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Furthering Automatic Feature Extraction for Fit-for-Purpose Cadastral Updating: Cases from Peri-Urban Addis Ababa, Ethiopia

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Abstract: Fit-for-purpose land administration (FFPLA) seeks to simplify cadastral mapping via lowering the costs and time associated with conventional surveying methods. This approach can be applied to both the initial establishment and on-going maintenance of the system. In Ethiopia, cadastral maintenance remains an on-going challenge, especially in rapidly urbanizing peri-urban areas, where farmers' land rights and tenure security are often jeopardized. Automatic Feature Extraction (AFE) is an emerging FFPLA approach, proposed as an alternative for mapping and updating cadastral boundaries. This study explores the role of the AFE approach for updating cadastral boundaries in the vibrant peri-urban areas of Addis Ababa. Open-source software solutions were utilized to assess the (semi-) automatic extraction of cadastral boundaries from orthophotos (segmentation), designation of "boundary" and "non-boundary" outlines (classification), and delimitation of cadastral boundaries (interactive delineation). Both qualitative and quantitative assessments of the achieved results (validation) were undertaken. A high-resolution orthophoto of the study area and a reference cadastral boundary shape file were used, respectively, for extracting the parcel boundaries and validating the interactive delineation results. Qualitative (visual) assessment verified the completed extraction of newly constructed cadastral boundaries in the study area, although non-boundary outlines such as footpaths and artifacts were also retrieved. For the buffer overlay analysis, the interactively delineated boundary lines and the reference cadastre were buffered within the spatial accuracy limits for urban and rural cadastres. As a result, the quantitative assessment delivered 52% correctness and 32% completeness for a buffer width of 0.4 m and 0.6 m, respectively, for the interactively delineated and reference boundaries. The study proposed publicly available software solutions and outlined a workflow to (semi-) automatically extract cadastral boundaries from aerial/satellite images. It further demonstrated the potentially significant role AFE could play in delivering fast, affordable, and reliable cadastral mapping. Further investigation, based on user input and expertise evaluation, could help to improve the approach and apply it to a real-world setting.

Keywords: automatic feature extraction; cadastral mapping; fit-for-purpose; interactive delineation; mean-shift segmentation; random forest classification; land administration

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1. Introduction

1.1. Fit-for-Purpose Cadastral Mapping to Accelerate the Implementation of FFPLA

Despite remote sensing and photogrammetry technologies now being increasingly commonplace in land administration, interest in emerging tools and technologies continues to rise [1]. Contemporary remote sensing technologies provide centimeter-level spatial resolution satellite images at a reasonable cost and time compared to aerial photography [2]. Unmanned Aerial Vehicles (UAVs) deliver high-resolution photographs and point cloud data for a parcel or parcels of interest quicker than conventional surveying using total station or Global Positioning System (GPS) [3,4]. Global Navigation Satellite System (GNSS)-enabled mobile devices and web applications boost live data collection and facilitate cloud data storage [5].

Fit-for-purpose land administration (FFPLA) focuses on simplifying the preliminary work of the underpinning spatial framework for cadastral mapping. It prefers flexible, affordable, and upgradable technologies to stringent technical standards and sophisticated innovations for addressing current land administration issues [6]. Emerging geospatial technologies provide efficient tools and techniques for cadastral mapping and registration of insecure tenure rights across the globe, as per the FFPLA requirement [7].

Focusing on cadastral mapping, their is a complex process that takes into account both technical and legal principles to determine parcel boundaries for new right registration or updating existing cadastral databases [3]. Maintaining the cadastre and keeping the data up-to-date is essential, especially, for example, in rapidly urbanizing peri-urban areas of Ethiopia, where the farmers' land rights and tenure security are often jeopardized [8]. However, it is still a challenge even for countries with well-established cadastral systems to track and update the dynamic nature of man-to-land relationships [4,9]. Given the varying views on the term "cadastre", this study decidedly refers to it as the mapping of the "where" component of the land administration system in a fit-for-purpose manner to facilitate new registration or updating of the "who", "what", "how", and "when" aspects [10].

Thus, the primary concern of cadastral mapping is identifying the spatial extent of the boundary of the land parcel, the best unit to locate and define ownership rights in land management [1,11]. A parcel boundary is a spatially referenced demarcation line between two adjacent properties where one land-use right ends and the other begins [12–14]. It can be physically marked and mapped using a fixed or general boundary approach [12]. A fixed boundary defines the property line precisely using accurate surveying equipment and techniques. A general boundary, on the other hand, is a rough determination of a parcel that typically uses existing artificial or natural features for demarcation, such as hedges, ditches, walls, fences, roads, etc. [12,14,15]. The general boundary focuses more on the tenure security of individual owners than the spatial accuracy and is often preferable for rural and peri-urban areas [16].

The nature and type of parcel boundaries matter when it comes to defining and applying methods and technologies for reliable cadastral mapping. In participatory mapping, parcel owners and concerned parties actively participate while delineating general boundaries on printed aerial/satellite imagery, which is later converted to a digital format in the office using an on-screen digitization technique [12,17]. The approach is viable for acquiring reliable boundary information; however, the digitization process is time- and resource-consuming, less accurate, and difficult to repeat in case revision is required [18]. According to Chandrarathna [19], the digitization process took about 8% of the overall production time to delineate and map 500 plots from UAV imagery in Sri Lanka. Yagol et al. [20] also consumed 19% of the total time for digitizing and processing 102 parcels while making a cadastral map from high-resolution satellite imagery in Nepal. Moreover, it can deliver inconsistent results between individual experts: the experts may not delineate the same parcel uniformly, in addition to the subjectivity of image interpretation [5].

In summary, cadastral mapping is necessary for creating cadastral databases or updating existing ones; however, both hardly differ in methodological approach and materials used for the mapping [21]. While new creation is crucial for any country that seeks to establish a reliable land administration, updating is essential whenever land use or ownership changes occur. According to Bennett et al. [21], cadastral data subject to frequent changes include spatial data, party data, and rights data. Spatial or geographic data could involve subdivision, consolidation, or layering. A party or parties may be entitled to the land parcel by transfer, inheritance, or acquisition. Land use rights may vary with the time set: a specific period, ad hoc, repeated, or continuous.

The overall cadastral database creation or updating process could be carried out systematically, covering the entire area plot by plot or sporadically triggered by the landholder [9,21]. However, sporadic cadastral mapping is usually used for ground-based surveys; mapping with geospatial technologies or Automatic Feature Extraction (AFE) developments fits the systematic approach [22]. The AFE approach is supposed to be economical in peri-urban areas where tenure security is at risk due to fast-paced (peri-) urbanization.

1.2. Urbanization, a Threat to Tenure Security of Peri-Urban Areas of Addis Ababa

Ethiopia is experiencing haphazard urbanization towards the peri-urban outskirts in response to the high growth rate of the population [8,23]. Due to the absence of a demarcated administrative boundary between the rural and urban in Ethiopia, as in the case of many African countries, the highly dynamic peri-urbanization process is uncontrolled [24]. Most of Ethiopia's large cities, including the capital Addis Ababa, arose without proper planning, and urban centers continue to do so to this day [25]. What is peri-urban currently will be changed to a complete urban system within a few years. The small cities and towns across the country are the outcomes of such undetermined peri-urbanization [26].

The peri-urban areas are in high demand, both legally as part of government-led development projects and illegally in informal settlements [27]. Ethiopia strategically fosters peri-urbanization by evicting agricultural land from peri-urban farmers for residential house building or private investment [28]. According to the World Bank Group [29], well-managed urbanization might boost Ethiopia's economic growth; otherwise, loss of land rights and rural–urban migration would be the adverse effects that reduce productivity.

The consequence of the unplanned rapid urbanization is manifested in the peri-urban areas of the country's capital, Addis Ababa, the hub of numerous national and international organizations. The spontaneous expansion of the city, at an approximate rate of 2% per year, appears to be its distinctive characteristic and a threat to the peri-urban land rights [8,27,30]. Teklemariam and Cochrane [8] demonstrated that changes in the tenure system due to rapid urbanization highly endangered the Addis Ababa peri-urban farmers' land rights. An efficient cadastral and land registration system is vital to manage the impacts of rapid urbanization and ensure tenure security [31].

A real property registration proclamation was enacted in Ethiopia a century ago in 1907, which allows land transactions in Addis Ababa [32,33]. The 1960 property registration article and the 1975 urban land and extra housing reform are remarkable developments in the country's land tenure system history [33,34]. Since the 1994 urban land lease holding regulation, the Addis Ababa City Administration has initiated a cadastral project and worked to register properties for taxation and tenure security purposes [34]. This was a pilot project designed to serve as the basis for a national solution and a model for other regional cities and urban areas. However, inefficient integration and updating mechanisms have rendered the cadastre unable to control the informal settlements and land encroachments that threaten tenure security [35]. Studies have further declared that the urban cadastral system of Addis Ababa is not functioning as expected [36,37] for a variety of reasons, including a lack of broad strategic orientations [38], technical shortcomings, legal gaps, and insufficient institutional structures [39].

Nonetheless, according to Metaferia et al. [40], the legal, spatial, and institutional frameworks for the undergoing cadastral project favor emerging geospatial technologies to boost the efforts in a fit-for-purpose manner. International aid and financial organizations also advocate the utilization of freely available, cutting-edge open-source software technologies for quick tenure registration and cadastral updating [41].

