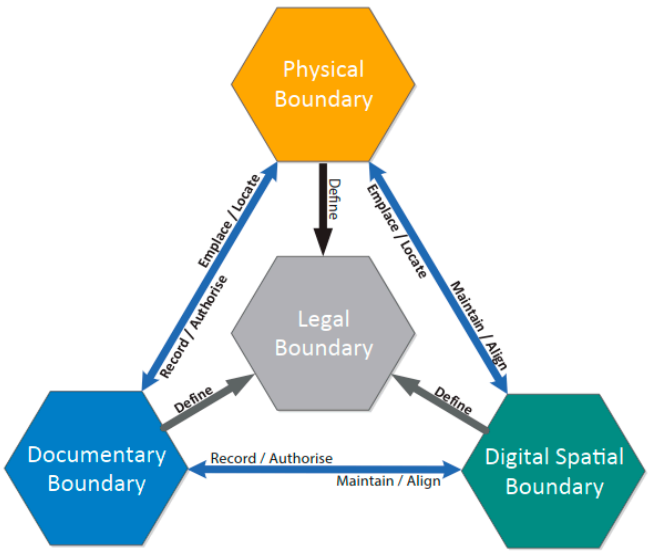



**Figure 1.** Cadastral Triangular Model (CTM) [33].

A documentary boundary is evidence of a recorded boundary based on documents that are legally backed up by a regulated procedure, such as an adjudication or a cadastral survey. This type of information includes survey measurements, e.g., measurements on boundary markers, offsets to other features, calculated boundary dimensions, etc. It also includes cadastral maps and plans showing the relationships between land boundaries, markers, and other features. The documentary boundary also includes survey plans, field notes, and other documents based on the cadastral survey. The arrows pointing to the documentary boundary (Figure 1) represent the recording and approval of field notes, calculation sheets, reports, and survey plans based on the measurement of boundary stones or other markers and physical features. Paper-based cadastral maps of boundaries are also classified as documentary boundaries.

A digital spatial boundary is a boundary that is stored in a digital spatial database. This database is usually initially created by scanning and georeferencing analogue cadastral maps. The points, lines, and polygons are defined as spatial objects that have coordinates with respect to an official coordinate reference system and the topological relationship between spatial objects is defined. Arrows pointing to the digital spatial boundary

(Figure 1) represent the use of documented boundary information or information about the location of physical boundary features (coordinates) to maintain data on spatial objects in the database by adding changed or new boundaries (e.g., subdivisions) and to update and adjust the digital spatial database based on the surveying of physical boundaries using improved measurements.

### *2.2. Cadastral Boundary Data*

Most designs of land administration GIS solutions are characterised by the fact that the position of land boundaries is represented by derived coordinates rather than by original measurements [29]. This approach has also affected the maintenance and management of cadastral data. Many cadastral systems today are coordinate-based and have various, sometimes only a weak reference to measurements or the origin of the information [34].

The LAS of North Macedonia and Slovenia were selected for this study. The selection is justified by the availability of similar cadastral data on land boundaries, which are based on measurements and coincide with the elements of the CTM. Specifically, the focus is on cadastral districts that have field books from land surveying in addition to analogue cadastral maps. In addition to data collection, literature research and interviews with key informants were also conducted.

#### 2.2.1. Measurement-Based Data and Analogue Cadastral Maps

In North Macedonia, the main functions of the LAS are performed by the Agency for Real Estate Cadastre (AREC). In Slovenia, the same functions are performed by two public bodies. The Surveying and Mapping Authority of the Republic of Slovenia (SMA) is responsible for the cadastre, and land registration is carried out at the Supreme Court. Both countries have a complete cadastre, and the maintenance of the cadastre, such as cadastral surveying and the determination of cadastral boundaries, is carried out by private surveying offices [24,35]. In North Macedonia, the Real Estate Cadastre is the public register of registered real estate boundaries (land plots, buildings, parts of buildings), real estate rights and parties involved. The Real Estate Cadastre was created mainly through three types of registrations: systematic, sporadic and conversion [36]. In the latter, the measurement-based cadastral data of boundaries were converted from Land cadastre into Real Estate cadastre through a digitisation process [24]. The Slovenian LAS is very similar. The Slovenian Real Estate Cadastre, introduced in 2022 by merging the former land cadastre and building cadastre [35], includes data on land boundaries, buildings, and parts of buildings. The data on building parts forms the basis for the registration of strata titles in the land registry.

In North Macedonia, the measurement-based cadastral survey (field book known as tacheometric survey) was conducted from 1928–1945. It covered some towns and their surroundings (see Figure 2a, in light grey). The cadastral survey was carried out using the surveying technologies of the time, such as theodolites. During this period, 549 cadastral districts were surveyed. The total surveyed area was about 7000 km$^2$, which is almost 30% of the total territory. For the rest of the territory, around 70% of cadastral maps were produced using airborne methods (Figure 2a, in white). From 1950 to 1990, analogue stereo plotters were used to produce analogue cadastral maps. From 1998 to2005, cadastral maps were produced directly in digital format using stereo instruments SD2000 and SD3000 [36].

