Design and Implementation of a 3D National Digital Cadastral Database based on Land Administration Domain Model: Lessons Learned from a 3D Cadaster Project in Malaysia

Abbas RAJABIFARD, Behnam ATAZADEH, Australia, Kit Meng YIP, Malaysia, Mohsen KALANTARI, Mohsen RAHIMIPOUR ANARAKI, Hamed OLFAT, Farshad BADIEE, Davood SHOJAEI, Australia, Chan Keat LIM and Mohd Azua MOHD ZAIN, Malaysia

Key words: Land Administration Domain Model, 3D-NDCDB, 3D cadaster, Malaysia

SUMMARY

With the growing dominance of urban infrastructures in Malaysia, 2D-based cadastral systems in this country are facing new challenges in recording, managing and visualizing the spatial extent of urban land parcels. In Malaysia, surveying and cadastral measurements are currently stored in the National Digital Cadastral Data Base (NDCDB), which is a 2D-based database in the form of planimetric coordinates (X, Y). However, cadastral parcels exist in three dimensional (3D), and 2D coordinates are not adequate to communicate these 3D objects. Therefore, the existing methods of data collection, calculation and adjustment of survey and processing data needs to be upgraded for the purposes of implementing 3D cadastral database and producing digitally certified 3D plans. The upgrade from 2D to 3D environments should be in line with a standardized approach. In this context, the international Land Administration Domain Model (LADM) standard provides a formal conceptual model for recording and managing cadastral data. It provides an extensible basis for the development and refinement of efficient and effective land administration systems, based on a Model Driven Architecture (MDA), and enables involved parties, both within one jurisdiction and across different countries, to communicate based on a shared vocabulary or ontology implied by the model. A good ontology underpins an interoperable sharing and exchange of cadastral data.

The aim of this paper is to propose a new LADM-driven approach to develop and implement a 3D cadastral prototype system for Malaysia. The proposed approach comprises new changes in the current cadastral surveying practices and workflows, a new architecture to support 3D land parcels, and a new database for creating an LADM-based 3D cadastral system which is aligned with jurisdictional settings of Malaysia. In a simple term, moving from 2D-NDCDB to 3D-NDCDB consists of capturing, processing and management of height of survey points that define parcel boundaries. However, this will bring many changes to existing surveying practices in order to capture height components in land parcels, data modelling to be compliant with the LADM standard, application stack to utilize open source technologies and workflow to minimize the overall changes to 2D-NDCBD. This study demonstrated and confirmed that Malaysian cadastral infrastructure is ready for an upgrade to support 3D digital

data. The integration of vertical data with existing horizontal data will require a careful consideration due to different degrees of uncertainty that would result from the various methods of data collection. Based on the outcomes of the pilot study, it is recommended that the Government of Malaysia lay the groundwork for a 3D cadastral system by:

- Investigating legislative requirements for the introduction of 3D data collection into the current workflows
- Investigating the legal significance of the cornerstone as opposed to the land parcel in the context of the current cadastral system
- Trialing the current prototype system in selected land development and infrastructure projects
- Conducting a pilot project to investigate the integration of strata development subdivisions into the current prototype system
- Developing a roadmap for a fully operational 3D cadastre system in Malaysia considering developments in Spatially Enabled Government (SEG) including artificial intelligence for visual communications and analysis as well as integrating building information modelling (BIM) into land administration systems.

Design and Implementation of a 3D National Digital Cadastral Database based on Land Administration Domain Model: Lessons Learned from a 3D Cadaster Project in Malaysia

Abbas RAJABIFARD, Behnam ATAZADEH, Australia, Kit Meng YIP, Malaysia, Mohsen KALANTARI, Mohsen RAHIMIPOUR ANARAKI, Hamed OLFAT, Farshad BADIEE, Davood SHOJAEI, Australia, Chan Keat LIM and Mohd Azua MOHD ZAIN, Malaysia

1. INTRODUCTION

With the growing dominance of urban infrastructures in Malaysia, 2D-based cadastral systems in this country are facing new challenges in recording, managing and visualizing the spatial extent of urban land parcels. In Malaysia, surveying and cadastral measurements are currently stored in the National Digital Cadastral Database (NDCDB), which is a 2D-based database in the form of planimetric coordinates (X, Y). However, in reality, cadastral parcels exist in 3D, and 2D coordinates are not adequate to communicate these 3D objects (van Oosterom 2013, Atazadeh, Kalantari, and Rajabifard 2016, Atazadeh, Kalantari, Rajabifard, *et al.* 2016, Stoter *et al.* 2017). Therefore, the existing methods of data collection, calculation and adjustment of survey and processing data needs to be upgraded for the purposes of implementing 3D cadastral database and producing digitally certified 3D plans.

The upgrade from 2D to 3D environments should be in line with a standardized approach (Kalantari *et al.* 2017, Rajabifard, Atazadeh, *et al.* 2018). In this context, the international Land Administration Domain Model (LADM) standard provides a formal conceptual model for recording and managing cadastral data (ISO19152 2012, Lemmen *et al.* 2015). It provides an extensible basis for the development and refinement of efficient and effective land administration systems based on a Model Driven Architecture (MDA), and enables involved parties, both within one jurisdiction and across different jurisdictions to communicate based on the shared vocabulary (that is, an ontology), implied by the model (van Oosterom 2018). Ontology is required for sharing and exchange of cadastral data in interoperable environments. This paper presents a new LADM-based approach to develop and implement a 3D cadastral prototype system for Malaysia. The proposed approach comprises new changes in the current cadastral surveying practices and workflows, a new architecture to support 3D land parcels, and a new database for creating an LADM-based 3D cadastral system which is aligned with jurisdictional settings of Malaysia.