1.3. AFE Practices for Mapping Cadastral Boundaries

The AFE method is commonly used to delineate patterns with predictable arrangements, and it has been applied in various disciplines more reliably than the manual approach [42]. It employs the spectral information in each pixel (pixel-based) or the geometry and spatial relationships of a group of pixels (object-based) to automatically extract parcel boundaries [12]. Studies prove that the object-based feature extraction provides more reliable results than the pixel-based approach, for it considers the image texture, pixel proximity, feature size, and shape in addition to the spectral information [5,12,43–45]. Crommelinck et al. [12] summarized the steps involved in extracting object-based boundary features as image segmentation (segmenting the image into spectrally similar features), line extraction (identifying edge lines or boundary features), and connecting edge or boundary lines (contour generation) (Figure 1).

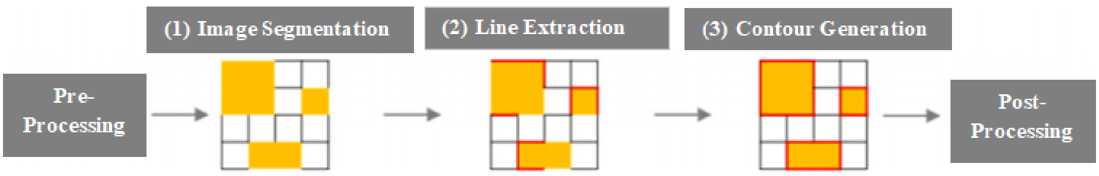

Figure 1. Object-based AFE workflows [12].

Although still in development, the AFE methods are suggested as a viable FFPLA alternative to mapping cadastral boundaries in a timely and cost-efficient manner [18,46]. It is highly favored by the periodical improvements in the spatial resolution of the satellite/aerial images to extract general boundary objects without or with fewer human inputs [18]. AFE could eventually replace the labor- and time-intensive on-screen digitization.

Several scholars have practiced and proved the potential of different machine-learning algorithms to fully or semi-automatically extract boundary features from satellite or aerial images. Although the methodological approaches and the applied algorithms vary, promising results are obtained for detecting and semi-automatically extracting farmland boundaries, which could enhance the rural cadastre [5,16,47–49].

Babawuro and Beiji [47] employed edge detection, morphological operations, and Hough-Transform (HT) algorithms for detecting and extracting farmland cadastral boundaries from high-resolution satellite imagery. Turker and Kok [48] applied a rule-based perceptual grouping algorithm to automatically extract agricultural field boundaries from SPOT5 and SPOT4 images, which performed better on high-resolution imagery (SPOT5) than coarser imagery (SPOT4). The mean-shift image segmentation algorithm has been used for semi-automatic boundary extraction in rural areas from 0.5 m resolution pan-sharpened and orthorectified WorldView-2 satellite images [16]. Similarly, Nyandwi et al. [5] used the World View-2 images to extract general parcel boundaries using an Object-Based Image Analysis (OBIA) approach that delivers Geographic Information System (GIS)-compatible vector files. The method involves breaking the image into objects (Segmentation) and grouping them based on the spectral properties and contextual information (Classification). The authors tested both fully automated and expert knowledge techniques using commercial software (eCognition) and the Estimate Scale Parameter (ESP2) tool to set optimal parameterization values. Crommelinck [49] has developed a procedure for boundary feature extraction that takes advantage of visible cadastral boundaries on high-resolution aerial/satellite images. First, it employs Multi-resolution Combinational Grouping (MCG), an extended version of the globalized probability of boundary (gPb) algorithm, for identifying closed boundaries between objects or segments based on the image texture, color, and brightness information. Then, a training dataset is generated, labeling the contour lines with "boundary" and "not boundary" to train a classifier algorithm and predict boundary likelihoods for unseen testing data without a boundary label. The third step encompasses interactively delineating lines with the highest boundary likelihoods to create final cadastral boundaries. A Quantum GIS (QGIS) "BoundaryDelineation" plugin is created to guide the interactive delineation by determining a least-cost path between user-selected nodes or connecting around a selection of lines or end points of selected lines generated in the first step.

Despite the problem of determining an appropriate threshold value to avoid over- or under-segmentation, which could yield extra boundary features [16,48], statistical validation of the achieved results confirms the potential of the AFE approach for mapping cadastral boundaries. Turker and Kok [48] attained 82.6% for the SPOT5 and 76.2% for the SPOT4 images matching between the automatically extracted agricultural field boundaries and the reference dataset. With a sample set of images that possessed haystacks and bushes, Wassie et al. [16] obtained 55.4% completeness, 16.3% correctness, and 14.4% quality, buffering the extracted and reference lines by 0.5 m and 3 m, respectively. The OBIA approach implemented by Nyandwi et al. [5] extracted 45% of visible boundaries in rural areas (completeness) and 47.4% correctness, although it failed in urban areas due to the features' complexity and spectral reflectance ambiguity.

The accuracy assessment of interactively delineated cadastral boundaries in Crommelinck's [49] study delivered 67% spatial correctness and 37% completeness. Additionally, compared to manual on-screen digitizing, the interactive boundary delineation approach reduced the time required to extract boundary lines by 38% and the number of clicks by about 80%. Koeva et al. [50] also evaluated the boundary delineator QGIS plugin against the seven characteristic elements of FFPLA. The tool has proven to be attainable and upgradeable, for it is freely available and open for further improvement.

Overall, the AFE approach uses fewer resources and produces results faster than conventional methods and manual digitization, but with less absolute and relative accuracy for both individual parcels and the breadth of the cadastral area being mapped. Promising results have been obtained while employing the approach in rural, peri-urban, and urban settings [5,16,51].

1.4. Objective and Structure of the Study

Thus, tenure security challenges due to rapid (peri-) urbanization and the opportunities from emerging geospatial technologies for cost- and time-effective cadastral mapping are the basis for the overarching motivation and objectives of this research. As mentioned, several authors illustrated the viability of the AFE approach for cadastral mapping in different ways, such as by using open-source tools (e.g., Wassie et al. [16]), employing proprietary software solutions (e.g., Nyandwi et al. [5]), and developing codes for the complete process (e.g., Crommelinck [49]). However, studies have yet to assess the significance of emerging and freely available geospatial technologies for automatically extracting cadastral boundaries, as advised in [2,18,52].

Therefore, the purpose of the study is to explore the potential role of the AFE approach for extracting parcel boundaries in peri-urban areas in a fast, affordable, and reliable manner, as required by FFPLA. It employs ready-to-use open-source software solutions for the (semi-) automatic extraction, classification, and delineation of cadastral boundaries, focusing on peri-urban areas in Addis Ababa. The approach is supposed to contribute to the overall endeavor to register land tenure rights and update cadastral records in a fit-for-purpose manner.

For further setting, the next section illustrates the methodological approach with a brief description of the case of peri-urban areas and the datasets for the study (Section 2). Then, the AFE test and processing results are presented (Section 3) and thoroughly discussed (Section 4) in sequence. Finally, conclusions and recommendations for future improvements are made based on the study findings (Section 5).

2. Methods and Materials

2.1. Study Area

Addis Ababa is one of the fastest-growing cities in Sub-Saharan Africa. Its geographic location is roughly 9°2′N Latitude and 38°45′E Longitude, at an average altitude of 2400 m above sea level. Addis Ababa covers 540 square kilometers of territory and contains ten administrative divisions known as "sub-cities" (recently restructured to eleven). The six peripheral sub-cities (Akaki-Kitaly, Bole, Kolfe-Keranio, Gulele, Nifas-Silk-Lafto, and Yeka) account for 92% of the total area [27]. These sub-cities are subject to a high rate of urbanization in the peri-urban areas of the neighboring Oromia Special Zone cities, resulting in chaos like farmers' displacement and environmental deterioration [53]. The Akaki-Kality sub-city was chosen as the case study region because it demonstrates the influence of increasing urbanization on the tenure system of peri-urban areas of Addis Ababa (Figure 2).

