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FIT-FOR-PURPOSE LAND ADMINISTRATION: AN IMPLEMENTATION MODEL FOR CADASTRE AND LAND ADMINISTRATION SYSTEMS

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Abstract

Many countries, chiefly in the developing world, do not have a statutory land administration / tenure system. Such countries often want to implement cadastre and land administration systems but need a solution that fits their needs. The fit-for-purpose land administration approach described in the International Federation of Surveyors (FIG) and the World Bank's joint publication provides a blueprint for implementing fit-for-purpose land administration and cadastre systems. The approach is characterised by flexibility, inclusiveness, affordability and reliability, and is attainable and upgradeable. Having defined the fit-for-purpose approach there is now a need for a model which details applicable methodologies, systems and data and the associated costs for their implementation. This paper will briefly describe the fit-for-purpose approach and propose a model for its implementation.

Key Words:

aerial imagery, land administration system, open source software, satellite imagery, unmanned aerial vehicle

Introduction

Many countries, chiefly in the developing world, do not have a statutory land administration / tenure system. Such countries often want to implement cadastre and land administration systems but need a solution that fits their needs. The fit-for-purpose land administration approach described in the International Federation of Surveyors (FIG) and the World Bank's joint publication (FIG Publication No 60, 2014) provides a blueprint for implementing fit-for-purpose land administration and cadastre systems. Having defined the fit-for-purpose approach there is now a need for a model which details applicable methodologies, systems and data and the associated costs for their implementation. This paper will briefly describe the fit-for-purpose approach and propose a model for its implementation.

Fit-For-Purpose Approach

This approach as defined by the FIG and the World Bank is oriented to authorities who have an urgent need to build cost-effective and sustainable land administration systems which identify how land is occupied and used. This in turn will allow for the provision of secure land rights.

The approach is characterised by:

- flexibility - in capturing spatial data allowing for varying use and occupation;
- inclusiveness - covers all tenure and all land;
- participatory for data capture and usage - ensures community support;
- affordable in establishment, operation and use;
- reliable - provides authoritative and up-to-date information;
- attainable within a short timeframe, utilising available resources; and
- upgradeable - allows for incremental upgrading and improvement over time in response to social and legal needs and emerging economic opportunities.

The fit-for-purpose approach consists of four key principles:

- usage of visual land field boundaries to delineate rural and peri-urban land areas (these boundaries are not precisely determined and relate to physical features, rather than fixed boundaries);
- usage of medium resolution aerial imagery or high resolution satellite imagery for land delineation, which costs far less than field surveys;
- basing land information accuracy requirements on purpose rather than on technical standards which are often incompatible with existing infrastructure of a country; and

- continuous updating, upgrading and improving of spatial data on a as necessary / relevant basis and in accordance with land policy objectives.

The fit-for-purpose approach is characterized by its cost effectiveness with regard to large scale map data and the operational components of a sustainable land administration system. It provides the best solution for the purpose and not just any solution.

Because this approach differs from systems which demand high levels of accuracy, countries considering making use of this pragmatic and effective approach may need to revise their land administration and institutional frameworks. The implementation of the approach needs to be within a robust land governance framework which makes the land information accessible to all interested or concerned users.

It should be noted that the fit-for-purpose approach can also be applied for urban areas.

Implementation Model for Fit-For-Purpose Approach

The fit-for-purpose land administration approach has already been applied in a few cases, such as in Rwanda, Ethiopia, Namibia etc. (FIG Publication No 60, 2014). However, no detailed implementation model for this approach has yet been described. The model proposed in this paper should help interested land administration or cadastre authorities to adopt this approach and implement it.

The implementation of a cadastre and land administration system can be divided into two parts:

1. data collection, and
2. land administration system (LAS) development.

Data Collection

With regard to data collection there are a number of options or platforms which utilize satellite imagery and / or aerial imagery. The aerial imagery can be acquired by aircraft or drones (unmanned aerial vehicles – UAV / systems - UAS).

Data collection may be required for rural and / or urban areas. High resolution satellite imagery or medium resolution aerial imagery is often used for surveys of rural areas. High resolution satellite imagery is also used when the airspace access in urban areas is not possible or is difficult for security reasons. In addition small areas, which are remote, can often be covered with high resolution satellite imagery since mobilising an aircraft to such areas is costly. Table 1 lists the advantages and disadvantages of satellite imagery.