In a simple term, moving from 2D-NDCDB to 3D-NDCDB is about capturing, processing and management of height of survey stones around the parcels to improve urban land management. However, this impacts a) the existing surveying practices in order to capture height component of the land parcel, b) data modelling to be compliant with the LADM Standard, and c) application stack to utilize open source technologies and workflow to minimize the overall changes to 2D-NDCBD. The data is captured in the field by surveyors, then it will be uploaded to the office to be processed. The process of data includes: height adjustment, modifying new points, insert new points into database and generating the certified plan. This cycle will be completed in terms of capturing, processing and managing 3D data as illustrated in Figure 1.

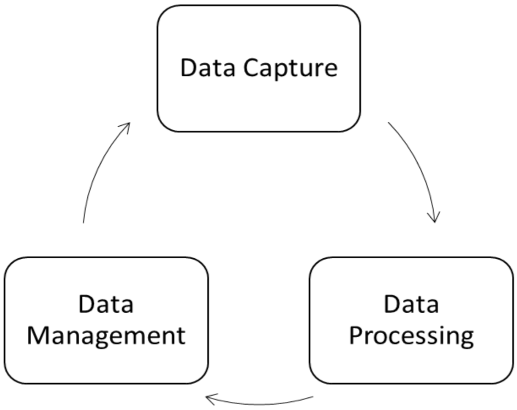

Figure 1 Cycle of data in 3D-NDCDB

In this study, design and implementation of a 3D-NDCDB comprises four major steps:

- Developing a survey methodology (see Section 3.1)
- Adjustment computations to ensure height accuracy (see Section 3.2)
- Adoption of a new LADM-based data model (see Section 4).
- Implementation of 3D-NDCDB prototype and 3D visualization of land parcels (see Section 5).

2. LITERATURE REVIEW

There have been significant investigations on the adoption of LADM to adequately handle registration and maintenance of various types of land data related to legal, administrative, and technical aspects (Felus *et al.* 2014, Zulkifli, Abdul Rahman, and Van Oosterom 2014, Kalogianni 2015, Paulsson and Paasch 2015, Atazadeh *et al.* 2018, Kitsakis *et al.* 2018, Rajabifard, Agunbiade, *et al.* 2018). Some countries investigated and considered LADM as a possible data model for their cadaster related strategies. For example, Vučić et al. (2017) raised the importance of legislation in implementation of technological options to realize 3D cadasters in the Republic of Croatia. They conducted a research to analyze land-related registers in the Republic of Croatia to evaluate the condition of land-related data such as parcels, buildings, and utilities as well as rights, restrictions, and responsibilities (RRRs) associated with those features and spaces. They aimed to determine the level of redundancy between the registers closely related to the domain of land administration, in which LADM was used for this purpose. In addition, a detailed analysis of the current legislation was conducted. As another example, in Czech Republic, GeoInfoStrategy was developed based on

LADM for effective use of the spatial data in public administration to fulfil the government priorities in the fields of environmental protection, cadastre, and protection of cultural heritage (Janečka and Souček 2017).

Some researchers have moved beyond the theoretical research and implemented prototype systems based on LADM. For example, a prototype system has been developed in Kenya using free and open source software (FOSS) (Kuria *et al.* 2016). The open source tools used for the implementation include: Dia (for Unified Modelling Language (UML) PostGIS and PostgreSQL (for database development and management); QGIS (for GIS data preparation, management and cleaning); Eclipse (as the Integrated Development Environment) and Leaflet, Mapnik, Geodjango & Django (for the web map application development). Python programming language was used for writing the code for the system implemented. This system was developed as a web application using the Django Python Framework tools.

In the context of Malaysian jurisdiction, there has been significant research on the adoption of LADM for this country. Zulkifli et al. (2015) highlighted the importance of the need for LADM country profile for Malaysia by identifying three arguments to upgrade land administration systems and enable e-Government services: government guarantee of indefeasibility of title to private properties; data integration to support good governance of land administration; and systematic and accurate capturing and curating of land and property taxation purposes as an important source for state revenue. More specifically relevant to 3D cadastre, Zulkifli *et al.* (2014) described modelling and registration of 3D strata objects in line with the conceptual framework of LADM. In another study, Zulkifli *et al.* (2014) proposed a new country profile of LADM for Malaysian jurisdiction, which provides the required entities to support 2D and 3D cadastral parcels at a conceptual level. To evaluate the developed country profile, Zulkifli *et al.* (2014) presented an LADM prototype system for Malaysia which used some sample data from Department of Surveying and Mapping Malaysia (JUPEM) and land office. Database architecture was developed based on Oracle spatial. The prototype frontend development was based on Bentley MicroStation. This prototype had limited functions and only covered small area for the assessment of the Malaysian LADM country profile. More recently, strategies were proposed for the implementation of 3D-NDCDB, which includes the processes for upgrading the existing datasets and data collection methods to support the 3D digital data and the creation of 3D spatial database based on the elicited user requirements (Rajabifard, Agunbiade, *et al.* 2018). It was also highlighted that the implementation of 3D-NDCBD is an initial step to develop 3D cadastral system in Malaysia. The major motivation for this upgrade is to introduce an open-source 3D database, which is LADM compliant, to address issues with regards to the existing cadastral practices in Malaysia. This paper provides the final outcomes of the study.