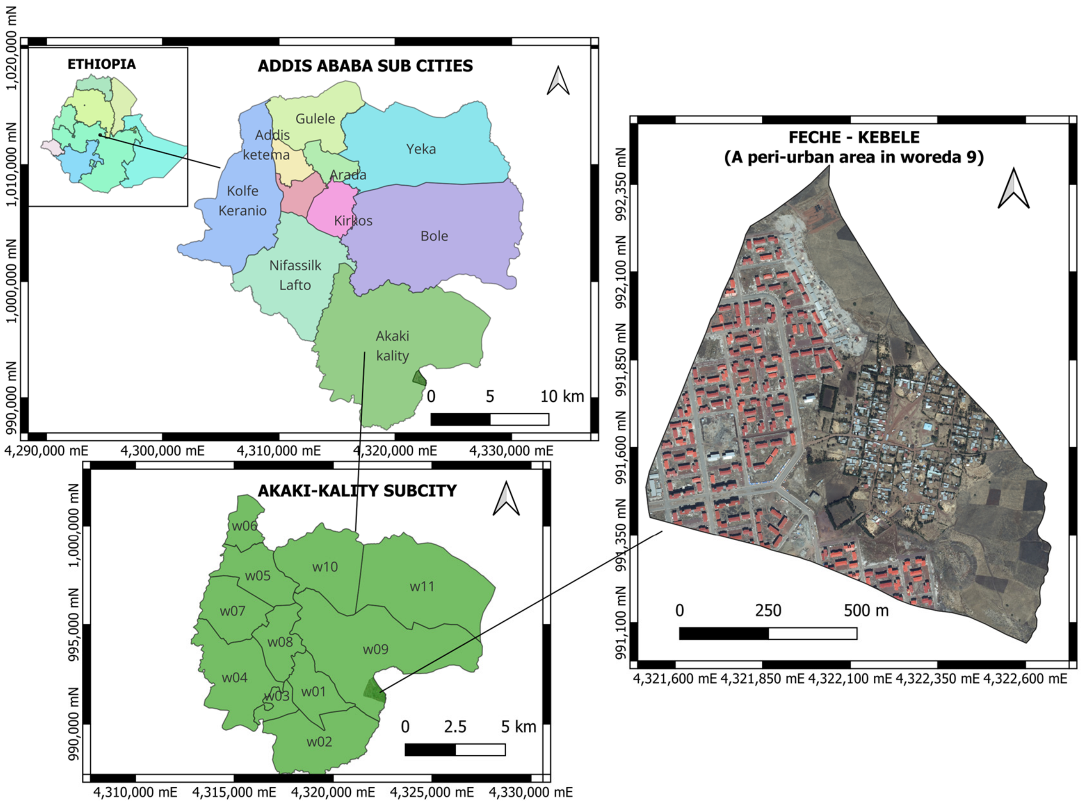

Figure 2. Study area location map.

Akaki-Kality is one of the largest sub-cities, covering 156 square kilometers of land, the majority of which are industrial zones and agricultural fields [54]. It is located in the southeast of Addis Ababa, where substantial urbanization has occurred in recent years at the expense of its peri-urban agrarian communities [55]. For instance, while condominium housing occupied 11% of the city in 2016, the majority of the land was acquired from the peri-urban areas of the Akaki-Kality sub-city [27]. According to Koroso et al. [55], the built-up area of the sub-city increased by 115% within fifteen years (from 2004 to 2019). Several scholarly articles have also revealed the severe impact of unplanned rapid urbanization on land tenure security generally in Addis Ababa [8,27,53,56–58], notably in the Akaki-Kality sub-city peri-urban areas [54,55,59].

The study specifically determined a peri-urban village in Woreda 9, locally called Feche (Figure 2), where many condominium houses are being developed, and rapid urbanization is still occurring. One of the researchers also has more familiarity with the area, which might help with visual inspection and field verification of the results. Furthermore, due to the high rate of urbanization in the surrounding area and the perceptible variability between the image and the reference data, it helps validate the approach for cadastral map updating.

2.2. Data

A high-resolution (0.25 m by 0.25 m) orthophoto was used for extracting the study area's peri-urban parcel boundaries. The aerial photograph was acquired by the Ethiopian Mapping Agency (EMA) (recently named the Space Science and Geospatial Institute, SSGI) in 2016. A cadastral boundary shape file, obtained from the Akaki-Kality sub-city land administration office, was used as reference data for the AFE result validation (Table 1). It was produced from aerial photographs acquired in 2010 and was used as a base map for cadastral survey work and planning purposes [35]. Both datasets were subsetted to the identified area of interest for extraneous data removal and manageability for boundary extraction and validation purposes.

Table 1. Description of the data for the study.

S/N	Data	Source	Description	Purpose
1	Aerial photograph of the study area (Orthophoto)	Space Science and Geospatial Institute	The orthophoto is produced by SSGI from an aerial photograph acquired in 2016	To extract parcel boundaries automatically
2	Cadastral parcel map of the study area (Shape file)	Akaki-Kality sub-city land administration office	The shape file is extracted from an aerial photograph acquired in 2010	To validate automatically extracted parcel boundaries

2.3. AFE Implementation

This study intends to explore the outstanding role of the AFE approach for fast, inexpensive, and reliable cadastral mapping by validating the results with cadastral reference data. It adopted the AFE approach developed by Crommelinck et al. [51], which involved image segmentation, boundary classification, interactive delineation, and validation (buffer overlay accuracy assessment). Segmentation delivers available boundary outlines from the image. Classification helps determine conceivable cadastral boundaries from the set of extracted outlines. Interactive delineation enhances the precise delimitation of the identified cadastral boundaries. Validation of the interactively delineated cadastral boundaries ensures the reliability of the result for further cadastral applications. Furthermore, combining the automatic approach with manual interactive delineation is supposed to reduce time and resource consumption while maintaining the desired accuracy [45].

Thus, this study proposed publicly available and ready-to-use open-source software tools for each process pursuant to previous studies. It also outlines a workflow to apply the proposed software solutions and demonstrates the outstanding role of the AFE approach for fast, affordable, and reliable cadastral mapping. After open-source tools and plugin identification, the implementation process of the AFE approach is performed sequentially, starting with image segmentation followed by boundary classification, interactive delineation, and validation of interactively extracted boundaries relative to a reference cadastre, as depicted in Figure 3.

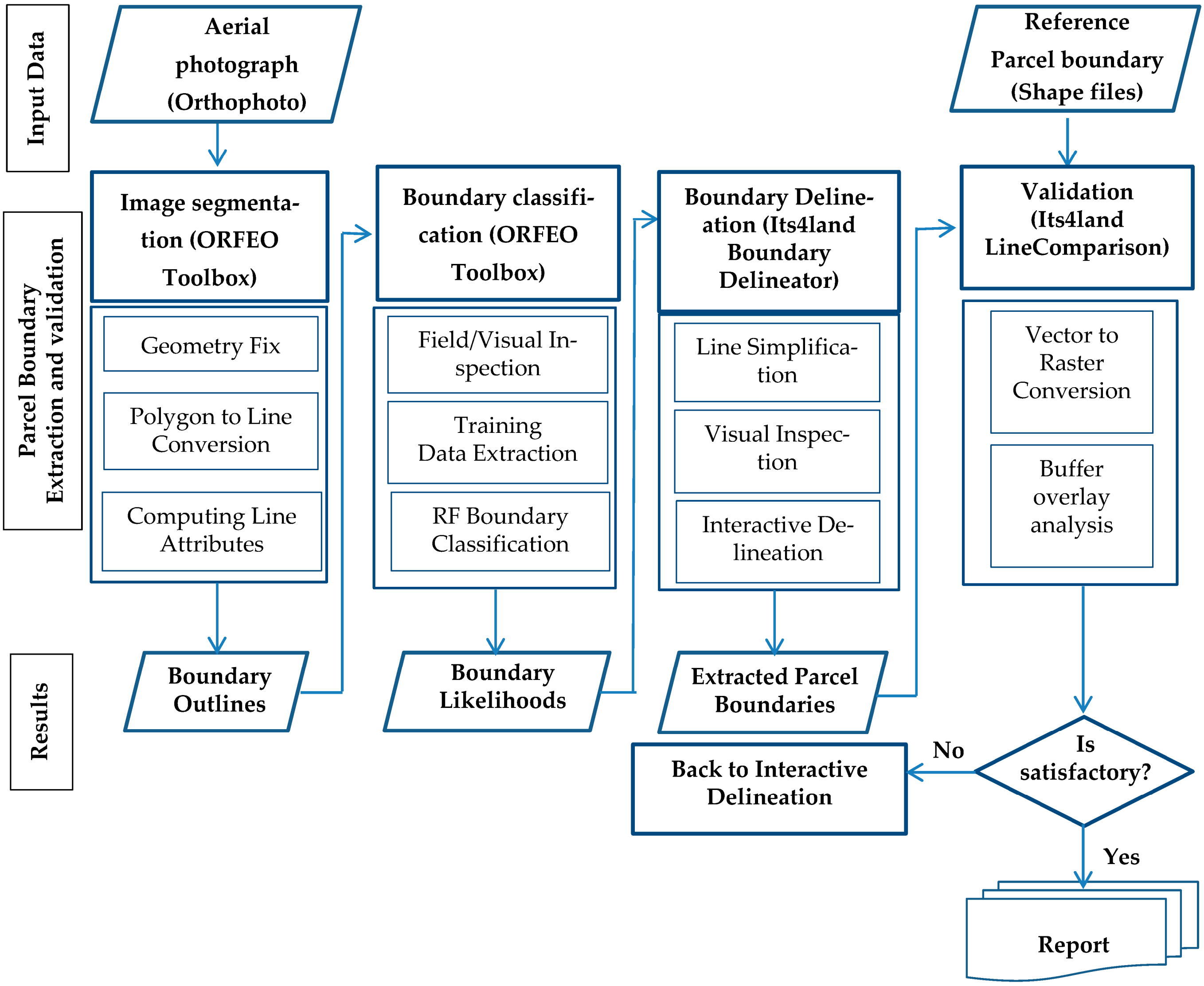

Figure 3. AFE approach for cadastral mapping using open-source software tools.