Advantages of high resolution satellite imagery	Disadvantages of high resolution satellite imagery
Satellite platform is operational 365 days of the year; frequent re-visit times; satellite can easily access remote or restricted areas; no air traffic control restrictions	Imaging time is fixed; cannot be optimized with respect to weather conditions and cloud coverage¸ strong possibilities of cloud cover and thus occlusions;
Large area footprints decrease the need for block adjustment and creation of image mosaics	Image acquisition geometry is not very flexible
	Image quality is often impaired by different factors (atmospheric etc.)
	Typical off-nadir viewing angle of up to 25° is problematic in image matching
	Cost of the imagery may be too high (when compared to aerial photography); especially multi-images (>2 images covering the objects)

Table 1: Advantages and disadvantages of high resolution satellite imagery (Source: GEO Informatics, 2012)

There are some disadvantages to using aerial imagery; however, these are of an administrative or cost nature. Administrative disadvantages include the issuance of flight permits for conducting aerial surveys. Some developing countries are reluctant to issue flight permits because of security concerns. Nowadays such concerns are irrelevant or unfounded since high resolution satellite imagery is available to all. A central cost disadvantage is the price of ferrying aircraft to the project area for an aerial survey. The remoteness of a project area will increase the cost of ferrying; however, the larger the project area the less expensive the ferrying will be since costs will be distributed over a wide area. In other words, economies of scale apply.

In comparing the aerial imagery with satellite imagery one has to note the advantage of aerial imagery with regard to user licensing. Aerial imagery acquired for a client can become his property with full rights over it, while satellite imagery is restricted by licensing procedures set by the satellite operator. Satellite imagery providers usually grant the entity acquiring their products a non-transferable and non-exclusive license to use their product, but not to own it. In addition the price of the imagery will increase when a group license is requested. Depending on the number of users in a group the increase can be up to 45% (e-GEOS S.p.A. Price List, 2016). Therefore when authorities acquire satellite imagery they pay for each user who would like to use this imagery; thus the number of users will determine the final price of acquiring the satellite imagery.

Another source of aerial imagery is the unmanned aerial vehicles (UAV) or drones. Aerial imagery acquired using UAVs or drones is slowly emerging as a good alternative for the coverage of small and remote areas. However, it has some disadvantages, namely:

- many countries still have no regulations about the operation of UAV
- the UAVs can only fly / cover small areas.

Matese et al. (2015) compared UAV, aircraft and satellite remote sensing platforms for precision viticulture and found the costs of UAV to be competitive with traditional acquisition platforms. Operational costs are low, the deployment is flexible, and the spatial resolution of the imagery is high. The cost analysis showed that the UAV is chiefly advantageous for small areas. For areas larger than 5 hectare airborne and the satellite platforms are less expensive. Nevertheless, a fit-for-purpose approach should compare data acquisition costs across platforms, and select that which is most effective in terms of price and in meeting the parameters of requirements analysis.

The size and the location of the area to be mapped will also help determine which of the spatial data capture platforms will be used. The choice between satellite imagery or aerial imagery is thus determined by area size, data acquisition costs and accuracy requirements.

Irrespective of the imagery platform selected stereo imagery is necessary (1) to generate a digital elevation model, (2) to produce digital orthophotos, (3) to perform vector mapping of the land parcels or plots.

Aerial Imagery from Manned Aircraft

Methods of image acquisition are usually determined by the size of the area to be surveyed. Experience has shown that aerial imagery acquired at medium resolution of 30cm for rural areas is usually the best option for areas larger than 1,000 square kilometers. This will yield optimum accuracy and optimum cost effectiveness. Though high resolution satellite imagery with 30cm resolution is available it is often more expensive for areas larger than 1,000 square kilometers when compared to the cost of aerial imagery. If the area is less than 1,000 square kilometers then the cost of ferrying the aircraft to the area might be high when compared to the area concerned. In addition aerial imagery is acquired in stereo at no additional cost whereas for high resolution satellite imagery higher prices are demanded for stereo imagery. Table 2 shows the cost of aerial imagery at different resolutions

Aerial Image Resolution	Resolution Type	Average Price per Square Kilometer in USD
10cm	high	300.00
20cm	high	75.00
25cm	high	65.00
30cm	medium	30.00
40cm	medium	20.00
70cm	low	6.00

Table 2: Average price of aerial imagery with different resolutions (Source: Hansa Luftbild, 2015)

The prices given in Table 2 are for stereo imagery with 0% cloud cover.

High resolution aerial imagery is ideal for urban areas and can be used depending on the level of detail required to be captured. Figure 1, Figure 2, Figure 3 and Figure 4 show aerial imagery at 10cm, 20cm, 30cm and 70cm resolutions. The average prices of Table 2 will fluctuate according to the remoteness and size of the area to be surveyed. These, however, may be offset against each other. While the costs of ferrying increase according to remoteness, per unit image capture decreases over large areas.

On the basis of the average price for 10cm resolution aerial photography, if one considers that the size of a land parcel in an urban area is on average 500 square meters, then one square kilometer will cover 2,000 parcels which will render the cost of aerial photography per parcel at around 15 US cents. With regard to the rural areas if one takes a medium resolution of 30cm as a base to determine the cost per land parcel or plot with an average size of 5,000 square meters then the cost per parcel will be around 15 US cents. This shows how cost effective aerial imagery is. Of course the cost of producing digital orthophotos or stereoscopic / photogrammetric data capture is to be added to the price of aerial photography. This additional cost can range between one times the cost of aerial photography for orthophoto mapping to 4 times for photogrammetric parcel mapping.