3. SURVEY METHODOLOGY AND HEIGHT ADJUSTMENT

The surveying method for height to implement the 3D cadastral system in Malaysia will be presented in this section. The fundamental data for 3D cadastral system is the height of the land plots (i.e. boundary stone and land surface). The main objective of this part is to determine the procedure of adding the height information to lot boundary marks in the 2D-NDCDB to create a 3D-NDCDB.

Currently, JUPEM has fully digitalized its NDCDB. The current version of NDCDB contains only 2D planimetric coordinates, namely longitude and latitude, for boundary points of each land parcel. To upgrade 3D coordinates (longitude, latitude, and height) for each boundary point, the current methods of data collection, calculation and adjustment of traverse survey should be modified.

3.1 Method for Capturing Height for 3D-NDCDB

Based on the current cadastral surveying practice and existing equipment resources in Malaysia, the trigonometric levelling has been chosen for capturing the height information. This method is a particular type of surveying in which slope distances with angular measurements, i.e. zenith and horizontal angles, are precisely determined using surveying instruments such as total stations. According to Figure 2, the differential height between two points can be calculated if the vertical angle (zenith) and the slope distance between two points are measured, given the heights for the instrument and the target points.

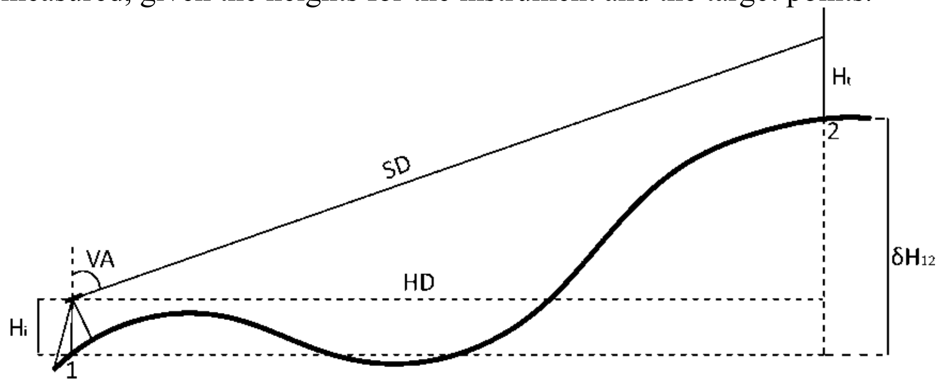

Figure 2 A schematic of Trigonometry

The differential height is obtained as follows:

$$\delta H_{12} = H_i - H_t + SD \times Cos(VA) \quad (1)$$

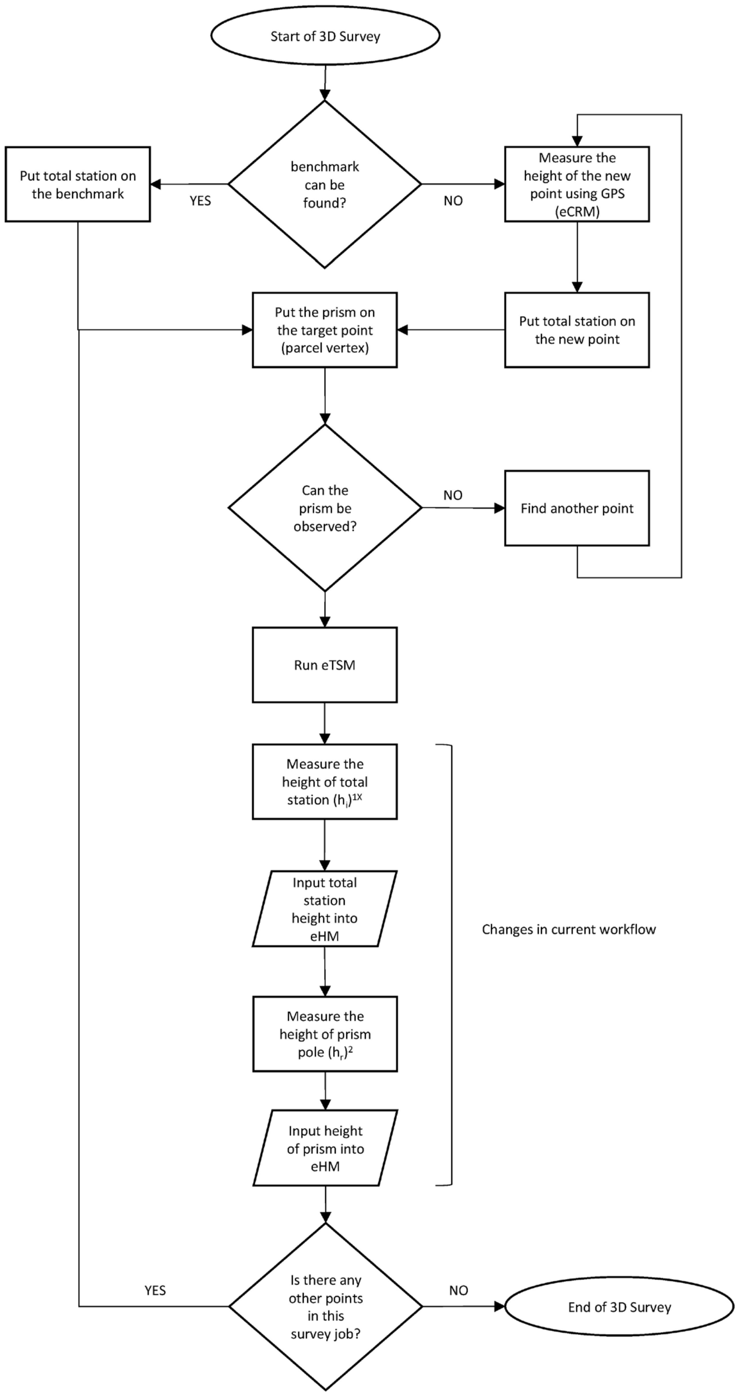

Figure 3 Height capturing flowchart

Where δH is the height difference between two traversed points, Hi is the instrument height, Ht is the height of the target, SD is the slope distance and VA is the vertical angle. It is noted that the instrument and target heights must be measured accurately. The zenith and slope distance, in equation (1), are the mean of the direct and reverse readings in an angle set, meaning reading the zenith first in face left position and second, loosen both the horizontal and vertical motions of the instrument, plunge the scope, rotate the alidade half a circle and re-point to the target in the reverse position. The average of vertical angle is calculated from the following equation:

$$VA = \frac{VACL + (360 - VACR)}{2} \tag{2}$$

Where $VACL$ and $VACR$ are the angular measurements of the zenith in the direct and reverse positions, respectively. The height measurement workflow is presented in Figure 3.

3.2 Accuracy for Survey Methodology

Two independent sets of observations between every two successive points are required to improve the height accuracy measurement. The key advantage of these two independent measurements is recognizing any mistakes/blunders that may occur during the measurements for any reason. To have two independent measurements, it is suggested that the measurement components in equation (1) are collected twice by setting up the instrument once on the head of the edge and pointing to the target on the tail and vice versa. Figure 4 compares a height network whose edges for the major loop were collected as suggested with a network whose edges were conventionally measured. In this figure (right), one wrong measurement is added to show the benefit of having two independent sets between two vertices for the recognition of local blunders and thus remeasurement of that edge.

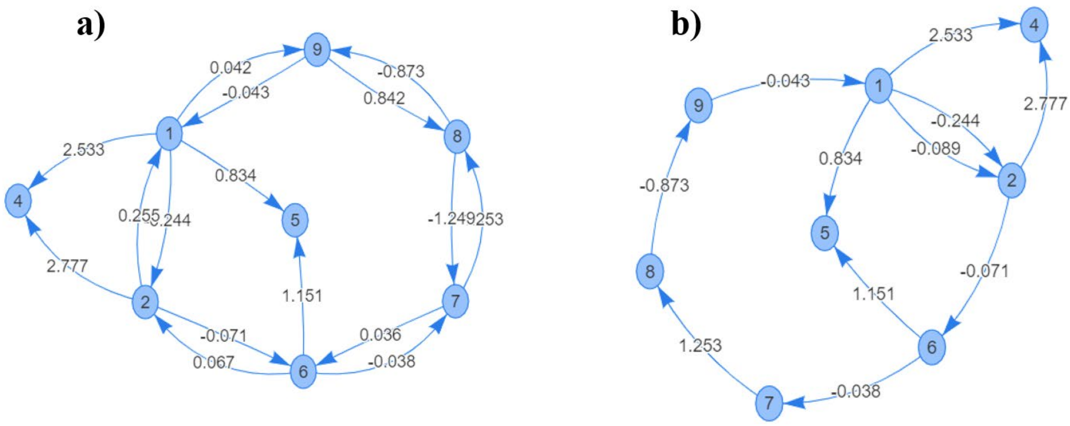

Figure 4 a) A height network including 2 independent sets of measurements on each edge of the major loop. b) A height network without independent measurements on each edge (the independent set of observation between node 1-2 is only added to show the values)

Comparing the average standard deviation of these two networks, the network with two independent sets of observations achieved better accuracy due to more observations across the network and therefore higher redundancy. Although the overall accuracy improves about 1 mm, this method guarantees that the network does not suffer from any mistakes or erroneous measurements to a certain degree.

4. DATA MODEL

The international land administration domain model (LADM) standard provides a formal conceptual model for recording and managing land administration data. It provides an extensible basis for the development and refinement of efficient and effective land administration systems, based on a Model Driven Architecture (MDA), and enables involved parties, both within one country and between different countries, to communicate, based on the shared vocabulary, implied by the model.

The current Malaysia 2D-NDCBD is not compliant to LADM. In addition, its design does not follow the best practices in relational database. These issues have been addressed in the new design for 3D-NDCDB.