Following Crommelinck et al. [51] and Crommelinck and Ivanov [60], each step is further described below, along with the proposed open-source tools and plugins for each process:

(i) Image segmentation: at this stage, the orthoimage pixels are grouped into segments to deliver the outlines of the visible boundary features. This study employs the mean-shift image segmentation algorithm implemented in Orfeo ToolBox (https://www.orfeo-toolbox.org/, accessed on 9 January 2023) (OTB), an open-source state-of-the-art image processing library freely available for use [61,62]. The OTB is integrated into QGIS Version 3.16.0 for ease of use and further analysis of the extracted parcel boundaries.

(ii) Boundary classification: this step requires training a machine-learning model with a training dataset to enable it to predict the most probable boundary lines from the vector files obtained through image segmentation. The training and validation datasets are extracted from the segmentation result by manually selecting and assigning 1 and 0 attribute values, respectively, to the boundary and non-boundary line features. This study applied Random Forest (RF) machine-learning algorithms for parcel boundary prediction. Although Crommelinck et al. [51] tested and found that Convolutional Neural Network (CNN) machine-learning algorithms provide better precision and accuracy in boundary likelihoods, various studies have also proven that RF could provide good accuracy in image classification [2,63,64]. Moreover, it is one of several machine-learning models implemented in the OTB.

(iii) Interactive delineation: at this stage, the final cadastral boundaries are created by interactively delineating the boundary outlines based on the classification result. The line segments classified as parcel boundaries were further visually inspected and interactively delineated using the QGIS Version 3.16.0 "BoundaryDelineation" plugin. The plugin is developed by the Its4land (https://Its4land.com/, accessed on 29 September 2022) initiative, a European Horizon 2020-funded project, for quick cadastral mapping and land rights registration [65]. It is one of the six tools created by the initiative to support Sub-Saharan African countries with innovative technologies and consulting services in order to improve the time- and cost-consuming field surveying procedure for cadastral mapping. The plugin is supposed to expedite the interactive delineation process and minimize human resources and infrastructure costs [66,67]. It is also thought to enhance cadastral mapping where visible cadastral boundaries are predominant and fit-for-purpose land administration is favored [68]. Although it needs further investigation to refine the plugin [14,51], Crommelinck et al. [69] have suggested applying the technology for real-world cadastral mapping scenarios.

The "BoundaryDelineation" plugin provides six different interactive functionalities (Table 2) that facilitate precise delineation of the parcel boundaries, as demonstrated in Figure 3.

Table 2. Description of the "BoundaryDelineation" interactive functionalities [51,60].

Functionality	Description
Connect around selection	Connects lines surrounding a click or selection of lines (Figure 4a,b)
Connect lines' end points	Connects endpoints of selected lines to a polygon regardless of the segmentation lines (Figure 4c)
Connect along optimal path	Connects vertices along least-cost-path based on a selected attribute, e.g., Boundary likelihood (Figure 4d)
Connect manual clicks	Manual delineation with the option to snap to input lines and vertices
Update edits	Updates input lines based on manual edits
Polygonize results	Converts created boundary lines to polygons

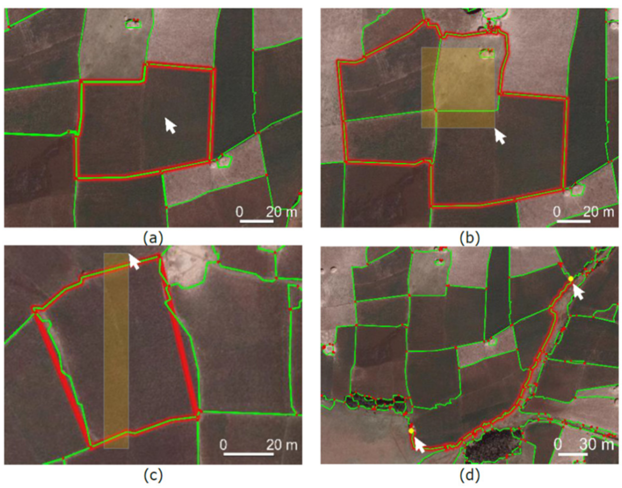

Figure 4. Examples of the interactive delineation functionalities: (**a**) connect lines surrounding a click, or (**b**) a selection of lines. (**c**) Close endpoints of selected lines to a polygon. (**d**) Connect lines along least-cost path [60]. The mouse pointer arrows show where to click to initiate the desired actions.

2.4. Accuracy Assessment

Accuracy assessment provides confidence to apply the adopted AFE approach in a real-world scenario for peri-urban cadastral mapping. This study employs both qualitative (visual inspection) and quantitative (buffer overlay) assessment methods. The qualitative assessment visually compares the interactively delineated cadastral features with ground reality. The quantitative validation uses the buffer overlay method to compare the interactively delineated boundary lines with the cadastral reference boundary. The buffer overlay method creates a buffer around a more accurate spatial feature to assess the positional accuracy of a less accurate test line by computing the percentage of its length that lies within the buffer [70]. Several studies have applied the buffer overlay method to assess classification results quantitatively [5,16,51,71].

Studies have used different radius buffer sizes for the extracted and reference boundary lines for buffer overlay analysis. Crommelinck et al. [51] used a 30 cm buffer size for validating automatically extracted and interactively delineated cadastral boundaries from UAV datasets for both rural and peri-urban areas in Rwanda and Kenya. Fetai et al. [4] performed the accuracy assessment with buffer widths of 0.25, 0.50, 1.0, and 2.0 m for cadastral boundaries extracted from UAV images. Wassie et al. [16] used 0.5, 1.0, and 2.0 m buffer radii to validate automatically extracted boundary lines from high-resolution satellite images for rural areas of Ethiopia. A study for the FFPLA implementation model suggested 1 m accuracy for rural area cadastral mapping from an orthophoto of 0.3 m resolution [72].

Considering that the test case is a peri-urban area where the urban-to-rural transition is undetermined, this study prompts validation of the interactively delineated boundary lines with different buffering sizes (from high to coarse). Thus, three moderate buffer radii for the extracted (0.4, 0.5, and 1.0 m) and reference (0.6, 1.0, and 1.5 m) lines were arbitrarily selected within the limits of the FDRE's [73] minimum spatial accuracy for urban cadastre (0.4 m) and the IAAO's [74] suggested accuracy level for rural boundaries (2.4 m).

The QGIS "LineComparison" plugin developed by the Its4land project was employed for the buffer overlay accuracy assessment of the interactive delineation result. It requires first rasterizing and buffering the reference dataset (Figure 5, Green) and overlaying it with the interactively delineated boundary lines (Figure 5, Red). Thus, the number of correctly extracted (True Positive (TP)) (Figure 5a), incorrectly retrieved (False Positive (FP)) (Figure 5b), and missing (False Negative (FN)) (Figure 5c) boundary features was used to statically compute the completeness, correctness, and quality of the interactive delineation result.

As discussed briefly in Heipke et al. [71], Crommelinck et al. [75], and others,

- Completeness is the percentage of the reference boundary that lies within the buffered extracted data (the reference data explained by the extracted data) and is given as

$$\text{Completeness} \approx \frac{\text{TP}}{\text{TP} + \text{FN}} \times 100\%$$

- Correctness refers the percentage of the extracted boundary that lies within the buffered reference data (the extracted data explained by the reference data), and is given as

$$\text{Correctness} \approx \frac{\text{TP}}{\text{TP} + \text{FP}} \times 100\%$$

- Quality is derived from the completeness and correctness of the extracted data, for these two metrics are complimentary and computed concurrently in order to indicate the quality or the overall accuracy of the extraction approach [76].

$$\text{Qulaity} \approx \frac{\text{TP}}{\text{TP} + \text{FP} + \text{FN}} \times 100\%$$

For ease of visualization and statistical computation, the "Expected" and "Extracted" number of pixels that belong to the TP, FP, FN, and TN categories are organized in a table (error matrix), as shown in Table 3.

Table 3. Error matrix.

		Expected	
		Boundary Lines (1)	Non Boundary Lines (0)
Extracted	Boundary lines (1)	True Positive (TP) /Extracted boundaries that coincide with the reference boundaries, Figure 5a/	False Positive (FP) /Extracted boundaries that do not coincide with the reference boundaries, Figure 5b/
	NonBoundary lines (0)	False Negative (FN) /Reference boundaries that are not extracted, Figure 5c/	True Negative (TN) /nonBoundaries identified as nonBoundaries/

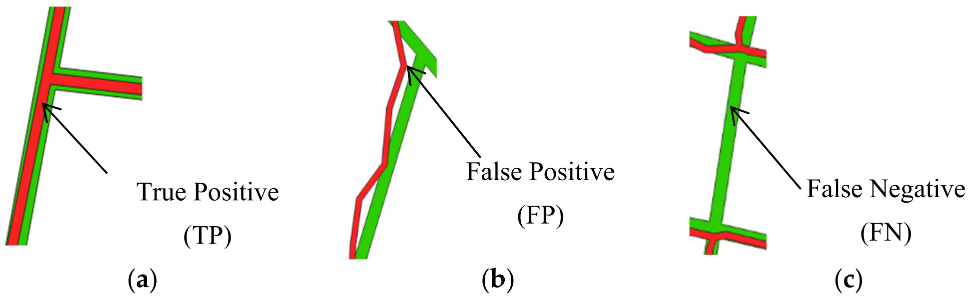

Figure 5. Examples of correctly extracted (**a**), incorrectly retrieved (**b**), and missing (**c**) boundary lines.