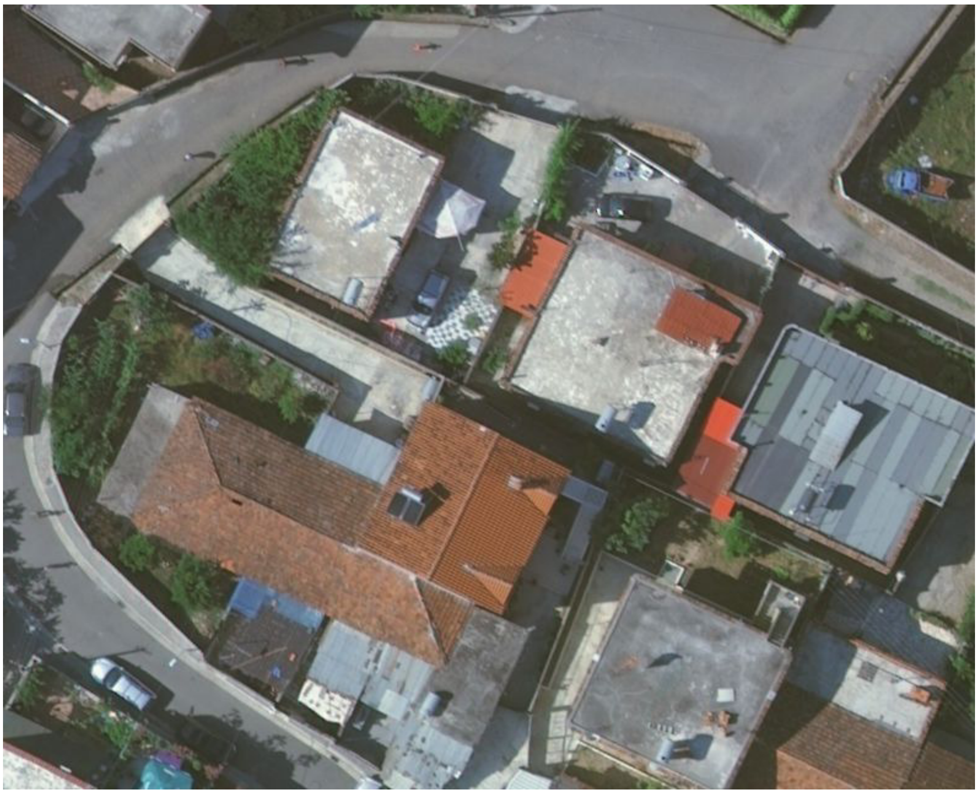

Figure 1: High resolution 10cm aerial imagery (Source: Hansa Luftbild, 2015)

Figure 2: High resolution 20cm aerial imagery (Source: Hansa Luftbild, 2015)

Figure 3: Medium resolution 30cm aerial imagery (Source: Hansa Luftbild, 2015)

Figure 4: Low resolution 70cm aerial imagery (Source: Hansa Luftbild, 2010)

The accuracy of orthophoto mapping or photogrammetrically captured data is dependent on the aerial image resolution and the quality of the ground control being used. However, one can expect an accuracy which is in the order of two times the resolution. That is, vector map data captured photogrammetrically using 10cm ground resolution will have an accuracy of 20cm. This is sufficient for urban areas where obsolete data or no data exists. For the rural areas the visual boundaries mapped using digital orthophotos with 30cm resolution the accuracy is better than 1 meter.

High Resolution Satellite Imagery

High resolution satellite imagery is readily available to cover the world. The cost of this differs according to satellite system used, area size and the age of imagery. Currently commercial high resolution satellite imagery is available for land administration purposes. Satellite imagery, which is considered high resolution, has a ground sampling distance of better than 1m. Table 3 shows some of the commercial high resolution satellite imagery available and its standard cost per square kilometer for stereo imagery.

Satellite System	Satellite Image Resolution	Standard Price for New Tasking per Square Kilometer in USD
Worldview-3	30cm	78.00
Geoeye-1	41cm	61.50
Worldview-2	46cm	55.00
Worldview-1	50cm	55.00
Pléiades-1A / Pléiades-1B	50cm	29.00
KOMPSAT-3	70cm	32.00
EROS-B	70cm	32.00

Table 3: Some of the available high resolution satellite imagery for land administration purposes (Source: e-GEOS S.p.A. Price List, 2016; Geo-informatics and Space Technology Department Agency Price List, 2015; Geoserve B.V, 2016)

These prices can be compared with the cost of aerial imagery in Table 2.

The prices are subject to standard tasking procedures with regard to time and delivery. Image acquisition can take up to 120 days, depending on the type of area to be covered. If priority tasking is ordered, ie delivery within a shorter period of time, then higher prices are to be expected.

Figure 5, Figure 6 and Figure 7 show samples of high resolution satellite imagery at different ground resolutions.