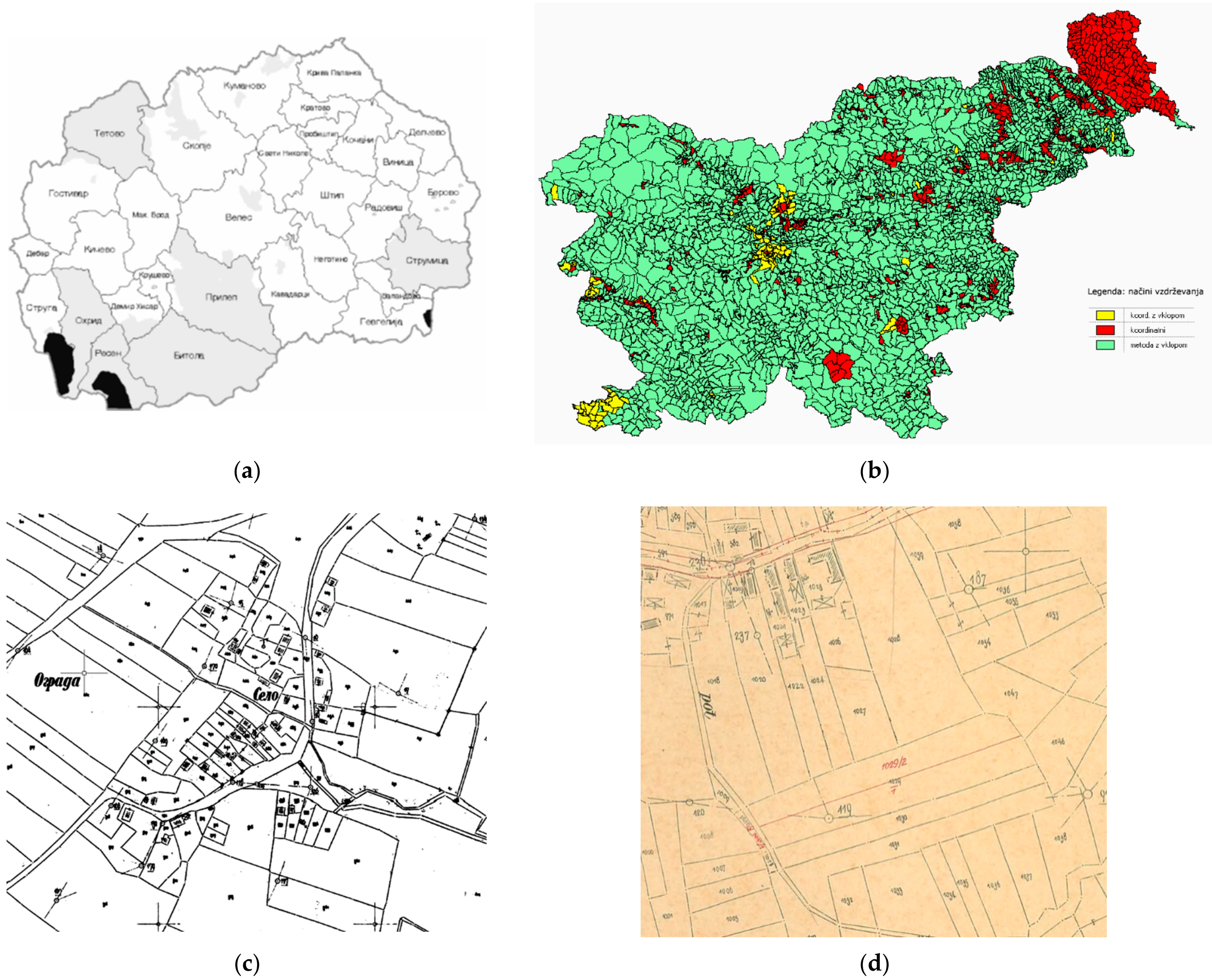


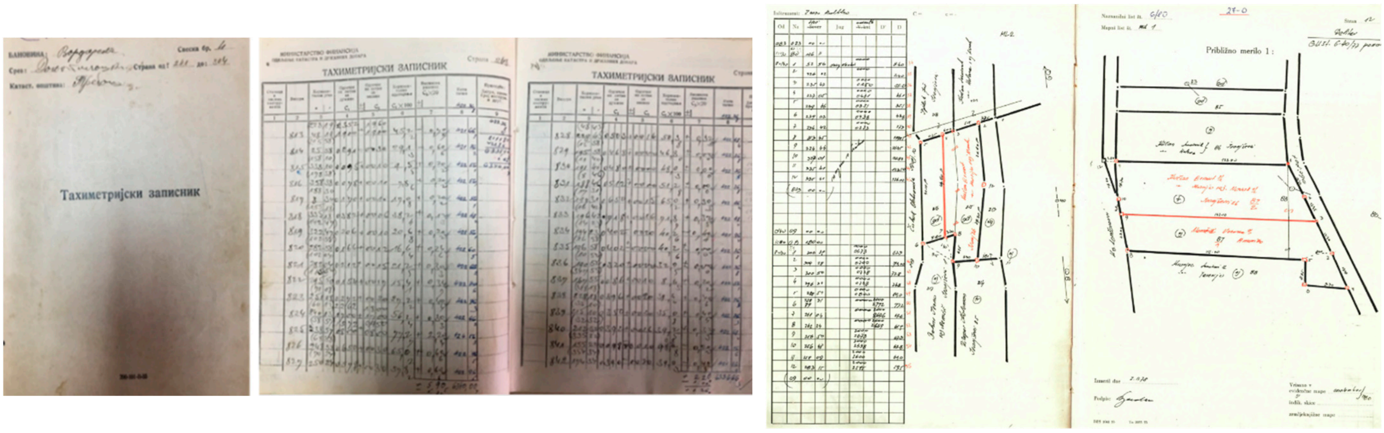

**Figure 2.** Regions with measurement-based cadastral survey including surveying field books; (**a**) Cadastral survey in North Macedonia in the period 1928–1945 (grey) [36]. (**b**) Cadastral survey in Slovenia in the period 1945–1974 and in the period 1975–2005 (red and yellow) [37]; (**c**) Example of archived/initial cadastral map at 1:2500 scale; (**d**) Example of working cadastral map at 1:2500 scale.

As far as their origin is concerned, cadastres were established on the territory of present-day Slovenia in the period between the middle of the 18th and 19th centuries. The Theresian cadastre was characterised mainly by the fact that land was not surveyed but only inventoried and assessed in terms of its yield on the basis of the estimated area, soil quality and type of crops. The Josephinian cadastre from the end of the 18th century was characterised mainly by the fact that the land was surveyed using the prescribed surveying instruments (wooden surveying stick, surveying chain, wooden pegs, and wooden posts), but the cadastral maps were not prepared for all inventoried areas. An important role in the introduction of a more stable cadastre was played by the patent of Emperor Franz Joseph I in 1817. Surveying with surveying instruments (surveying table, diopter with ruler, plumb bob, stake-out flags, and target marks) was carried out by trained surveyors, but the maps were drawn directly in the field, and there were only limited numerical data archived in the cadastre—the so-called graphic cadastre. The use of surveying tables was abolished in the 1920s, while the modern polar and orthogonal surveying methods with the required field books had already been introduced at the end of the 20th century [38].

Cadastral surveying of wider areas, e.g., of the whole cadastral district or part of it, based on field books (tacheometry) was carried out partly already before 1945, but more massively in the period 1945–1974, when the new coordinate system D48/GK was introduced [39]. Systematic cadastral surveying and maintenance of cadastral data continued on the basis of the legislation from 1974 until 2000; however, with the new legislation in 2000, systematic land surveying of larger areas was no longer supported by the state; there have been only a few projects in the last two decades, except for land consolidation, which has also contributed to higher coverage of quality cadastral data. Consequently, the land cover with the so-called numerical cadastre is still very limited in Slovenia [37,40]. Systematic land surveying was conducted in urban areas and the north-eastern part of the country covering approximately 12% of the territory (Figure 2b, red and yellow) [37]. This was and still is reflected in the method of updating cadastral maps, i.e., in the areas with the new cadastral land survey, the measurement-based method is used for updating maps while in the areas of the old graphic cadastre concerning its origin maps are updated using some geometric and positional adjustments [39].

In North Macedonia and Slovenia, the map of the first cadastral survey is called the "archived map" (Figure 2c). Boundary updates for all cadastral-related events (e.g., subdivisions, land consolidation) were drawn on a cadastral map called a "working map" (Figure 2d), which was a copy of the archived cadastral map. Cadastral boundaries were mapped mostly at a scale of 1:2500. In urban areas, scales of 1:500 and 1:1000 have also been used, while the land boundaries in mountainous areas were mapped at a scale of 1:5000.

In both cases, all cadastral maps were accompanied by field books detailing the measurements of each cadastral boundary point (Figure 3). In addition, special geodetic reference networks were designed for the surveyed parts, using the network points as station/orientation points from which the survey (direction, distance) of each boundary point was made. These networks are very dense and accurate as they are connected to the national trigonometric network. The network points are often situated underground (30–40 cm deep) and are still available nowadays. If a control point is damaged or lost, the next control points are located at a distance of about 150–200 m (Figure 2c,d).