4.1 3D-NDCDB Design based on LADM

The design of 3D-NDCDB is compliant with LADM and follows the standard practices of relational database design. A simplified overall version of the 3D-NDCDB is represented in Figure 5. It includes 'Primary Keys' for all entities. It has 'Foreign Keys' and 'Link Tables' to represent relationship of various entities based on LADM. 'Look up' tables have been used to represent the code lists in LADM.

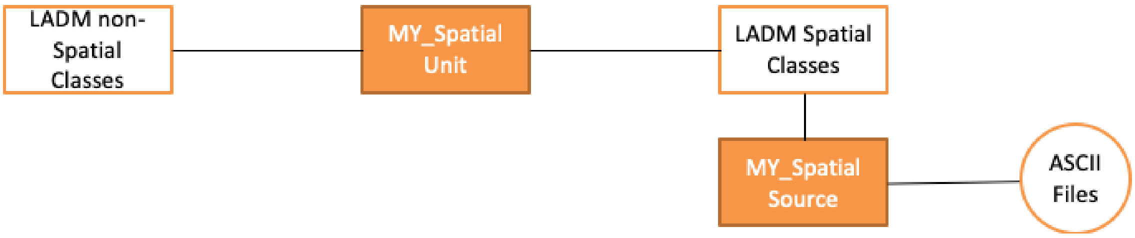

Figure 5 Overview of 3D-NDCDB design based on LADM

4.2 Classes of Spatial Unit Package

This package mainly represents the features that are related to parcels. This representation in 3D database has been illustrated in Figure 6. Based on LADM, a parcel can be represented based on 'LA_SpatialUnit' Class. However, Malaysian country profile suggests that a parcel should be presented based on four different classes; The 2D parcel is presented in 'MY_lot2D' subclass and 3D parcel in 'MY_lot3d' subclass. 'MY_GenericLot' is a superclass of ‘MY_Lot2D’ and ‘MY_Lot3D’ which does not have any geometric attribute and is a subclass to ‘MY_ SpatialUnit’ which is defined based on LADM ‘LA_SpatialSource’ class. Although this separation of subclasses in Malaysian country profile may be helpful at a conceptual level, it is not efficient for implementation in a relational database. In addition, in reality, a land parcel (2D or 3D) is one entity and using 4 entities may create duplication of data and decrease its integrity.

Malaysian country profile suggests that ‘MY_Lot2D’ and ‘MY_Lot3D’ are subclasses of ‘MY_GenericLot’ class. This implies that these two subclasses’ representation in the relational database as two entities would have a one-to-one relationship to the entity that would represents the ‘MY_GenericLot’ in the database. Similar situation would happen between ‘MY_GenericLot’ as a subclass of ‘MY_SpatialUnit’ in Malaysia country profile. Therefore, all these 4 classes proposed in the country profile should be represented as one entity in a relational database. To comply with LADM, this entity is based on ‘LA_SpatialUnit’. To follow the Malaysia Country profile convention, this entity would be called ‘my_spatialunit’ and its attributes come from ‘MY_SpatialUnit’, ‘MY_GenericLot’, ‘MY_Lot2D’ and ‘My_Lot3D’.

Storing all attributes related to parcels in one entity (‘my_spatialsource’) is similar to the data model of 2D-NDCDB for parcels which makes it easier for data migration from 2D to 3D. If the database follows the data model of Malaysia country profile, four entities (tables) should be created to represent each parcel which requires creation of foreign keys and inner joins. This will affect the performance of database enquiries and visualization and decrease the data integrity. Therefore, in 3D database, a parcel has been represented in ‘my_spatiallunit’ table.

4.3 Relationships Between LADM Classes

We considered three types of relationships between two entities (each entity represents one class of LADM) in the relational database: one-to-one, one-to-many and many-to-many.

Some classes in LADM are subclasses of a superclass. This can be represented as a one-to-one relationship in a relational database. However, it is more efficient for the database to combine them in one entity to reduce number of relationships between tables and maintain the data integrity without using foreign key (see Figure 6). For example, both ‘my_lot2d’ and ‘my_lot3d’ are subclasses of ‘MY_GenericLot’ superclass in Malaysia country profile. ‘MY_genericlot’ is a subclass of ‘MY_SpatialUnit’ which is based on LADM ‘LA_SpatialUnit’ class. In this case ‘gid’ has been used as a foreign key to connect ‘MY_genericlot’ to other two entities.

If two entities have a one-to-many relationship, this would result in a new table that keeps track of this relationship using the primary key of both entities as a foreign key in a new ‘link’