Figure 5: Sample of Worldview-3 high resolution 40cm satellite image (Source: DigitalGlobe Inc., 2014)

Figure 6: Sample of Pléiades-1 satellite imagery with 50cm resolution (Source: Centre National d'Études Spatiales [CNES], 2014)

Figure 7: Sample of KOMSAT-3 satellite imagery with 70cm resolution (Source: Korean Aerospace Research Institute, 2015)

The image resolutions given in Table 3 are for the nadir (center) part of the image / scene on flat terrain. Towards the edges (fore and aft) of the image the resolution will be lower due to the off-nadir angle.

Orders for stereo satellite imagery require a minimum area purchase which ranges between around 50 square kilometre and 250 square kilometers, depending on the satellite system. In addition cloud cover for tasking orders are usually specified by the satellite system operator at 15%. If cloud cover is to be less than 15% then the price increases.

Satellite system operators sometimes offer discounts for larger areas. In addition operators also offer archive imagery at lower cost. Here the price per square kilometre can drop by 50%, depending on the time of image acquisition.

The accuracy obtained from satellite imagery is dependent on the ground control distribution, number of points used, and processing type. The average accuracy of the basic satellite imagery on offer can range from 5.0m for the Worldview-3 (DigitalGlobe Data Sheet Standard Imagery, 2016) to 40.6m for KOMPSAT-3 (KOMPSAT-3 Image Data Manual, 2016). However, a higher accuracy can be achieved by using an appropriate number of control points which are well geographically distributed over the project area. Nevertheless, accuracy should always be determined according to requirements and purpose.

Unmanned Aerial Vehicles (UAVs) - Drones

UAVs are emerging as a good alternative for collecting aerial imagery. Pilot projects have been conducted and presented to land administrators or interested audience. During the 2015 World Bank Conference on Land and Poverty papers were presented about the results of using drones to acquire aerial imagery for boundary mapping. In addition there was also a MasterClass given about using small UAVs for high resolution mapping (World Bank Conference Land and Poverty, 2016).

The usage of UAVs with automatic feature extraction will also be researched between 2016 and 2020 as part of the Geospatial Technology Innovations for Land Tenure Security in East Africa – ITS4LAND Project which is funded by the European Commission under the Horizon 2020 Progam (Hansa Luftbild, 2015).

UAVs should be considered for collecting high resolution aerial imagery where areas are small, ie less than 20 square kilometer, and remote. If the project areas are bigger a comparison between using a manned aircraft and an UAV should be made prior to deciding on the data collection platform.

Currently there is a large number of companies which offer UAVs. The website www.geo-matching.com (UAS for Mapping and 3D Modelling, 2016) lists more than 30 manufacturers of UAVs / UASs. Some of the manufacturers have more than one system on offer. For example the company Germap GmbH in Germany (www.germap.com) offers four types, two fixed wings and two rotary / copter ones. Sensefly of Switzerland (www.sensefly.com) also offers 4 systems for different tasks. Hence there is a large number of suitable UAVs for land administration purposes on offer.

The price of an UAV for boundary mapping can start at under 5,000.00 USD and go up to 100,000 USD, depending on the type and range and capabilities. Reliable and stable UAVs with good flight endurance and capabilities can be found on the market at a price of 20,000 USD. In addition to the cost of the UAV the cost of additional power packs for extending the flight endurance, of training and processing software should be included in the total cost of acquiring and operating an UAV.

Figure 8 and Figure 9 show two examples of high resolution aerial imagery acquired with the Germap G47-X8 multicopter.

Figure 8: Sample of high resolution 10cm UAV image (Source: Germap GmbH, 2015)