(**a**) (**b**)

**Figure 3.** (**a**,**b**) Surveying field books; (**a**) Surveying field book from initial cadastral survey—North Macedonia; (**b**) Surveying field books in process of cadastral maintenance—Slovenia.

Field books represent a measurement-based cadastral survey, and the derived data on land boundaries based on CTM can be categorised as documentary boundaries.

2.2.2. Digital Cadastral Data—Process of Digitisation

In countries with complete cadastral coverage, the most common method of creating digital cadastral maps, i.e., the land boundary data layer, is to scan and vectorise boundaries from analogue cadastral maps. This was selected in North Macedonia and Slovenia as a suitable method for extracting boundary features in vector format. However, the cadastral measurements from the field books were not considered in the digital conversion, although the analogue cadastral maps were derived from the measurements archived in the field books.

The digitisation of analogue cadastral maps was essentially done in a three-steps process: (1) analogue cadastral maps were scanned, (2) georeferenced, and (3) vectorised (Figure 4). This approach introduced additional geometric errors in each of these three steps. In addition, there is a mapping error due to the map scale. The field books, on the other hand, may only contain errors from surveying.


**Figure 4.** Digitisation of analogue cadastral maps in North Macedonia and Slovenia. Field books with measurement data were not considered in this process.

This approach resulted in all cadastral features being in vector format and initially maintained in the file system. Later they were converted to coordinate-based GIS platforms and stored in cadastral spatial databases. Field books containing surveying measurements were not integrated into such a GIS platform, nor was the coordinate-based GIS established by calculating coordinates from surveying measurements.

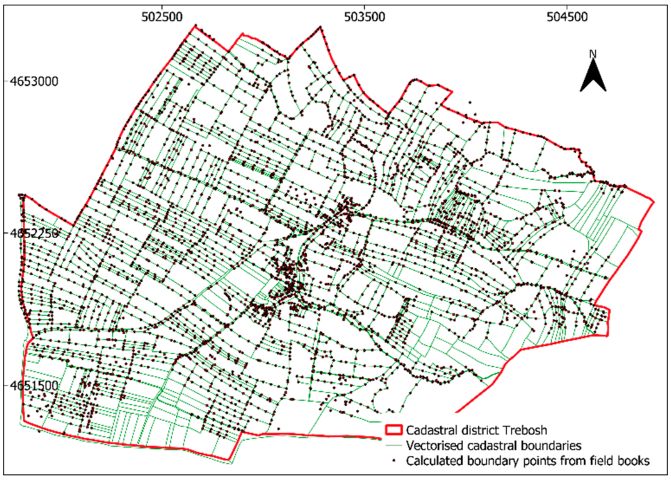
In addition, the separate maintenance of two databases, the cadastral spatial database and the land registry database, resulted in numerous inconsistencies between the two databases, such as a cadastral parcel being updated (divided) in the administrative part but not in the graphical part, mismatch on numeration of cadastral parcels, inconsistencies in the data on cadastral parcel area (one data on parcel area in the land title certificate, another data on parcel area in the graphical part) etc. [24,25]. These inconsistencies were one more reason to start harmonising process between the two databases. The harmonisation was based on vectorised land boundaries in both cases.

Vectorised cadastral boundaries are categorised as digital spatial boundaries according to the CTM.

### *2.3. Study Areas—Inconsistencies in Cadastral Boundary Data*

Two cadastral districts (municipalities), one from North Macedonia and one from Slovenia, were selected to identify the inconsistencies in the boundary data and to revise the digitisation process. The cadastral districts of Trebosh and Ivanjševci were selected for North Macedonia and Slovenia, respectively (Figure 5). Trebosh is located in the northwestern part of North Macedonia and has an area of 446 hectares. Ivanjševci is located in the north-eastern part of Slovenia and has an area of 235 hectares.

The data collection included cadastral survey measurement data such as tacheometric reports, official georeferenced cadastral maps (used in the vectorisation process), vectorised cadastral boundaries, and official coordinates of the geodetic network from which the points of the boundaries were surveyed (Figure 5). Data were collected from local cadastral offices and e-portals of both countries [41,42].




(**a**)


(**b**)

**Figure 5.** Calculated coordinates of land boundary points from field books overlaid on vectorised land boundaries; (**a**) Cadastral district of Trebosh, North Macedonia; (**b**) Cadastral district Ivanjševci, Slovenia.

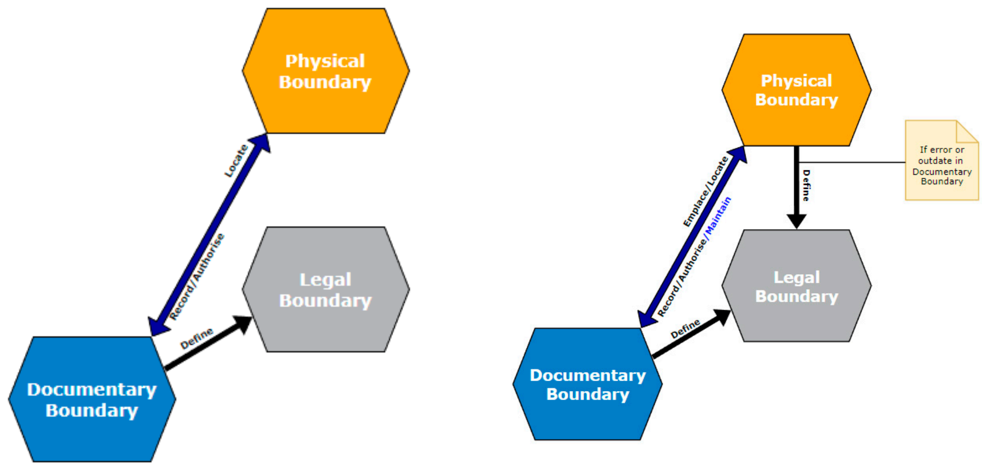
A comparative method was used to analyse the digitisation and location differences between the two data layers (measurement-based and vectorised data). First, the coordinates of the boundary points were calculated from the field books/tacheometric reports. Second, the parcel boundaries were plotted considering the calculated coordinates from the tacheometry, which are in the formal state coordinate system. Then, the cadastral boundaries constructed from the tacheometric reports were compared with the vectorised land boundaries.

Positioning accuracy was assessed as root mean square error (RMSE). The value of RMSE is usually calculated using a series of control measurements (coordinate values from an independent source with higher accuracy for identical points). In this study, the boundary coordinates obtained from the field book data were considered as ground truth, while the coordinates obtained from the vectorised boundaries were considered as measured values. In addition to calculating the differences in east and north directions, another distance-based analysis was performed. Moreover, after the parcel boundaries were constructed based on field books, the area differences between the parcels between the two layers were assessed.