3. Results

The adopted methodology for the study was procedurally implemented to automatically extract boundary outlines from the orthophoto and classify the segmentation outlines into cadastral "boundary" and "non-boundary" features. The segmentation outlines classified as "boundary" were further delineated interactively to precisely determine the cadastral boundaries. The interactively extracted boundary lines were validated to confirm the adopted AFE approach's encouraging results. In this section, the processing outputs from image segmentation, boundary classification, interactive delineation, and validation are presented in order.

3.1. Image Segmentation

Image segmentation is a technique for extracting significant information by grouping image pixels with some visual characteristics in common [77]. Visible parcel boundaries have common observable attributes and reflectance values that favor image segmentation techniques. The OTB mean-shift segmentation algorithm was applied to extract boundary features with a few changes to some of its default parameter values. The spatial radius, the region size, and the object size parameters were, respectively set to 50, 1000, and 100 by repetitive trial and error to merge smaller region sizes with the neighboring closest radiometry cluster and to disregard small areas (in pixels) during vectorization.

Executing the OTB segmentation algorithm automatically extracted 2652 polygon features over the study area, which includes visible boundaries bounded by vegetation and fences. Several boundary features also fall within the reference cadastral boundary buffered by 0.4 m, the minimal spatial accuracy for the urban legal cadastre set by regulation [73]. Figure 6 shows automatically extracted outlines and boundary features (Yellow) that fall in a 0.4 m buffer width of the reference cadastre (Green).

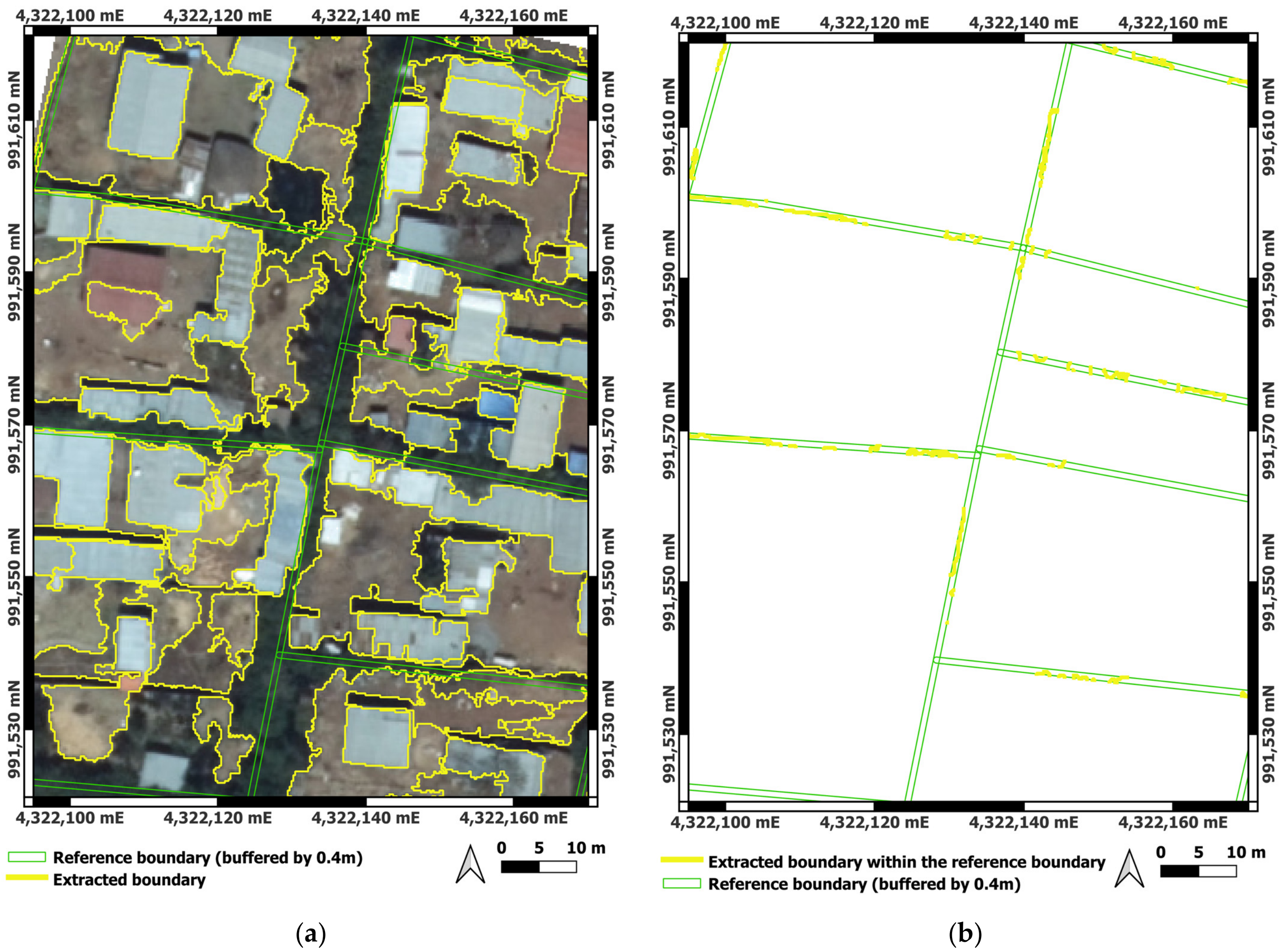

Figure 6. AFE results: (**a**) Automatically extracted outlines (yellow) and the reference cadastre (Green) buffered by 0.4 m; (**b**) Extracted boundary outlines that fall within 0.4 m buffer width of the reference cadastre.

The AFE approach quite precisely detected condominium buildings (Figure 7a), ditches, and cobblestone roads (Figure 7b) in the newly built-up areas due to their different reflectance property from the surrounding area. However, it also produced non-boundary objects within cadastral parcels due to the spectral differences and linear artifacts (horizontal and vertical straight lines) in the image areas, where there are no boundaries or spectral differences (Figure 7c). Despite these limitations, the AFE approach generated valuable information for detecting and mapping cadastral boundaries, including newly built-up areas.

The polygons were checked and fixed to meet the geometry properties and converted into lines using the QGIS "Fix Geometry" and "Polygon to Lines" built-in plugins. The length, the azimuth, and the vertexes of each line were computed using the QGIS "Field Calculator" built-in tool. These line features were inputs for training the RF model to predict the boundary likelihoods of the segmentation outlines [49].

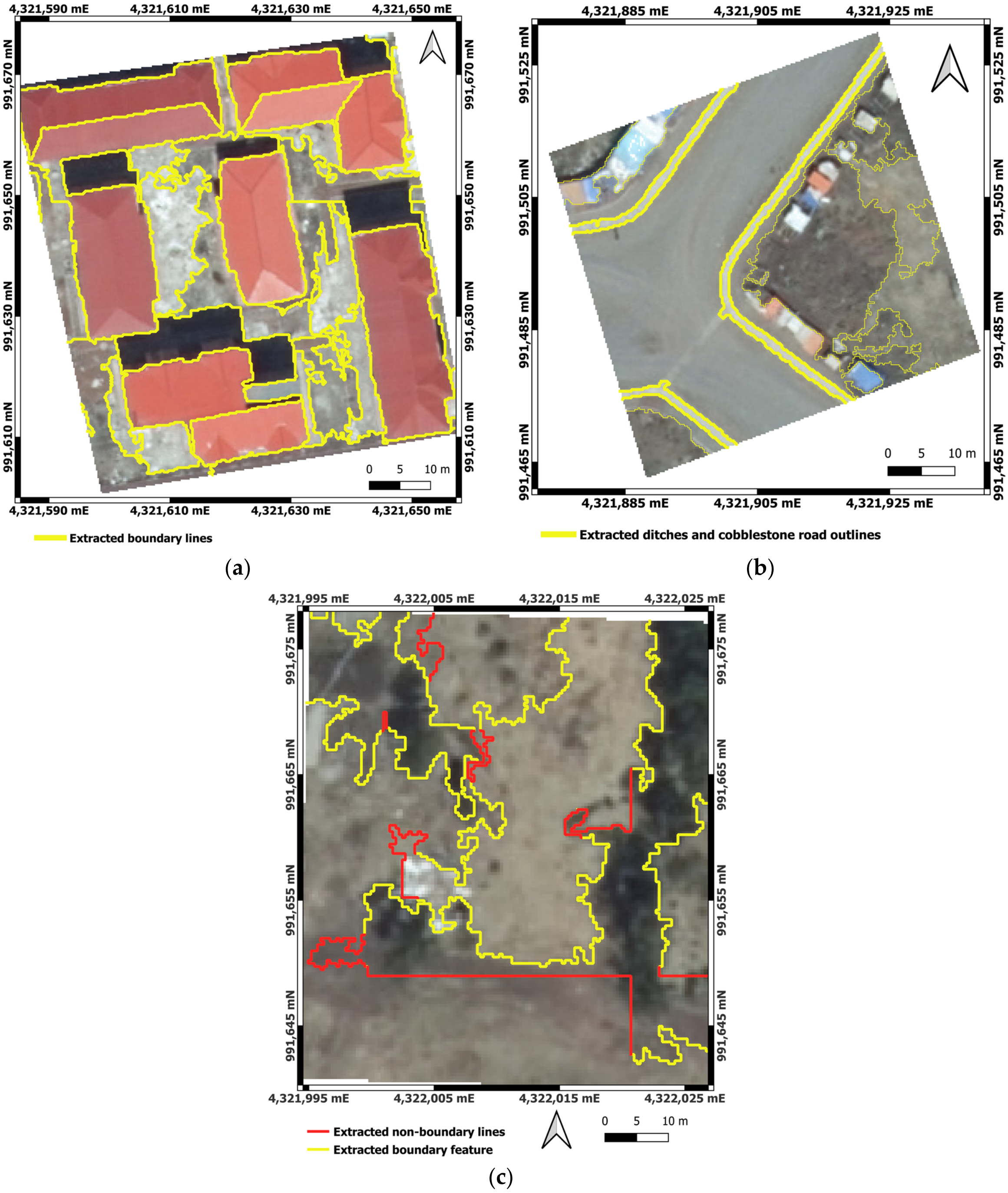

Figure 7. AFE results: Condominium buildings (**a**) Ditches and cobblestone roads (**b**), Non-boundary lines (**c**).