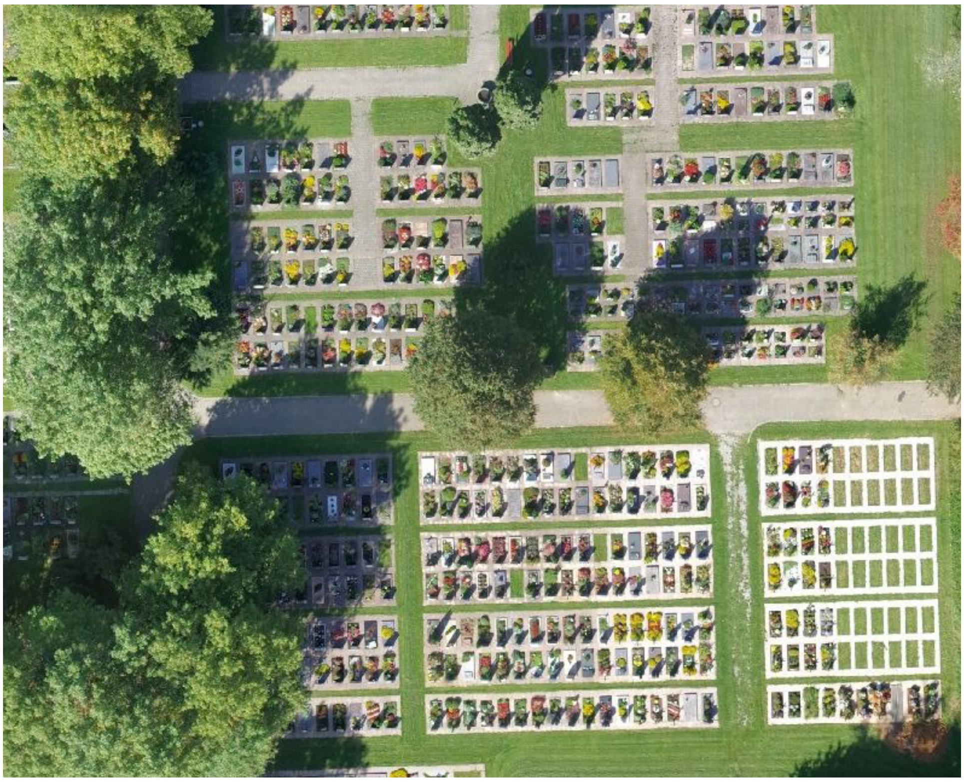

Figure 9: Sample of high resolution UAV 5cm image (Source: Germap GmbH, 2015)

As mentioned previously UAVs are ideal for small areas. For example aerial image acquisition of a 2 square kilometer block at 400m altitude above ground level with 10cm resolution can be covered in 30 minutes.

When one considers the total cost of the UAV with the processing software and training then the price of one square kilometer of aerial imagery can reach 750.00 USD if the block to be mapped is 10 square kilometers on average. Using this price estimate an average parcel size of 5,000 square meters in a rural area will cost 3.75 USD. In comparison aircraft aerial imagery or satellite imagery covering an area of 10 square kilometers will cost more than UAV aerial imagery when aircraft ferry cost or the minimum order requirement set by the satellite system operators are taken into account.

As with the aerial imagery or satellite imagery the accuracy of the mapping captured from high resolution aerial imagery acquired with an UAV is dependent on requirements and usage of ground control points.

Land Parcel Mapping

Any acquired airborne or satellite imagery is usually used to produce digital orthophotos for mapping land parcels in the rural areas. The orthophotos can be plotted on paper or copied on tablet computers for usage in the field. Digital orthophotos can also be used in the office for digitizing visible boundaries on computer screens in order to produce the spatial data – land parcels - required for the registration in the land administration system. Mapped visible boundaries are then verified in the field during the registration process.

By contrast urban areas are best covered with photogrammetric mapping using high resolution stereo aerial imagery. This can be acquired with aircraft equipped with large format digital cameras when the area to be surveyed is larger than 20 square kilometres. Stereo aerial imagery will allow the mapping of objects, land or structures, using photogrammetric techniques, which will result in reliable and accurate cadastral map data. In addition digital orthophotos can also be produced from the stereo aerial imagery which can then be used as a backdrop to the mapped data and as documentary evidence of the boundaries. When the area is smaller than 20 square kilometres then the usage of a UAV or UAS may be viable depending on the cost of acquiring and processing the data and the accuracy requirements set by the concerned cadastre or land administration authority.

Figure 10 shows visible parcels and structures mapped in an urban area using 20cm resolution aerial photography acquired with a manned aircraft equipped with a large format digital camera. Figure 11 shows the same parcel mapping with the orthophoto as a backdrop