## 3. Results and Discussions

### *3.1. Cadastral Boundary Data in Pre-Digitisation Phase*

The focus of this study has been on cadastral districts with measurement-based data on land boundaries along with analogue cadastral maps, i.e., the cadastral districts where ground-based cadastral surveying was conducted in the past century. Observation of the selected case studies, namely the cadastral districts of Trebosh and Ivanjševci, showed that the situation in the pre-digitisation period was clearer in terms of legal or cadastral boundaries. For example, during the adjudication (static model), survey-based data on physical boundaries were recorded and stored in field books. Analogue cadastral maps were created from the cadastral measurements to allow for more efficient data management and keep the geometric and positional accuracy derived from the quality of surveying. The field books, together with the analogue cadastral maps, formed the documentary boundary that also defined the legal/cadastral boundary (Figure 6a).




(**a**) (**b**)

**Figure 6.** Evaluation of land boundaries and inconsistencies based on cadastral triangular model (CTM); (**a**) CTM for static model in pre-digitisation period; (**b**) CTM for dynamic model/maintenance in pre-digitisation period.

While the cadastre was maintained, survey data on new land boundaries continued to be recorded in the field books and changes were mapped on paper-based cadastral maps. In the event of boundary disputes or missing boundary markers, data from the field books were used to locate the physical boundary on site.

Discrepancies between the physical boundaries and the documentary boundaries occurred when the documentary boundaries were incorrect or outdated (Figure 6b). The errors may have occurred during the cadastral survey, resulting in discrepancies in the location of the boundary. The outdatedness was usually caused by man-made informal changes of boundaries in the field or by natural changes such as riverbanks, and the time factor of these types of obsolescence gave some precedence to the physical boundaries so that in the case of disputes or other land-related legal events, they were considered legitimate because they had been in use for so long.

### *3.2. Digitising Cadastral Boundary Data—Revised*

In both cases, i.e., North Macedonia and Slovenia, analogue cadastral maps were used as the main input for the digitisation process. The georeferenced maps were vectorised, but the measurement data were not taken into account. On the contrary, the coordinates of the boundary points were to be calculated from the field books to avoid errors caused additionally by the scanning, georeferencing and vectorisation of the analogue cadastral maps. The scanned and georeferenced cadastral maps (in raster format) served as a background and were used as a guide to linking the calculated coordinates of the boundary points more efficiently. The digitisation process carried out in practice is shown in Figure 7a. The revised digitisation approach based on the CTM is shown in Figure 7b, and the workflow is reproduced in Figure 8.

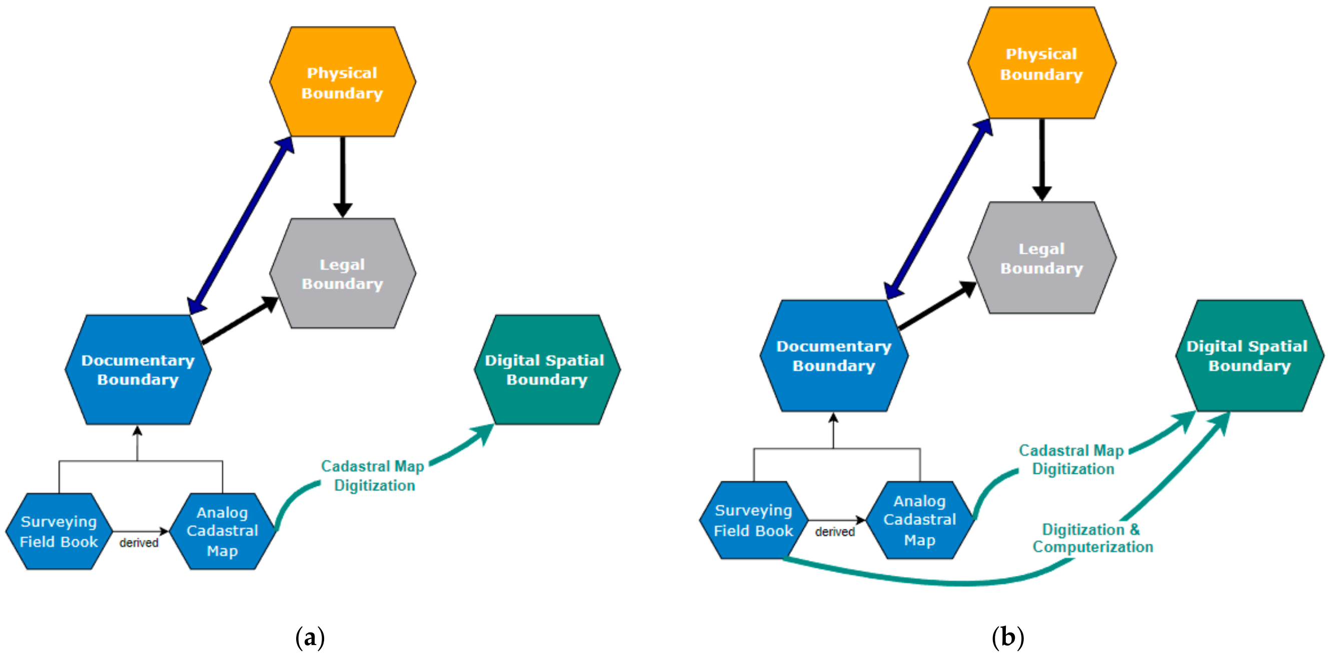



**Figure 7.** (**a**) The process of digitisation conducted in North Macedonia and Slovenia based on CTM; (**b**) Revised process of digitisation based on CTM by considering surveying field books.