3.2. Boundary Classification

The boundary classification approach requires a training dataset to train the classifier for the prediction of boundary and non-boundary line features. Random field inspection was carried out to become familiar with the surrounding parcel boundary types and identify “boundary” and “non-boundary” segmentation lines. The datasets were thus arbitrarily selected by visual appraisal of the segmentation lines with the features on the orthophoto based on ground reality and the coincidence of the extracted boundaries with the reference parcel boundary. Thus, lines ostensibly representing cadastral boundaries were randomly selected and labeled (1) to denote “boundary”, while sample lines that do not describe parcel boundaries or artifacts were allocated (0), denoting “non-boundary”. Consequently, 300 lines were identified equally for “boundary” and “non-boundary” features, as proposed in the work of Crommelinck [49].

The OTB RF model with the default parameter setting classified the overall AFE segmentation outlines (2652) into “boundary” (1811) and “non-boundary” (841) line segments. The “boundary” lines, represented by yellow, were identified as the most probable cadastral feature boundary of the AFE segmentation outlines, while the “non-boundary” lines, shown in red, encompass non-cadastral boundary features (Figure 8).

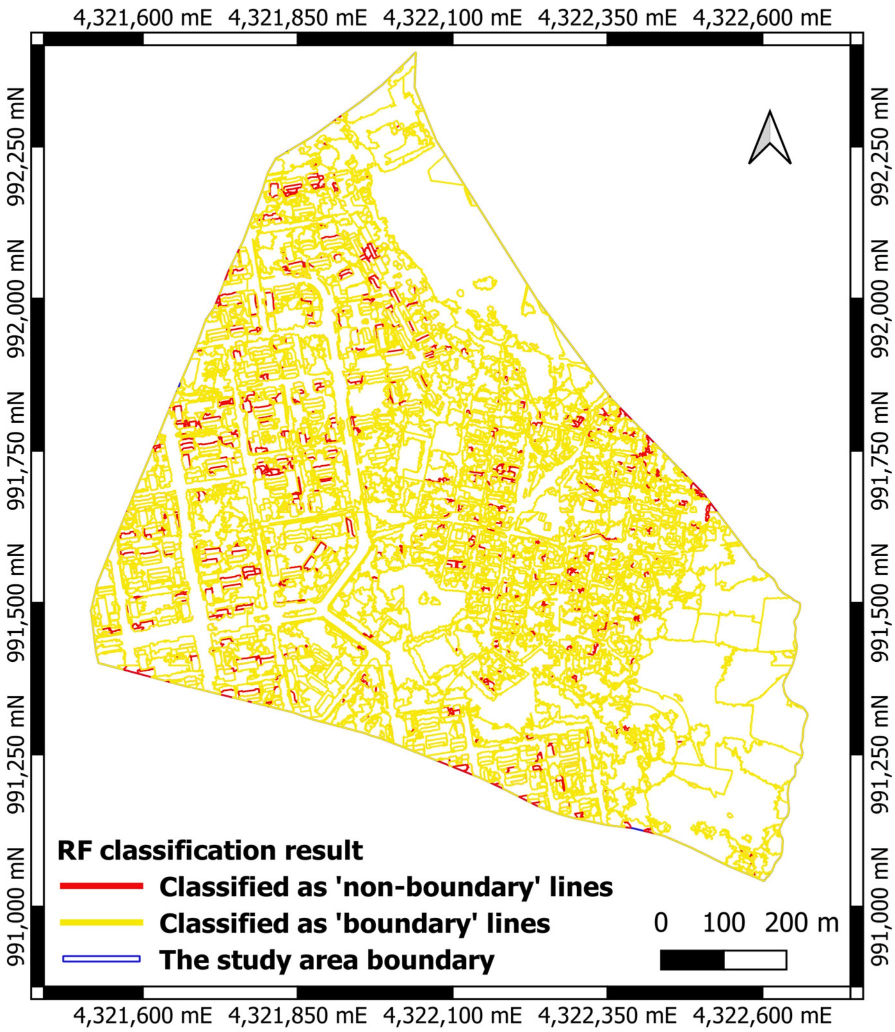

Figure 8. RF Classification result.

However, while inspecting the RF results visually, it was observed that there are instances where the classification is not as clear-cut, with some outlines exhibiting a combination of both “boundary” and “non-boundary” characteristics. Further analysis and refinement of the model may improve its performance and ensure a better classification of the ambiguous segments. This could involve collecting more training data, adjusting the model’s parameters, or incorporating additional features that capture the nuanced characteristics of the segmentation outlines.

3.3. Interactive Delineation

The QGIS “BoundaryDelineation” plugin automatically generates information from the orthophoto that helps interactively delineate cadastral boundaries [49]. It takes the study area image/orthophoto/and the probable boundary lines (identified by the RF classifier in this case). The lines are simplified at an appropriate scale to eliminate unnecessary details [78]. The interactive delineation needs careful visual inspection of the classified segmentation outlines based on the familiarity of the delineator with the study area. This makes it easy to use either of the "BoundaryDelineation" tool functionalities as appropriate (Table 2) for precise delineation. Thus, the cadastral boundaries and the building footprints are interactively delineated by snapping to the input lines and vertices, which can be accepted as final or rejected for re-delineation (Figure 9).

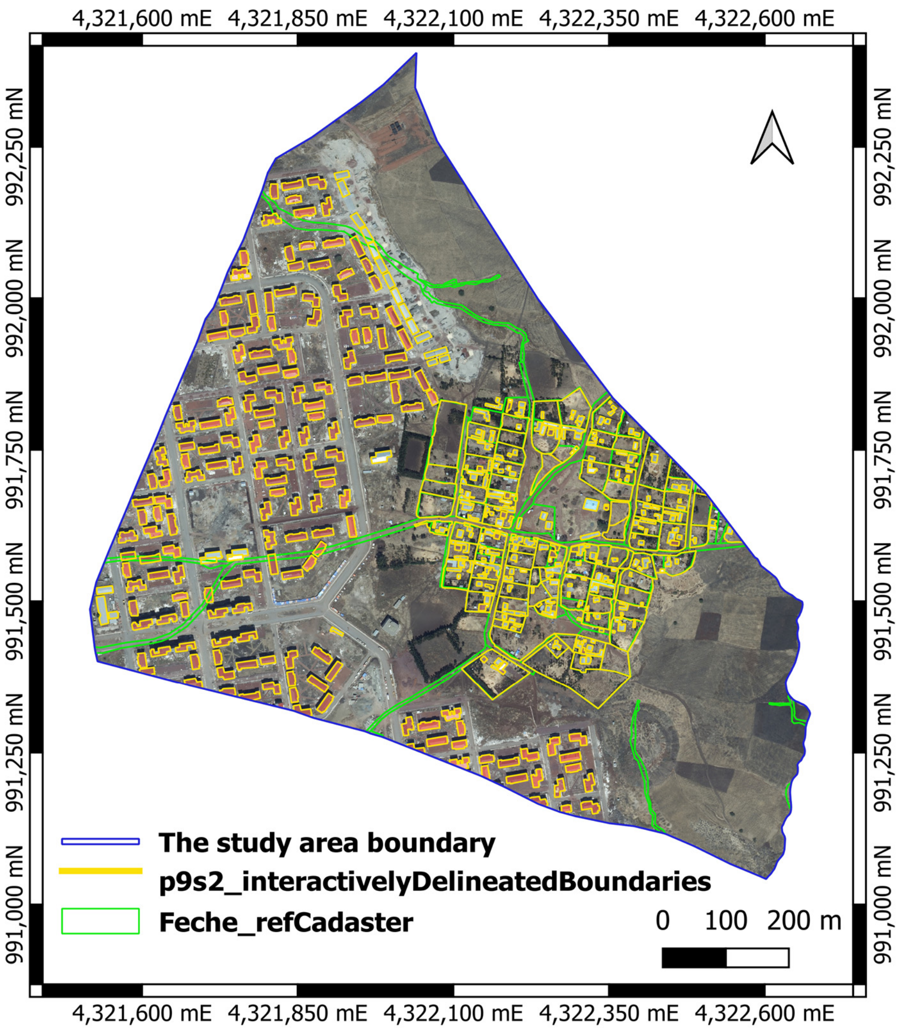

Figure 9. Interactively delineated building and parcel boundaries.