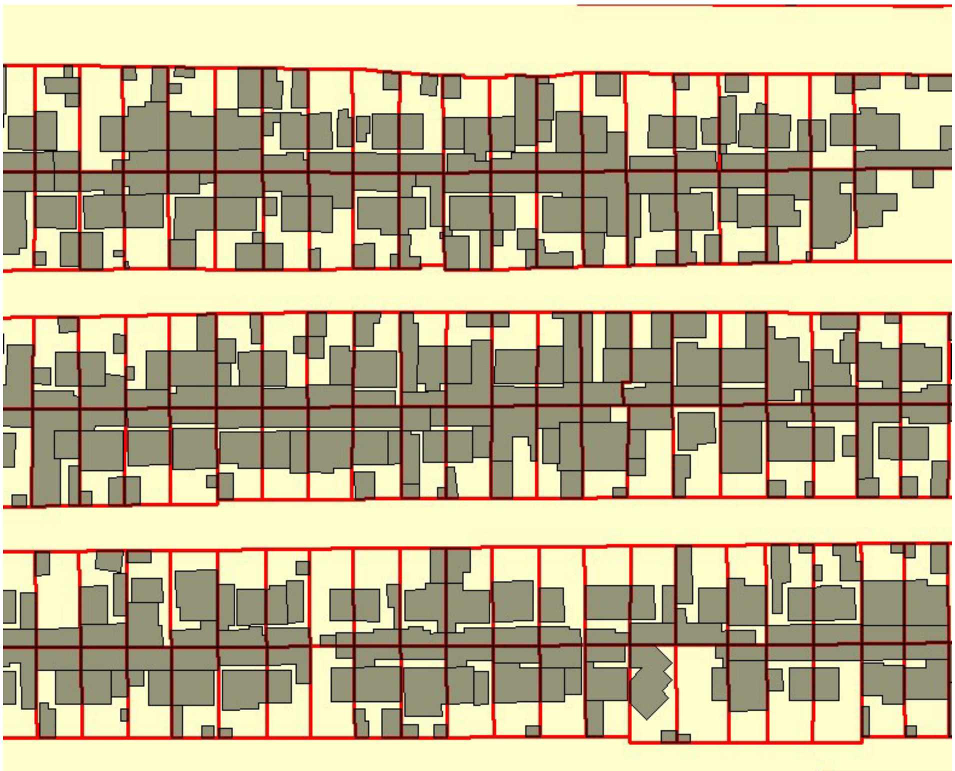

Figure 10: Parcels and buildings mapped using high resolution 20cm aerial imagery (Source: Hansa Luftbild, 2011)

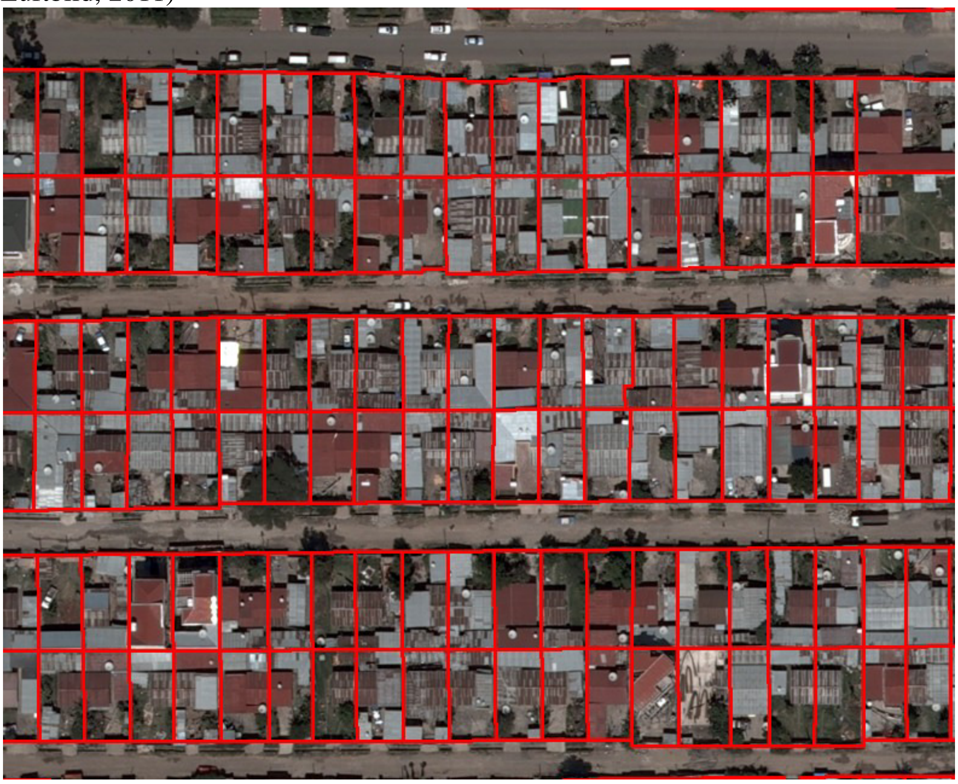

Figure 11: Parcels superimposed over orthophotos with 20cm resolution (Source: Hansa Luftbild, 2011).

Experience has shown that the cost of mapping the visible boundary of a parcel in an urban or rural area using 20cm resolution aerial imagery can range between 0.75 USD and 1.00 USD. Adding the cost of aerial imagery per parcel of 0.15 USD, then the total cost will be in the order of 1.15 USD per parcel.

Data Collection in the Field

Data collection also includes the gathering of information in the field / on the ground about land tenure, land use and land rights. For this purpose land administrators can use either printed paper plots or tablet computers. Both forms of representation for use in the field can be generated from orthophotos produced from aerial and / or satellite imagery. The advantage of using paper plots is that they allow the land owners / users to see and "touch" their land parcel or land holding. The disadvantage of plots is the additional work entailed in comparison with tablet computer use. Namely, the information gathered in the field has to be digitized to be input into the computer system of the concerned land administration authority. A better method might be using tablet computers with running applications that will allow the land administrators to input the data digitally in the tablets while in the field and to then transfer the data either online in real time to the computer server system or to upload it on returning to the office. Two disadvantages of using tablet computers in the field are the difficulty of acquiring a reliable power source in rural areas for battery recharging, and glarey screen when working outside in the open, especially in sunlight.