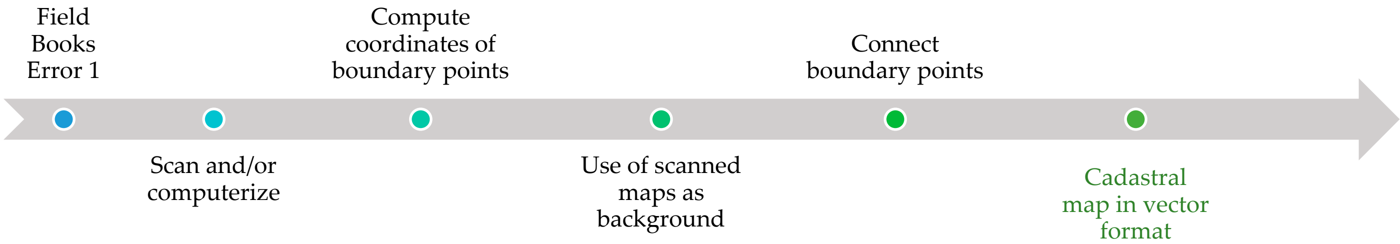


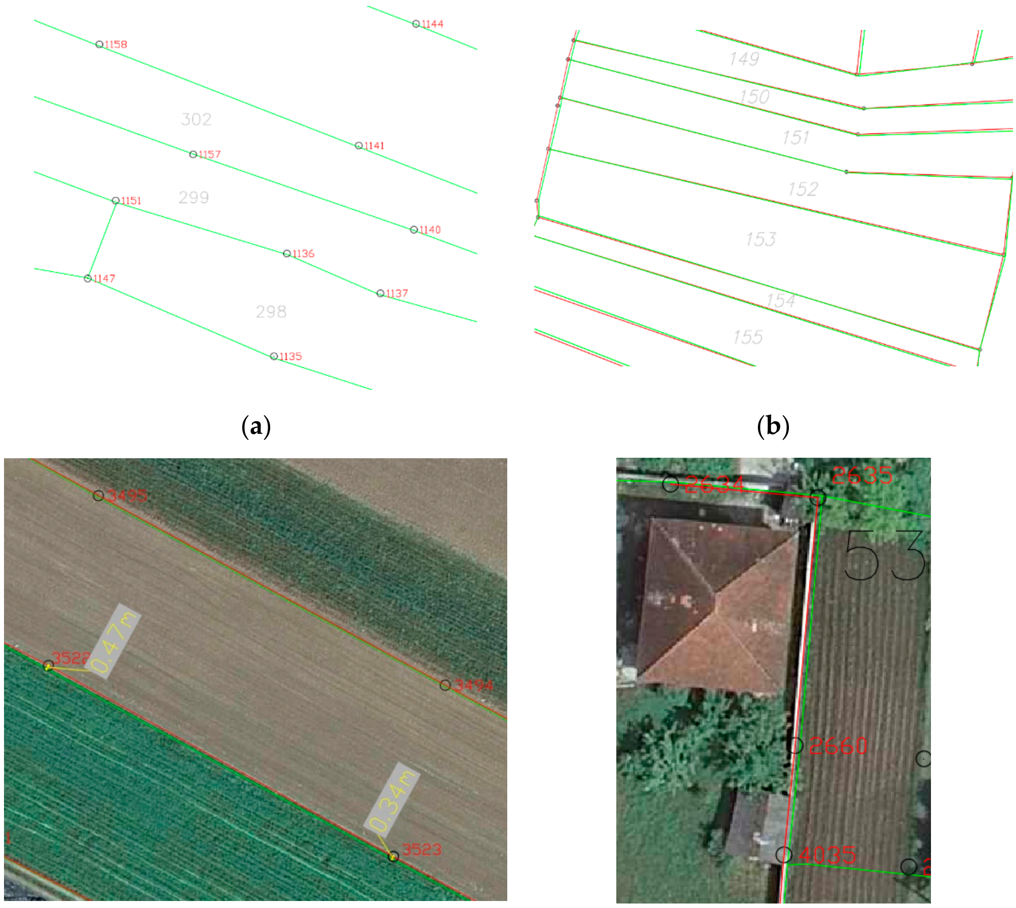

**Figure 8.** Workflow steps of revised digitisation process by respecting the importance of surveying field books.

The revised digitisation workflow still contains systematic errors from the cadastral surveying. In addition, errors can occur due to the computerisation of numerical surveying data or calculations. However, human errors can be easily detected and corrected in most cases. In contrast, the errors that occurred during the vectorisation of analogue cadastral maps cannot be simply traced or avoided (Figure 4).

### *3.3. Identification of Inconsistencies in Cadastral Boundary Data*

The proposed digitisation approach can be applied to both coordinate-based GIS and measurement-based GIS if it supports the storage and visualisation of scanned and/or computerised field books. In this study, a coordinate-based approach was used as the aim was to identify inconsistencies between the two layers of land boundaries.

Once the boundary points were imported and compared to the vectorised boundaries, inconsistencies in the position of the boundary points were also detectable by visual interpretation. Some examples of such inconsistencies are shown in Figure 9.

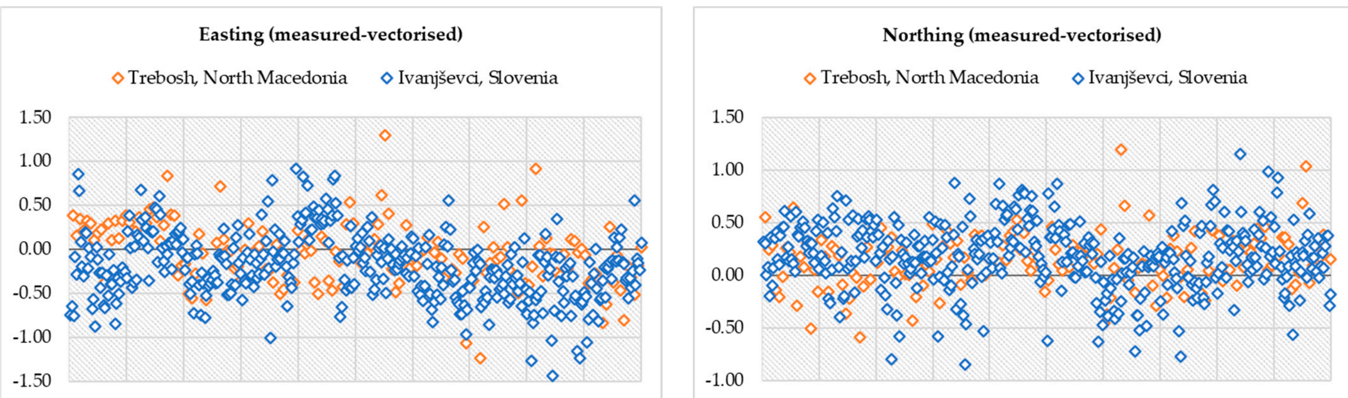



(**a**) (**b**)

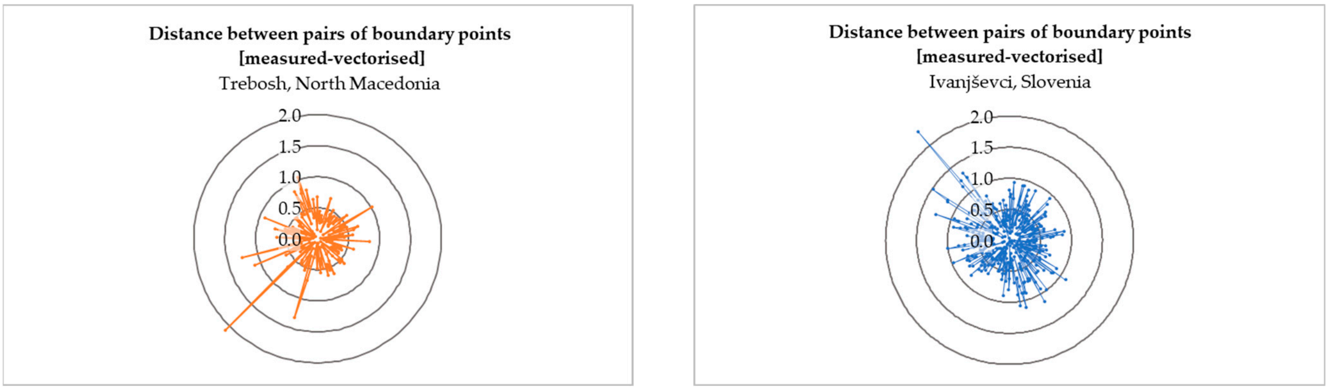
(**c**) (**d**)

**Figure 9.** Inconsistencies in cadastral data on land boundaries. (**a**) Calculated coordinates of boundary points from tacheometry (field book) and overlaid with vectorised boundaries (green); (**b**) Connected boundary points for area-based analysis; (**c**) Example of differences in boundary positions—natural boundary; (**d**) Example of differences in boundary positions—man-made boundary.