For validation and further processing, the interactively delineated boundaries were converted to polygons and checked to address the fundamental topological concerns using the QGIS "Topology Checker" plugin. Thus, corrections were made for topological errors which could break the relationship between boundary features [79], especially for overshoots, undershoots, and dangles.

3.4. Validation

The interactively delineated boundary lines were validated qualitatively by visual inspection and quantitatively by comparison with the reference cadastre. The visual inspection of the "BoundaryDelineation" result was satisfactory, for it was possible to exhaustively delineate cadastral boundaries and building footprints in the study area. However, dense vegetation and footpaths were extracted as cadastral boundaries. There are also extracted boundary lines that do not match with and deviate significantly from the reference cadastre.

This was further quantified using the QGIS "LineComparison" plugin, which compares the interactively delineated boundary lines to the reference cadastral dataset and computes the error of commission (false positives) and omission (false negatives). Accordingly, the "LineComparison" tool computed error matrices for the three buffering sizes of the input (0.4 m, 0.5 m, and 1 m) and the reference (0.6 m, 1 m, and 1.5 m) lines and generated the correctness, completeness, and quality of the interactively delineated boundaries for each buffer size as shown in Table 4.

Table 4. Validation of the interactively delineated boundaries with different buffer sizes.

	0.4 m by 0.6 m Buffer Size		**0.5 m by 1 m Buffer Size**		**1 m by 1.5 m Buffer Size**	
	Boundary (1)	Non-Boundary (0)	Boundary (1)	Non-Boundary (0)	Boundary (1)	Non-Boundary (0)
Boundary (1)	25,788	23,631	28,245	11,151	15,322	4124
Non-Boundary (0)	55,955	1,625,056	58,328	1,009,960	16,810	241,980
Completeness	32%		33%		48%	
Correctness	52%		72%		79%	
Quality	24%		29%		42%	

The validation result for the selected three buffer sizes is graphically depicted in Figure 10.

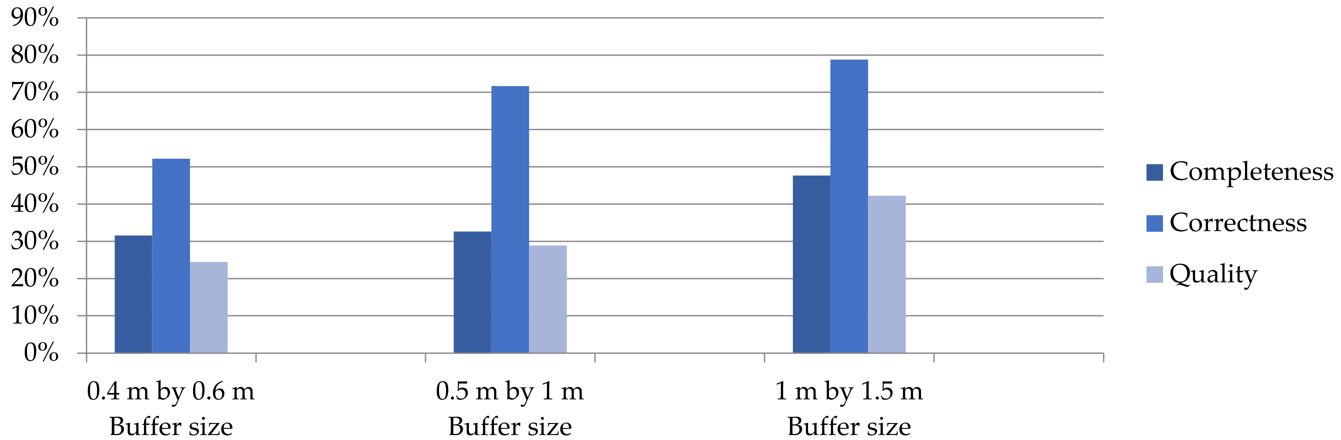

Figure 10. Completeness, Correctness, and Quality of the interactively delineated boundaries.

4. Discussion

The study explored freely available software tools and plugins for automatically extracting cadastral boundaries. An orthophoto and a reference cadastre for the case study of a peri-urban area in Addis Ababa, Ethiopia, were used for the demonstration. The orthophoto and the reference cadastre datasets were generated from aerial photographs acquired in 2016 and 2010, respectively. Publicly available open-source tools and plugins were identified and employed for image segmentation, boundary classification, interactive delineation, and validation. The OTB mean-shift image segmentation and classification tools were utilized to segment the image and classify cadastral and non-cadastral boundaries. The identified cadastral boundaries were interactively delineated and validated using the QGIS "BoundaryDelineation" and "LineComparison" plugins. The discussion clarifies the adopted approach and elucidates the outstanding role of the AFE approach in extracting parcel boundaries for cadastral mapping and refresh in a fit-for-purpose manner.

4.1. Image Segmentation and Classification Contribute to Cadastral Mapping

Image segmentation and classification are well-established techniques in remote sensing application studies. Segmentation is useful for detecting objects and boundaries, whereas classification is important to identify land cover types [80]. In recent studies [5,49], image segmentation and further classification of the segmentation result into "boundary" and "non-boundary" cadastral features delivered promising results for rural and peri-urban area cadastral mapping and updating.

The OTB mean-shift segmentation algorithm automatically extracted 2652 boundary features, including visible boundaries such as fences and vegetation (Figure 6). The number of extracted boundary outlines (2652) is much greater than the reference cadastre (131), partly due to new built-up areas between 2010 and 2016. There are also boundary outlines (Figure 6a,b) that fall within a reference cadastral boundary buffered by 0.4 m, the minimal accuracy for urban cadastral boundaries set by the Ethiopian Council of Ministers Regulation [73]. This could show the significant role of the AFE approach in automatically extracting cadastral boundaries, although it may require additional manual editing. Furthermore, the boundary lines of condominium buildings, cobblestone roads, and ditches were also precisely extracted (Figure 7), which did not exist in the reference cadastre.

According to the Addis Ababa context, the condominium building footprints are the basic spatial information for issuing condominium house ownership certificates that mention the block, the floor, and the house number of the individual room in the building. Thus, precise identification of the condominium building footprints aids significantly in the cadastral mapping and refreshing the peri-urban areas cadastre where a number of condominium houses have been and continue to be built in the past several years. In addition, the precise extraction and mapping of the outlines of condominium buildings could help future initiatives for developing 3D cadastre, for it is becoming important to capture the location and scope of the right of complex structures arising quickly following the rapid urbanization and population growth [81,82]. Automatic extraction of the cobblestone roads and ditches would also enhance the delineation of the spatial boundaries of blocks of buildings surrounded by them.

Even though the RF model classified some "boundary" features as "non-boundary" and vice versa (Figure 8), the classification approach minimized the number of segmentation outlines by 32% for the subsequent processing. Thus, the RF classification helps identify and exclude non-cadastral boundary features from the set of extracted boundary outlines. Furthermore, using only the outlines classified as "boundary" would be better than exploring the entire set of segmentation with a lot of artifacts and non-cadastral boundary features during the interactive delineation.

Various scholars have revealed image segmentation and classification prospects for extracting cadastral boundaries. However, the adaptations and implementations may not be as straightforward as with the open-source tools and plugins used for this study. For instance, Nyandwi et al. [5] used proprietary software (ENVI, eCognition) for image pre-processing and cadastral boundary extraction and found encouraging results in rural areas. While proprietary software may yield better results in image pre-processing and cadastral boundary extraction, its use could come at a higher cost. Wassie et al. [16] applied an open-source mean-shift image segmentation algorithm and automatically extracted rural boundaries and found it encouraging, especially compared to on-screen digitization. However, the iterative segmentation to identify the cadastral boundary from the entire set of extracted outlines is time- and resource-intensive. Crommelinck [49] employed the MCG method for image segmentation and a CNN algorithm for boundary classification to identify more probable cadastral boundaries. Although the source code is publicly available on GitHub (https://github.com/Its4land/delineation-tool/wiki/2b)-Convolutional-Neural-Network-Classification, accessed on 15 November 2022), it demands a certain level of technical expertise in programming for the necessary configuration and modification to adapt the approach.

4.2. Interactive Delineation Enhances the Traditional On-Screen Digitization

On-screen digitization is a traditional interactive process in geographic information systems to generate a digital map from several image sources [83]. The advancement in computer processing capabilities and machine-learning algorithms enhanced the traditional on-screen digitization for better and more precise identification and delineation of cadastral boundary lines. The Its4land "BoundaryDelineation" tool is an example of such a powerful tool that enhances the manual on-screen digitization technique. It facilitates semi-automated boundary line delineation by generating vertices along each line that would help interactively identify and delineate cadastral boundary lines precisely (Figure 9) with the different options it possesses (Table 2).

Both the qualitative (visual inspection) and quantitative (buffer overlay) assessments favor the interactive delineation approach over manual on-screen digitization. Visual inspection validated the complete extraction of cadastral boundary lines in the research area while excluding non-boundary outlines such as footpaths and artifacts. Dense vegetation along parcel borders is approximated and demarcated with less departure from the probable center. Significant cadastral changes in the study area between 2010 and 2016 are easily detectable visually. However, it is also worth considering the possible effect of the changes on the quantitative buffer overlay assessment results.