With regard to tablet computers there are free applications (apps) which can be installed and used for collecting information and land rights. For example the Open Tenure application, developed through a Food and Agriculture Organisation (FAO) managed project and the Mobile Application to Secure Tenure (MAST) developed by the United States Agency for International Development (USAID). Open Tenure is available for IOS, Android and personal computer operating systems. MAST is only available as an Android application. Both systems have, amongst other functionalities, in-the-field map and data recorders to perform systematic registration or digital lodgement for property registration. They fully support the fit-for-purpose approach, especially the participatory characteristics and the crowd sourcing approach which allows the local communities to collect the tenure related details.

The cost of tenure related details with land rights' data collection in the field is roughly equivalent whether plots or tablet computers are used. This cost can be around 5.00 USD per parcel.

Land Administration System Development

With regard to the land administration system development and its implementation there are often important decisions to be made. For example, should the concerned authorities use open source or proprietary software, both of which will have to be customized to fulfil requirements. The initial cost of developing a land administration system on the basis of open source software is estimated to be equivalent to using proprietary software. However, savings can be made through the lifecycle of a software system.

Land administration systems are established using base software and applications related to land administration and cadastre. During the lifecycle of such a system, which can extend up to 25 years, software maintenance will be required for the base software and the applications. For land administration systems built using proprietary software, maintenance has to be paid for the base software as well as for the applications; for systems built using open source software payment for maintenance will be for the applications only. This is because the open source base software is maintained by the open source community. Thus savings can be made on software system maintenance when using open source. In order to be in line with the affordable element of the fit-for-purpose land administration approach open source appears to be the most viable solution especially with regard to cost and flexibility.

In establishing a land administration system governmental authorities have two choices / options with regard to using open source. They may (1) adapt an already existent open source land administration system; for example, the Solutions for Open Land Administration (SOLA) project developed by the FAO, has already been adapted for a number of different countries. Alternatively the authorities may (2) use an open source platform to develop a new land administration system from scratch, which is frequently a viable solution, since the costs are relatively comparable to the option number one. Many countries, in putting out tenders for land administration systems, state in their terms of reference that the use of an open source platform should receive priority. Therefore the implementation model of the fit-for-purpose land administration approach will cover the establishment of a new land administration system on the basis of the client specified requirements.

In establishing a new software system a requirements analysis must be carried out first in order to propose a system. After the client accepting the proposal the architecture of the system is set and the system is designed.

The requirements analysis will include at least the following components:

- existing system and existing business processes
- assessment of the existing system's strength, weaknesses, opportunities and threats (SWOT)
- existing land / property laws and regulations

- existing digital systems (digital spatial and non-spatial systems) and data (spatial and non-spatial data)
- existing organisational structure
- existing stakeholders

After the existing situation has been analysed and documented any proposed land administration system should include:

- Purpose and scope of the system
- Functional and non-functional requirements
- Spatial cadastre system and data
- Land registration system and data
- Relating existing processes to reengineered or new processes described as use cases
- Reference and domain models
- Role of stakeholders in the new system

The acceptance of the concerned authority / the client of the proposed system will trigger the description of its architecture. A reference architecture on the basis of open source software and the Land Administration Domain Model (LADM) has been proposed by Zein, Timm and Hartfiel (2015). This architecture could be used in designing and implementing the land administration system (LAS). Figure 12 shows a high level overview of the proposed system and its components. The following four components, ordered as layers, incorporate all the parts required to build an LAS and can be implemented with existing OSS developments:

1. ExperMaps Data Level
2. Internal OGC Service Level
3. ExperMaps LAS
4. Desktop GIS - QGIS

ExperMaps is a web application which has been developed using the open source components PostgreSQL, PostGIS, QGIS, GeoSever, and OpenLayers (Zein, Timm & Hartfiel, 2015).

The lowest layer is the ExperMaps Data Level which provides the persistence services and is implemented in the PostgresSQL / PostGIS database. This data level also hosts the document management system (DMS) for storing the cadastre and land records documents and its implementation can be carried out with open source software, such as Alfresco or Agorum.