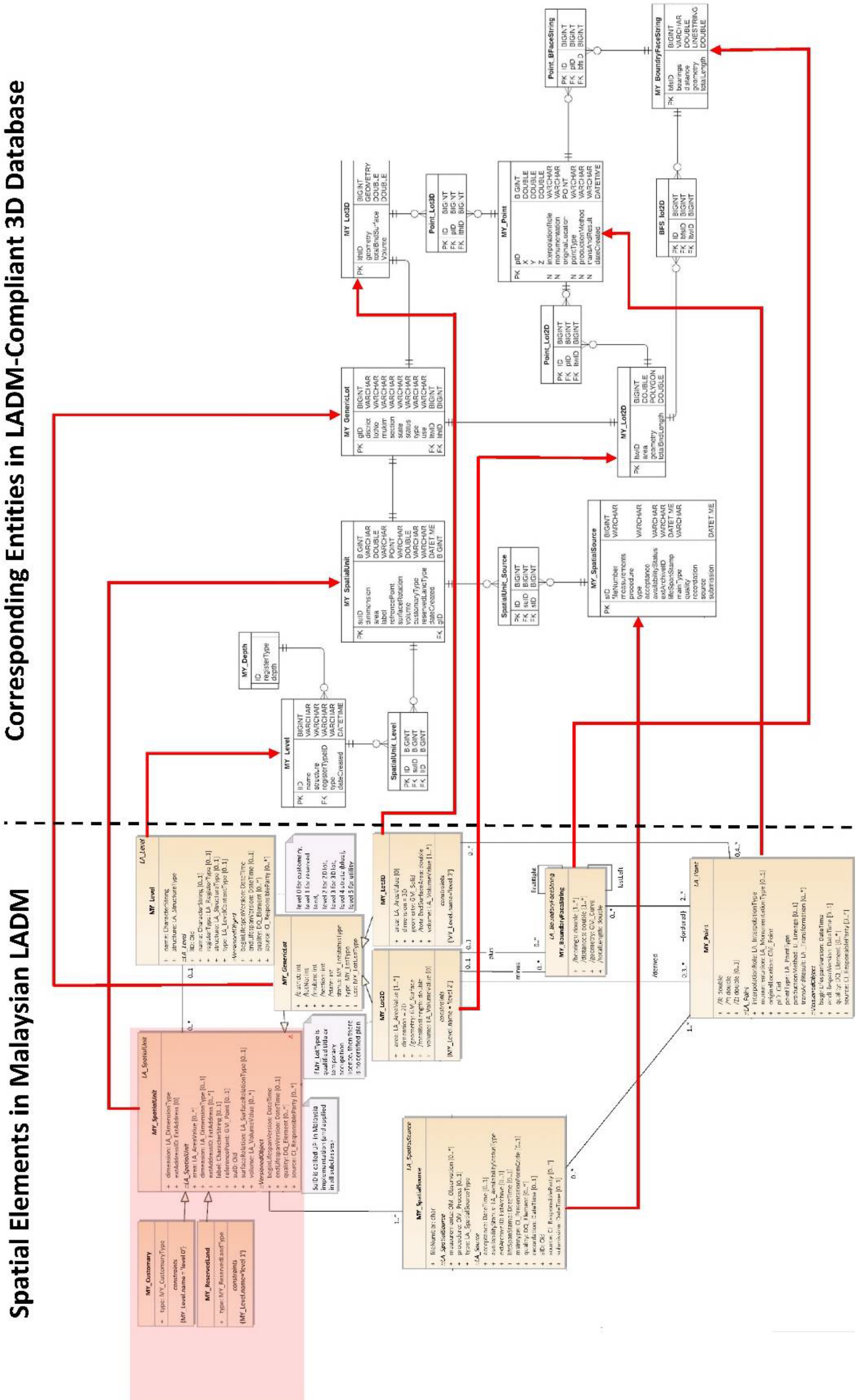

Figure 6 Mapping LADM to relational Database

table. For example, ‘point_lot2d’ table indicates which boundary points belong to which 2D parcel (lot2d). This kind of table (link table) is a major concept in relational databases and is mandatory for efficient data management.

4.4 Code Lists

Code lists from LADM and Malaysia country profile are set of predefined values for attributes in spatial and non-spatial classes. Since these attributes have been represented in entities in the relational database, the predefined values are stored in ‘look-up’ tables. These are tables which consist of a primary key (id) and predefined value(s) for each id. An ID in a ‘look-up’ table is being used as a secondary key in another entity (which represents spatial or non-spatial class) in the database. For example, in ‘my-point’ which is a spatial class in the LADM based on ‘LA_Point’ class, there is an attribute for point type called ‘pointtype’. This attribute can have predefined attributes from LADM code list. These values have been stored in a ‘look-up’ table called ‘la_pointtype’ which has one-to-one relationship with ‘my_point’ entity.

5. IMPLEMENTATION

Based on the developed rational 3D-NDCDB, a prototype system was implemented with these features (see Figure 7):

- Modular design: Every module can be used independently. This enables JUPEM to use any of these applications based on their future direction for development of 3D-NDCDB.
- Modern application framework: The system architecture follows the modern application design using APIs and web technologies.
- Platform Independent: System can be used on various operating systems and devices.
- Open Source Software and libraries: Except for STAR*NET (height adjustment software), the rest of system is developed using open source software and libraries.
- Parallel process to 2D-NDCDB: 3D process does not interrupt the existing system and is parallel to existing practices.