In addition to the visual analysis, an additional statistical analysis was performed. The differences in easting and northing of parcel boundary points are shown in Figure 10a,b.




(**a**) (**b**)




(**c**) (**d**)

**Figure 10.** (**a**,**b**) Coordinate differences (easting and northing) for boundary points in cadastral disrict Trebosh, North Macedonia, and (**c**,**d**) distance—based analysis between pairs of boundary points calculated from measurements and obtained from vectorisation.

Positional analysis was performed by calculating the RMSE and distances between identical boundary points from two spatial data layers (Figure 10c,d). The boundary points from the two layers had the same IDs, and a list of coordinate pairs was created to conduct the analysis. The differences in the boundary positions are listed in Table 1. Furthermore, an area-based analysis was performed by calculating the RMSE, and the minimum, mean, and maximum area differences. The area differences are shown in Table 2.

**Table 1.** Positional accuracy of boundary points—documentary boundaries compared to digital spatial boundaries.

| Cadastral District | RMSE (x) | RMSE (y) | RMSE (2D) | minΔ (D) | meanΔ (D) | maxΔ (D) |
|---|---|---|---|---|---|---|
| Trebosh, North Macedonia | 0.38 m | 0.29 m | 0.48 m | 0.05 m | 0.40 m | 2.10 m |
| Ivanjševci, Slovenia | 0.43 m | 0.36 m | 0.56 m | 0.01 m | 0.49 m | 2.29 m |

Δ difference.

**Table 2.** Differences of land parcel areas—documentary boundaries compared to digital spatial boundaries.

| Cadastral District | RMSE (Area) | minΔ (Area) | meanΔ (Area) | maxΔ (Area) | Average Parcel (Area) |
|---|---|---|---|---|---|
| Trebosh, North Macedonia | 25.9 $m^2$ | 1 $m^2$ | 18.7 $m^2$ | 81.1 $m^2$ | 2955.8 $m^2$ |
| Ivanjševci, Slovenia | 22.8 $m^2$ | 1 $m^2$ | 17.4 $m^2$ | 77.4 $m^2$ | 1252.4 $m^2$ |

Δ difference.

The results showed similar differences between the measurement-based and vectorised coordinates of the selected case studies. The horizontal RMSE was 0.48 m and 0.56 m for Trebosh and Ivanjševci, respectively. The distance-based differences yielded a mean of 0.40 m for Trebosh and 0.49 m for Ivanjševci. However, in some cases, the distance between the measurement-based coordinates and the vectorised coordinates resulted in a difference of more than 2 m (Table 1).

These types of differences in boundary data can be categorised as discrepancies between the measurement-based (or documentary) boundaries and the digital spatial boundaries. Simply put, discrepancies within cadastral data about boundaries. The selection of cadastral data for determining or staking land boundaries in the field should be considered critical. This has primarily to do with the certainty and confidence that the surveyor has in the cadastral data. In addition to the computable coordinates, the survey data provide additional spatial or metric information to locate the position of the boundary in the field, which brings confidence when staking boundary points [28,34].

Having only the coordinates of boundary points does not seem to be sufficient to locate the boundary in the field with certainty since there is no additional information or metric relationships to other spatial objects or geodetic points. The main advantage of a measurement-based system over a coordinate-based system is the ease of updating and improving accuracy over time due to the existence and value of measurements that are independent of other measurements [28,29,34]. For this reason, documentary boundaries are preferable for determining cadastral boundaries or relocating boundary points [33].

Consequently, the differences in boundary lines resulted in differences in the area of the plots. The area differences resulted in an RMSE of 26 $m^2$ for Trebosh and an RMSE of 23 $m^2$ for Ivanjševci, corresponding to average plot sizes of 2956 $m^2$ and 1252 $m^2$, respectively. However, the differences in area are not directly related to plot size. They are mainly related to the mapping scale, the shape of the plot, and the mapping skills of the operator. Sometimes the differences were larger for smaller plots; for example, a difference of 23 $m^2$ was registered for a plot of 933 $m^2$ and 8 $m^2$ for a plot of 2788 $m^2$. The mean area difference for Trebosh was 19 $m^2$, and for Invanjševci, 17 $m^2$ (Table 2).

The area is one of the most important units in the cadastre and especially in the land market [1,43]. Usually, prices for land are set per square meter. Thus, the question of which data should be considered relevant in the digitization process, namely the documentary or the vectorised, affects the cadastral procedures and the legal documents. It also affects the harmonization process between the attributes of the cadastre and the land registration.

For example, in the case of North Macedonia, the area is one of the attributes indicated in the land registration. In the harmonization of attributes between the cadastre and the land registry, vectorised cadastral boundaries were considered relevant, which resulted in a change of the areas in the land title certificates [24]. In addition, many cadastral boundaries were determined using documentary data on boundaries (prior to digitization), and these differences, in post digitizing phase, pose an additional challenge when formatting parcels, e.g., in subdivision procedures, i.e., half of the parcel from documentary data does not correspond to half of the vectorised parcel.

In Slovenia, the situation is different; the area is part of the cadastre and is not shown in the land title certificate. Therefore, during land formatting or harmonization, no additional changes need to be made in the land register or the land title certificates related to this area. Moreover, it offers the possibility of using both documentary and digital spatial boundaries (even if created by vectorising) as a sporadic process. The emplacement of land boundaries continues to be done with documentary boundaries case by case, where alignments are applied to digital spatial boundaries without complication regarding the changes in the area of land parcels.

As a rule, there are inconsistencies between cadastral and land registry data [24,25], mainly due to unclear definitions of attributes or duplication of attributes. Cadastral data, together with attributes generated from geometry, should be part of the cadastre and not duplicated in the land registry [3]. For this reason, many harmonization processes have been performed to eliminate such inconsistencies. The harmonization process requires data in digital format, namely vector format. However, before harmonisation, or more precisely during digitization, the inconsistencies between the cadastral data themselves should be systematically avoided.

### 3.4. Cadastral Boundary Data in Post-Digitisation Period

The digitisation approach has also affected the maintenance of cadastral data on land boundaries. In land surveying practice, determining the location of the parcel boundary and recording the land boundary data involves on-site measurements. Digitisation has led to changes in surveying technologies and methods, and it seems that the conventional approach to surveying is no longer a precondition for practising surveying, especially in the land administration domain.

In the case of North Macedonia, after establishing digital data the emplacement of boundary marks is done using digital spatial boundary coordinates. This approach is generally less common, considering that other evidence, such as documentary boundary, is available and more reliable. Prior to digitisation in areas where measurement-based cadastre was established, all cadastral procedures, including the emplacement of boundary points or to locate existing physical features that represent boundaries, were done using the field book data, i.e., through documentary boundary (Figure 11). Thus, once digital spatial boundaries were available, documentary boundaries are no longer used and maintained (Figure 12a).