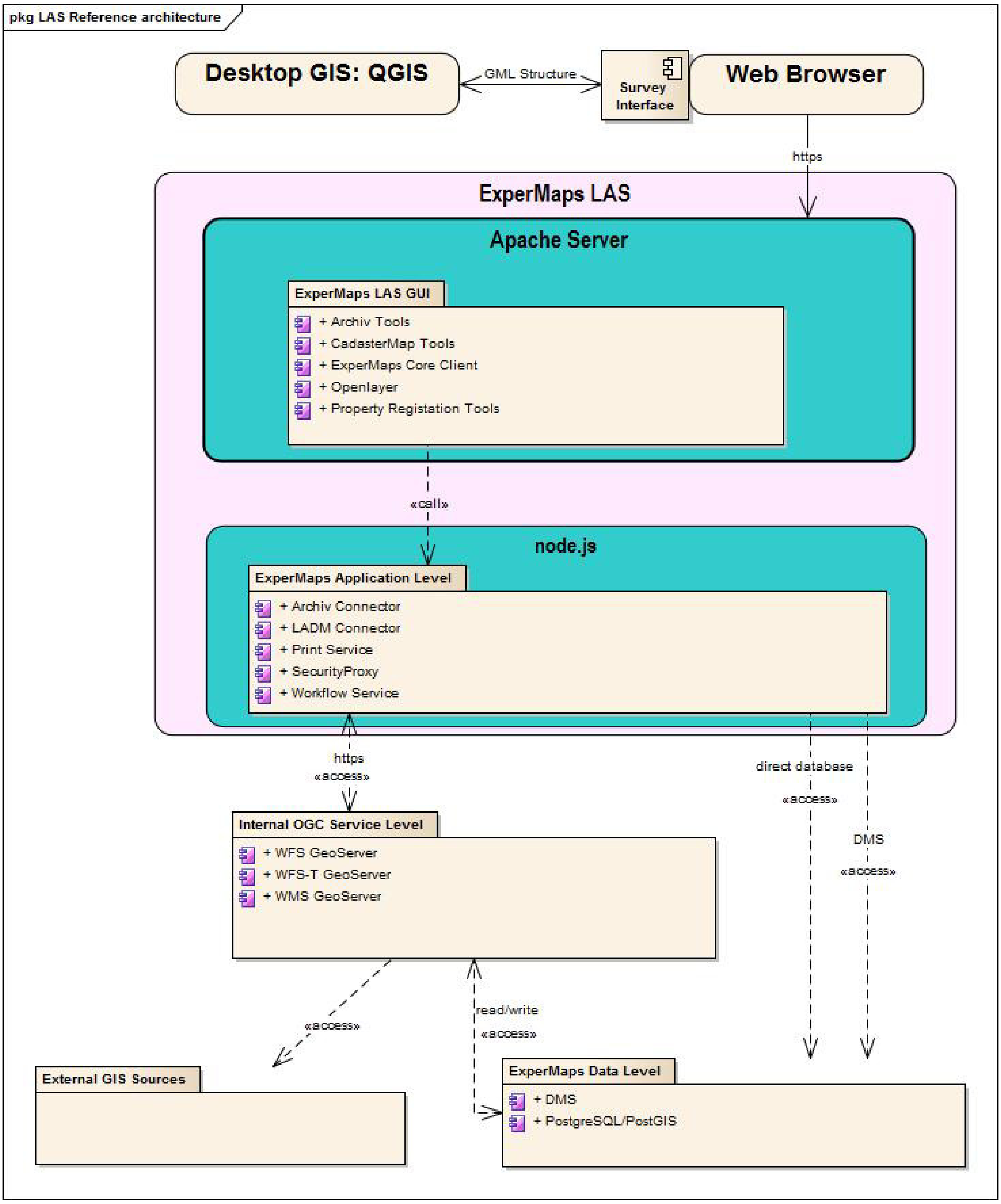

Figure 12: Diagram of a high level overview of the proposed system and its components (Source: Hansa Luftbild, 2015).

The next layer, the internal OGC service level provides the OGC compliant web services such as the Web Mapping Services (WMS) or the Web Feature Services (WFS or WFS-T) and is implemented on the open source platform GeoServer.

The ExperMaps LAS layer is the core component of the system with all the domain specific functionalities. This component itself is separated into two parts, the application level using the node.js development tool and the graphic user interface (GUI) which interacts with the core client. The GUI is based on OpenLayers and is implemented in Javascript.

The top layer is the desktop GIS – QGIS which provides advanced GIS operations, such as cartographic representation, spatial analysis, importing and editing of survey data, etc. QGIS provides most of these functionalities either out of the box or with existing add-ons. The data transfer between QGIS and ExperMaps LAS is performed via standard interfaces, such as the Web Feature Service (WFS or WFS-T).

The above mentioned architecture fully adheres to the characteristics of the fit-for-purpose approach, especially with regard to cost effectiveness and being attainable and affordable by government institutions.

With regard to the cost of developing and implementing an LAS, experience has shown that it can be achieved at a cost of around 1,500,000.00 USD (one million five hundred thousand USD). This includes the requirements analysis, and the design, development and implementation of a centralised system with the necessary hardware such as computer servers and a local area network for ten to fifteen user nodes.

On the basis of this cost the price of system implementation per land parcel is estimated to be 30 US cents, for a country which has 50,000,000 land parcels. Hence the total cost of mapping and registering a land parcel is far less than 7.00 USD (1.15 USD for image acquisition and mapping, 5.00 USD for field data collection and registration, and 0.30 USD for system implementation).

Conclusion

This paper has described in detail an implementation model for the fit-for-purpose land administration approach. It has shown that the characteristics and the key principles of this approach can be fulfilled at a cost not exceeding 7.00 USD per land parcel while producing reliable cadastre information and a state-of-the-art land administration system.

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Figures

Tables