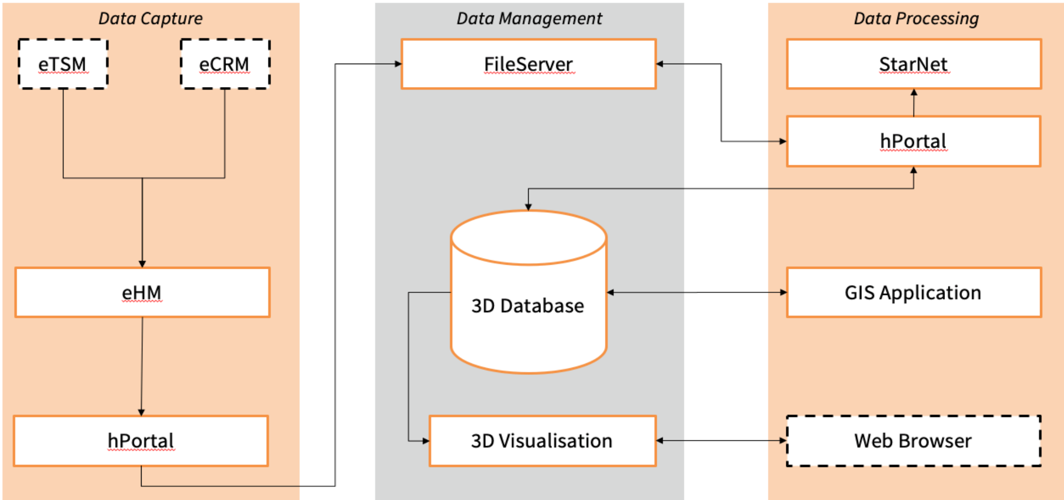

Figure 7 Architecture of prototype system

5.1 3D Database

The 3D database in this system is one of the first relational database designed based on LADM standard which was implemented in PostgreSQL. PostgreSQL is an object-relational database management system (ORDBMS) with an emphasis on extensibility and standards compliance. PostgreSQL is ACID-compliant and transactional. PostgreSQL has updatable views and materialized views, triggers, foreign keys, support functions and stored procedures, and other expandability. 3D- NDCDB utilizes PostGIS which is an open source software program that adds support for spatial objects to the PostgreSQL object-relational database. PostGIS follows SQL specification from the Open Geospatial Consortium (OGC). It also supports GIS functionality for various analyses and geometric calculations.

5.2 3D Visualization

This part of prototype system (LADM viewer) visualizes the 3D parcels, parcel boundaries and point boundaries on a customized Digital Elevation Model (provided by JUPEM) for Malaysia. It also enables some queries based on attributes in the 3D database. It is an open platform to provide information to other users since it is a web-based application which can be accessed using any modern web browser.

LADM viewer, which is shown in Figure 8, was developed based on 2 main open-source projects:

- CesiumJS: It is a JavaScript library for creating 3D globes and 2D maps in a web browser without a plugin. It uses WebGL for hardware-accelerated graphics, and is cross-platform, cross-browser, and tuned for dynamic-data visualization. CesiumJS can stream 3D content such as terrain, imagery and 3D Tiles.

- GeoServer: It is an open-source server that allows users to share, process and edit geospatial data. Designed for interoperability, it publishes data from any major spatial data source using open standards. GeoServer has evolved to become an easy method of connecting existing information to virtual globes as well as to web-based maps. GeoServer functions as the reference implementation of the OGC Web Feature Service standard and implements the Web Map Service, Web Coverage Service and Web Processing Service specifications.

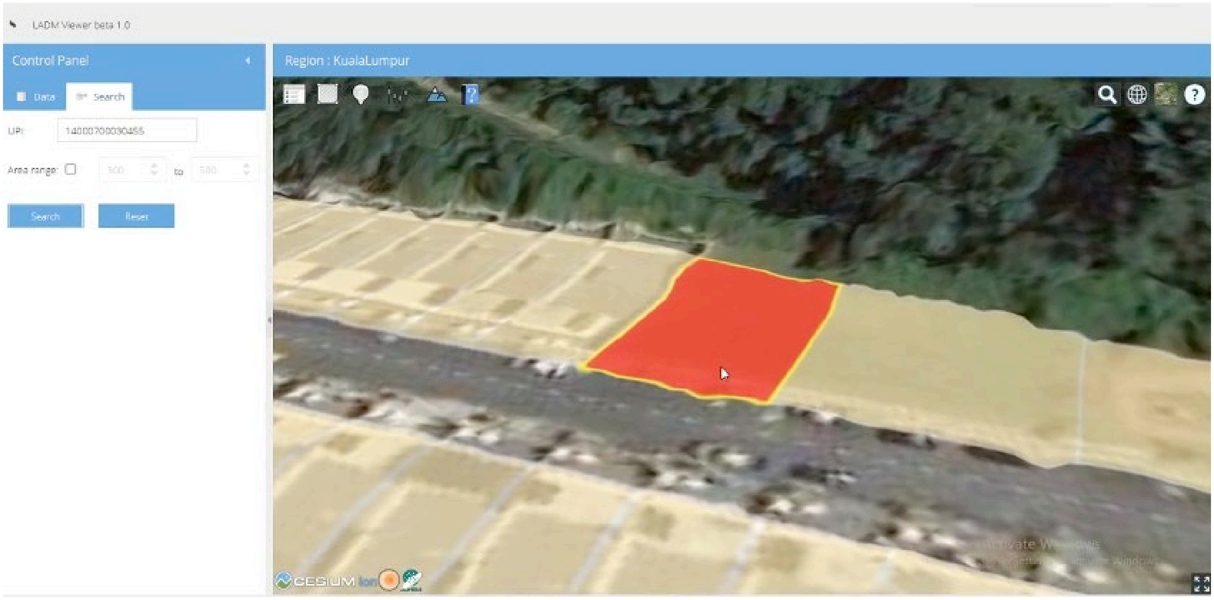

Figure 8 User Interface of LADM viewer, in which 3D parcels are visualized and queried based on their 'Lot Number'