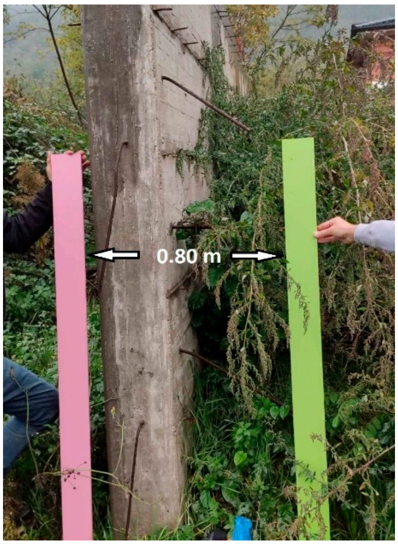
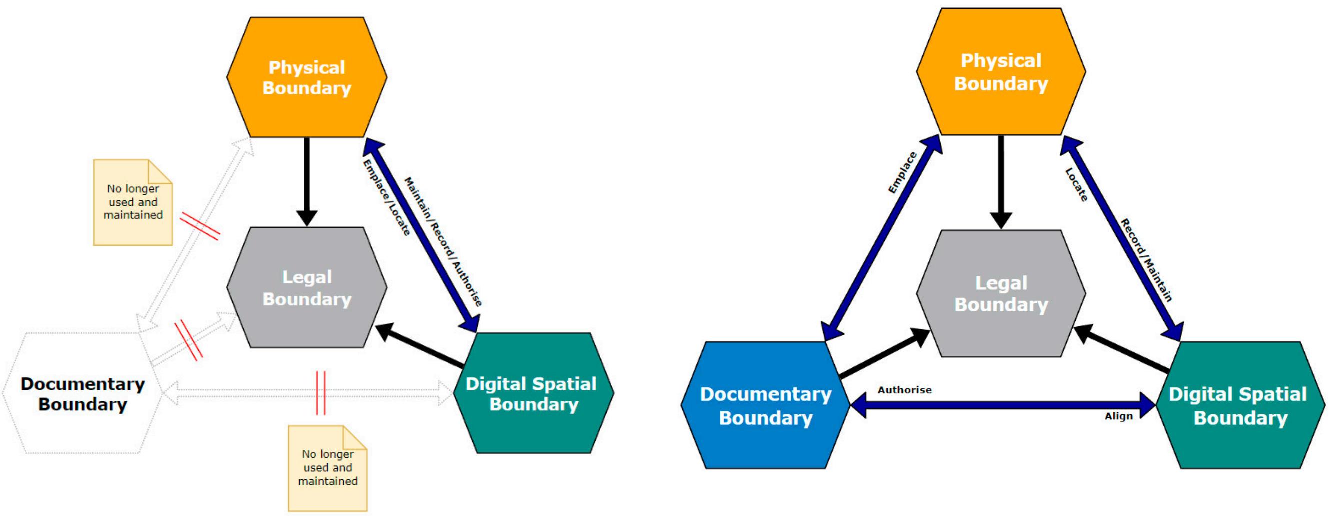



**Figure 11.** Example of differences in the location of boundary points: (red) calculated coordinates from the survey data; (green) coordinates from the vectorised cadastral map.




(**a**) (**b**)

**Figure 12.** Evaluation of land boundaries and inconsistencies based on cadastral triangular model (CTM) in the post-digitisation phase; (**a**) CTM for North Macedonia in the pre-digitisation period; (**b**) CTM for Slovenia in the post-digitisation period.

The Slovenian approach to post-digitisation is far too different. Although digital spatial boundaries have been created from analogue cadastral maps, even in the areas with high-quality survey data in field books, the emplacement of boundaries in the field still relies on documentary boundary records. In this case, the surveyor must refer to the records of documentary evidence and calculate the coordinates of the boundary points from the measurements. This approach is used only sporadically and on a case-by-case basis. Once the documentary boundary is determined onsite, the necessary alignments are made to the digital spatial boundary.

In the case of a new boundary, e.g., subdivision, the physical features representing the boundary are surveyed and considered as documentary as well as digital spatial boundaries. The newly surveyed boundaries, namely documentary boundaries, are stored in digital format in the form of surveying reports. In addition, these new records are used to reallocate the boundary in place if needed.

In both cases, North Macedonia and Slovenia, the new boundaries are surveyed using ground-based techniques, including total stations and GNSS receivers. The application of indirect-mapping techniques falls outside the scope of cadastral surveying and is usually used for other surveying purposes.

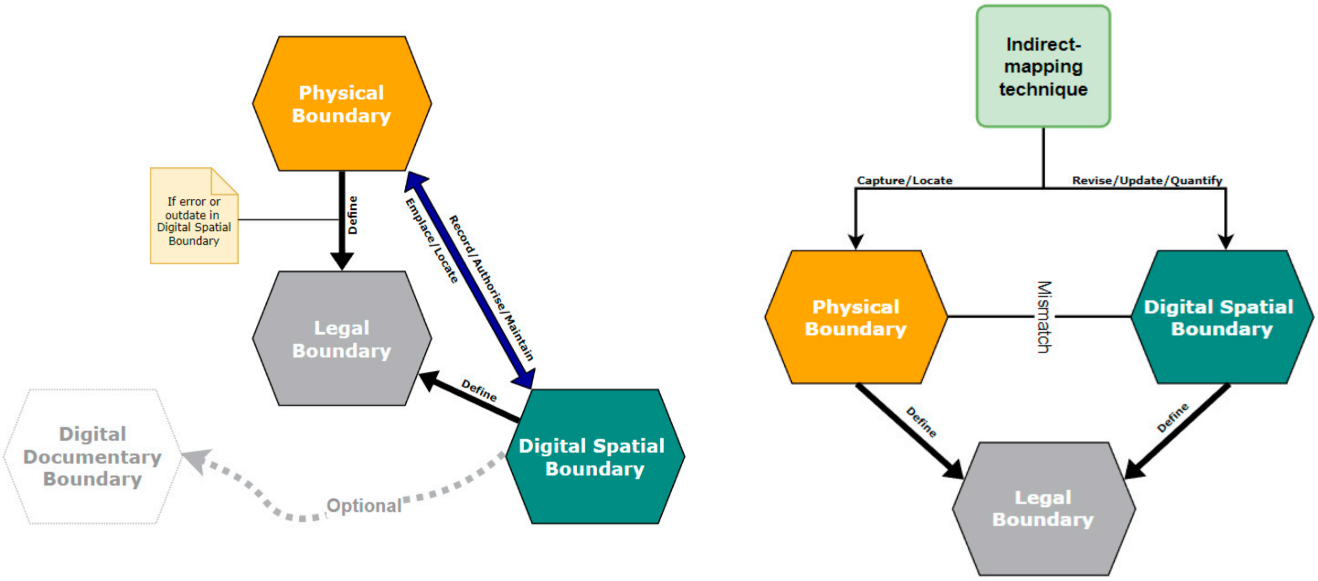
### *3.5. CTM for Indirect-Mapping Techniques—Fit for Purpose*

The current CTM, as proposed by Grant et al. [33], may be considered more appropriate for developed countries that have a long cadastral history and where ground-based surveying techniques were used, with the original cadastral output being on paper. This is primarily because digital spatial boundaries were created by digitising documentary boundaries in analogue format (Figure 7a).