Nonetheless, the quantitative validation of the interactively delineated boundary lines is also promising, especially for less accuracy-demanding rural and peri-urban areas. Considering possible shifts both to the interactively delineated boundary lines and the cadastral reference boundary, the buffer overlay analysis provided favorable results (Table 4, Figure 10).

Buffering the input lines by 0.4 m and the reference boundary by 0.6 m provided 52% correctness and 32% completeness. Increasing the buffer size of the input lines to 0.5 m and the reference cadastre to 1 m changed the correctness and completeness percentages to 72 and 33, respectively. An additional increase in the input and reference lines to 1 m and 1.5 m increased the correctness to 72% and the completeness to 49%. The rise in correctness and completeness percentages with increasing buffer size might indicate possible cadastral boundary shifts due to the unplanned peri-urban expansion.

The quality of the interactively delineated boundaries needs to be improved, although there is an increase in each scenario (24%, 29%, and 42%). Quality is derived from the completeness and correctness of the interactively delineated boundary lines. It requires maximizing the number of correctly extracted (TP) boundary lines and minimizing the errors of commission (FP) and omission (FN) (Figure 5, Table 3).

Whilst the results are quite good for cadastral applications, it seems much higher achievements, e.g., 80–90%, are still a long way off with these results. Advancements in data capture technologies and machine-learning algorithms are said to improve spatial accuracy, although new uncertainty sources like classification errors are introduced [82]. As noted in [82,84], various factors, such as the quality of cadastral surveys, operator errors, the origin of maps, and the projection of cadastral maps, can affect the computation of the area of parcels. However, despite the need for much more improvement, the accuracy assessment result is within the allowable limits of the country's urban cadastre regulation [73]. The regulation permits photogrammetric and remote sensing techniques for cadastral mapping and subsequent applications as long as the uncertainty of positional accuracy does not exceed 40 cm at a scale of 1:2000. However, any positional discrepancy in parcel boundaries for a specific cadastral application needs to be supplemented by a conventional field survey, as outlined in the FFPLA guiding principles [22]. That said, incremental improvements are visible, and the method does allow for a rough-cut cadastre. In addition to careful visual inspection of the extracted boundary outlines, the familiarity of the delineator with the study area is also likely to increase the quality of the interactive delineation result [2].

Earlier works' statistical validations demonstrated the possibility of better improvements. Wassie et al. [16] attained 16.3% correctness and 54.4% completeness with the mean-shift image segmentation algorithm. Nyandwi et al. [5] applied OBIA and demonstrated the potential of the AFE approach over traditional on-screen digitization, extracting 45% of the visible boundaries in the study area and achieving 47.4% correctness. Crommelinck's [49] interactive delineation approach performed better, delivering 67% correctness and 37% completeness for peri-urban areas in Rwanda.

Thus, the validation results indicated the possibility of attaining higher levels of correctness and completeness with improvement in the AFE approach. Accordingly, improving the image segmentation and classification algorithms used in this study could enhance the efficiency of the "BoundaryDelineation" tool to correctly extract cadastral boundaries found in the vicinity of the mapping area. Koeva et al. [2] anticipated the superiority of interactive delineation over the traditional on-screen digitization approach if some extra functionalities, such as line geometry checking and creating polygon attributes, are incorporated. Alternative image segmentation and classification techniques may improve the correctness of the "BoundaryDelineation" tool.

Additionally, unlike manual digitization, which visually depicts and digitizes the probable boundary lines, interactive delineation is guided by the vertices generated along the RF-classified boundary (input) lines. The interactive delineation approach can be repeatable if revision is required, saves time to digitize (fewer clicks than manual digitization [49]), and precisely delineates the boundaries despite some differences with the reference boundary. Although the approach tends to improve manual digitalization-based indirect surveying, user feedback and expertise evaluation are expected to improve it further for real-world scenario applications.

4.3. Open-Source Software Tools and Plugins Streamlined the AFE Approach for Cadastral Mapping

Open-source software tools and plugins provide a range of functionalities that help automate and streamline the cadastral mapping process. These made the traditional cadastral mapping and updating process faster, more affordable, and more reliable than conventional ground surveying. The study by Ajayi and Oruma [85] estimated the AFE approach to be 2.5 times faster and 9 times cheaper than conventional ground surveying. There are various proprietary and freely available open-source software solutions to implement the AFE approach for cadastral mapping and refresh. This study explored the readily available QGIS tools and plugins for (semi-) automatic extraction of cadastral boundary features.

The OTB mean-shift segmentation tool is used for extracting cadastral boundaries automatically, which segments the input image and delivers the feature boundary outlines in vector format. The "TrainVectorClassifier" and "VectorClassifier" tools are applied to train the RF model and classify the extracted boundary outlines into "boundary" and "non-boundary" lines. The Its4land "BoundaryDelineation" tool is employed to interactively delineate cadastral boundaries and building footprints, simplifying the RF-classified boundary lines to an appropriate scale. The "LineComparison" plugin is another tool from It4sland that rasterizes and buffers the interactively delineated boundary lines to carry out the validation. As shown in the methodology, the QGIS built-in plugins are utilized to manipulate the input image and the extracted lines for further processing.

The tools from OTB and Its4land provided the intended result for cadastral mapping and refresh. However, there were unconditional interruptions and breaks while running the algorithms behind the tools. Future enhancements and updates to the source code could resolve this issue; being open-source is an advantage. Nonetheless, this study demonstrated the availability of the free and open-source tools and plugins to implement the AFE approach for cadastral mapping and refresh.

Even though expertise and experience with geospatial technologies is necessary, the implementations and applications of the open-source tools and plugins are not complex. Thus, the study demonstrated the potential use of publicly available software solutions to accelerate systematic cadastral boundary mapping, enhancing AFE applications in compliance with the FFPLA requirement.

5. Conclusions

This study investigated the outstanding role of the AFE approach for mapping and updating cadastral boundaries, considering one of the vibrant peri-urban areas in Addis Ababa as a case study. It looked into the publicly accessible and open-source QGIS Version 3.16.0 software tools and plugins for implementing the AFE approach.

Although several studies have demonstrated the potential of the AFE technique for cadastral boundary extraction, either by using proprietary software solutions or developing codes, the approaches seem expensive or require expertise for immediate use. This study, therefore, streamlined publicly available and ready-to-use geospatial software solutions and demonstrated the potential of the AFE approach for cadastral boundary extraction, complying with FFPLA requirements.

Open source tools and plugins from OTB and Its4land are used for image segmentation and classification. The possible boundary outlines from the mean-shift image segmentation are further classified into "boundary" and "non-boundary" outlines to remain with the most probable cadastral boundaries. The classification reduced the non-cadastral boundary features and segmentation artifacts by about 32% and helped the identification and interactive delineation of the cadastral boundaries. Furthermore, it is possible to repeat the interactive delineation process with relevant accuracy if rework is required. It also saves the time needed to extract the boundary lines compared to the manual digitization approach.

Visual inspection confirms the extraction of the most probable visible boundary lines from the orthophoto with complete coverage of the study area, whereas the buffer overlay analysis provided 52% correctness and 32% completeness compared to the reference cadastre. Precise extraction of the building footprints favors systematic updating of the peri-urban cadastre, where multiple condominium houses have been developed in recent years. Precisely extracted cobblestone pathways and ditches can also help to delineate the spatial boundaries of the blocks of buildings. Despite various factors that could affect the accuracy of achieved results, the uncertainty of the extracted parcel boundaries are within the allowable limits of the urban cadastral surveying regulation for further application.

Nonetheless, as incremental refinements are seen in previous works, improving the image segmentation and classification algorithms behind the tools could enhance the efficiency of the approach and achieve better accuracies. Careful extraction of the training dataset and computation of more line attributes might reduce the misclassification of "boundary" lines into "non-boundary" features and vice versa. Additionally, the delineator's acquaintance with the study area and careful visual inspection of the orthophoto would help precisely delineate cadastral boundaries.

Despite the encouraging results of utilizing free and open-source software solutions for the AFE implementation, the challenge of determining threshold values to avoid over- and under-segmentation needs attention. The unconditional interruptions and breakouts while using the tools also highlight the need for future enhancements, with the open source being a benefit.

In summary, the study is expected to contribute to the overall endeavor for cadastral mapping and refresh in peri-urban areas in a fit-for-purpose manner: fast, cheap, and reliable. However, the general methodological procedure and the technical approach for the AFE implementation need users' feedback and expertise evaluation to enhance further and apply it to the real-world scenario.

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Abbreviations

UAVs	Unmanned Aerial Vehicles
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
FFPLA	Fit-for-purpose land administration
OBIA	Object-Based Image Analysis
GIS	Geographic Information System
MCG	Multi-resolution Combinational Grouping
gPb	globalized probability of boundary
QGIS	Quantum GIS
OTB	Orfeo ToolBox
RF	Random Forest
CNN	Convolutional Neural Network
FDRE	Federal Democratic Republic of Ethiopia
IAAO	International Association of Assessing Officers

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