For developing countries adopting a digital cadastre, this approach should be revised since no digitization process is required. Today, survey data and cadastral maps are directly available in digital format, and documentary boundaries may also be digital. However, the content of documentary boundaries is strongly dependent on surveying and mapping techniques that are applied and used.

For example, the Fit-for-purpose initiative [7] suggests using indirect mapping techniques instead of ground-based ones. In this sense, UAV-based cadastral mapping is increasingly being used to implement cadastres in countries with little or no cadastral coverage. In indirect mapping techniques, the documentary boundaries for land parcels may be in the form of photo sketches with additional survey data or reports, such as line dimensions of the land parcel or other objects visible in the image, sensor characteristics, flight parameters, image accuracy, ground sampling distance, etc. However, the need for documentary boundaries depends on the purpose of the application and the required positional accuracy. Namely, Fit-for-purpose can be only introduced digital spatial boundaries by delineating land boundaries from remote sensing imagery, while digital documentary boundaries can be optional (Figure 13a).

In more developed contexts that have full cadastral coverage, the maintenance of cadastral boundaries is usually done with ground-based techniques. The application of UAV-based cadastral mapping is very limited—there are few case studies on updating and evaluating the accuracy and compliance [18,44]. The main challenge in this context is the maintenance of cadastral data over land boundaries [6]. The changes in physical boundaries that cadastres attempt to map are complex and dynamic [30], and underestimating the dynamics of human-land relationships leads to outdated cadastral maps. In other words, this leads to inconsistencies between physical and cadastral boundaries—both digital spatial and documentary. An automated approach is needed to identify areas that need to be updated or where there is a discrepancy between physical and cadastral boundaries.




(**a**) (**b**)

**Figure 13.** Land boundaries and inconsistencies based on cadastral triangular model (CTM) for digital indirect-mapping techniques; (**a**) CTM for Fit-for-purpose and countries with no or low cadastral coverage; (**b**) Fit-for-purpose maintenance for countries with complete cadastre based on indirect-mapping techniques and CTM.

In cadastral applications, UAVs have shown great potential for mapping urban and rural areas. In addition, UAVs provide a fast, accurate, and flexible system for data collection. This is mainly due to the good visibility of physical boundaries (artificial or natural) in a UAV orthoimage [45]. Recent developments show that delineating visible physical boundaries can be automated using various image processing algorithms, computer vision, and machine learning methods, including deep learning [46].

Automatic detection of physical boundaries using remote sensing imagery, especially UAV imagery (since it is more accurate and flexible), opens new possibilities for countries with a complete cadastre. The approach can be used for maintenance purposes in the form of automatic revision of existing cadastral maps to automatically identify areas where discrepancies exist. Detected visible physical boundaries can be used as preliminary digital spatial boundaries that can later be manually aligned using UAV imagery or resurveyed using ground-based techniques, where documentary boundaries can be determined and reconciled with the digital spatial boundaries. For this reason, digital documentary boundaries are not emphasised as a special type of boundary. The approach can be classified as fit-for-purpose maintenance for countries with complete cadastres and can be expressed by the CTM (Figure 13b).

This study examined measurement-based data in North Macedonia and Slovenia, which are very similar in content and form. However, different countries or cadastral systems may have different approaches to the storage, content, and format of such data. Approaches may include measurements at boundary markers, offsets to other features, calculated boundary dimensions, etc. They may also include survey plans, field notes, and other documents based on cadastral surveys. The type of information and the surveying and mapping technique used can affect the accuracy of the land boundary positions and, consequently, the digitisation process.

## 4. Conclusions

Observations and analysis focused on identifying inconsistencies in cadastral boundary data resulting from digitisation. Specifically, the focus was on what cadastral boundary data were used as input during digitisation.

In the two selected case studies, one in North Macedonia and one in Slovenia, mainly analogue cadastral maps were used as input. The differences between the coordinates calculated from the measurements and those obtained from the vector representation were considerable, yielding a horizontal RMSE of 0.48 m for Trebosh and 0.56 m for Ivanjševci. Consequently, the area differences resulted in an RMSE of 26 $m^2$ for Trebosh and an RMSE of 23 $m^2$ for Ivanjševci. These differences can be considered a discrepancy in the cadastral data on land boundaries. The differences between the cadastral boundary data are due to digitisation, which introduces additional errors through scanning, georeferencing, and vectorization of analogue cadastral maps. The use of measurement-based data, i.e., the calculation and import of coordinates directly in digital format, avoids these errors. Moreover, it should be emphasised that in the pre-digitization phase, the situation regarding discrepancies was clearer; basically, discrepancies existed only in the case of errors or outdated documentary boundaries. Therefore, it should be pointed up that before harmonising the cadastral data with the land registry data, harmonisation within the cadastral data is first required, or duplication of cadastral attributes should be avoided. Removing the area information from the land registry extracts makes the maintenance of the cadastral boundary data more flexible by avoiding complications or changes that are required in the legal data.

In the case of North Macedonia, the documentary boundary data are not used or maintained after the digitisation of the cadastral maps. Since in the pre-digitisation phase, the cadastral boundaries were defined and relocated as documentary boundaries, the current approach (defining digital spatial boundaries as masters) leads to new obligations when re-locating the same boundaries or formatting land plots or other cadastral procedures—due to the different location of the boundaries and the different area of the land plots. In the case of Slovenia, although the documentary boundary data was deemed irrelevant during the digitisation process, it was still retained, and in the event of a boundary relocation, the documentary boundary data is calculated and staked in the field. This represents a sporadic approach to matching and integrating documentary boundaries into the digital spatial database. For this reason, countries that have survey data should use it as a data source for digitisation.

The content of the documentary boundaries depends on the surveying and mapping techniques used. Countries with complete cadastres in the past and today mostly use ground-based techniques, while countries with low cadastral coverage use more innovative approaches, such as indirect mapping techniques. In view of this, the current CTM is more suitable for countries that have a long cadastral tradition and where paper cadastral maps exist. This is mainly because the digital spatial boundaries within the model are derived from vectorising the documentary boundaries. However, it provides a basis for further analysis to identify the reasons for having dichotomy in land boundary data and to evaluate the cadastral systems. Today, all cadastral data can be digital; therefore, documentary boundaries should also be digital; even if no significant deviations from digital spatial boundaries are expected, they can still be used for further accuracy improvements. In short, the digital-based approach is different from the past—map scale and manual mapping are not a problem. Therefore, the digital documentary boundary can be its own type of boundary or integrated with the digital spatial boundary (as it did not exist in the past but was created from the documentary boundaries).

Based on this, a CTM for a fit-for-purpose cadastre in developing countries has been proposed, where digital documentary boundaries are optional. In addition, a cadastral maintenance model was proposed to identify inconsistencies between visible physical and digital spatial boundaries. The maintenance model is suitable for countries with full cadastral coverage using indirect mapping techniques, such as UAVs.

Further studies could revise the proposed approach or develop a new CTM for countries with low cadastral coverage and cadastres directly in digital format. In addition, studies could focus more on maintenance models for countries with complete cadastres, such as using artificial intelligence for automatic digitisation or improving accuracy based on measurement data.

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