6. CONCLUSION AND FUTURE DIRECTIONS

As the third dimension, height information is a critical piece of data in many government businesses including infrastructure development, urban planning, public safety and many more activities. Already some of the government activities in Malaysia benefit from the use of 3D data and its potential is well acknowledged in Malaysian government agencies. Unless a country-wide systematic approach is adopted, the potential of 3D digital data will not be fully realized. Upgrading the current cadastral information system from 2D (horizontal) data to a new system based on LADM-driven 3D digital data will lay the groundwork for Malaysia to become among the first nations in the world to have a 3D-enabled national spatial data infrastructure based on LADM.

This project demonstrated and confirmed that the Malaysian cadastral infrastructure is ready for an upgrade to include 3D digital data that follows the standard approach adopted by the LADM standard. It identified that the workflow of field surveying could be modified without significant overhead. The integration of vertical data with existing horizontal data will require a careful consideration due to varying degree of uncertainty that results from the different methods of data collection. The significant change in the upgrade is the change in the basic building block of the cadaster from the land parcel to the cornerstone. Based on the outcomes of the pilot study, it is recommended that the Government of Malaysia lay the groundwork for a 3D cadastral system by:

- Investigating legislative requirements for the introduction of 3D data collection into the current workflows
- Investigating the legal significance of the cornerstone as opposed to the land parcel in the context of the current cadastral system
- Trialing the current prototype system in selected land development and infrastructure projects
- Conducting a pilot project to investigate the integration of the strata development into the current prototype system
- Developing a roadmap for a full 3D Cadaster system in Malaysia considering developments in Spatially Enabled Government (SEG) including artificial intelligence for visual communications and analysis as well as integrating BIM into land administration (Atazadeh, Kalantari, and Rajabifard 2016, Atazadeh *et al.* 2018, Rajabifard *et al.* 2019) and querying 3D cadastral information (Atazadeh *et al.* 2019)
- Developing a roadmap to transition to open source geospatial solutions

REFERENCES

- Atazadeh, B., Kalantari, M., and Rajabifard, A., 2016. Comparing Three Types of BIM-based Models for Managing 3D Ownership Interests in Multi-level Buildings. *In*: *5th International FIG 3D Cadastre Workshop*. Athens, Greece: International Federation of Surveyors (FIG), 183–198.
- Atazadeh, B., Kalantari, M., Rajabifard, A., Champion, T., and Ho, S., 2016. Harnessing BIM for 3D digital management of stratified ownership rights in buildings. *In*: *FIG Working Week 2016 Recovery from Disaster*. Christchurch, New Zealand.
- Atazadeh, B., Rajabifard, A., and Kalantari, M., 2018. Connecting LADM and IFC Standards – Pathways towards an Integrated Legal-Physical Model. *In*: C. Lemmen and P. van Oosterom, eds. *7th International FIG Workshop on the Land Administration Domain Model*. Zagreb, Croatia, 89–102.
- Atazadeh, B., Rajabifard, A., Zhang, Y., and Barzegar, M., 2019. Querying 3D Cadastral Information from BIM Models. *ISPRS International Journal of Geo-Information* .
- Felus, Y., Barzani, S., Caine, A., Blumkine, N., and van Oosterom, P., 2014. Steps towards 3D Cadastre and ISO 19152 (LADM) in Israel. *In*: *4th International Workshop on 3D Cadastres*. Dubai, United Arab Emirates, 391–409.
- ISO19152, 2012. *Geographic Information- Land administration domain model (LADM)*.
- Janečka, K. and Souček, P., 2017. A Country Profile of the Czech Republic Based on an LADM for the Development of a 3D Cadastre. *ISPRS International Journal of Geo-Information* .

- Kalantari, M., Rajabifard, Williamson, and Atazadeh, 2017. 3D Property Ownership Map Base for Smart Urban Land Administration.
- Kalogianni, E., 2015. Design of a 3D multipurpose land administrative system for Greece in the context of LADM. *Athens, National Technical University of Athens (NTUA, Master Thesis)*.
- Kitsakis, D., Paasch, J., Paulsson, J., Navratil, G., Vučić, N., Karabin, M., El-Mekawy, M., Koeva, M., Janečka, K., and Erba, D., 2018. Chapter 1: Legal foundations. *In*: P. van Oosterom, ed. *Best Practices 3D Cadastres*. Istanbul, Turkey: International Federation of Surveyors (FIG), 1–66.
- Kuria, D.N., Ngigi, M.M., Gikwa, C.W., Mundia, C.N., and Macharia, M.W., 2016. A Web-Based Pilot Implementation of the Africanized Land Administration Domain Model for Kenya—A Case Study of Nyeri County.
- Lemmen, C., van Oosterom, P., and Bennett, R., 2015. The Land Administration Domain Model. *Land Use Policy*, 49 (535–545).
- van Oosterom, P., 2013. Research and development in 3D cadastres. *Computers, Environment and Urban Systems*, 40, 1–6.
- van Oosterom, P., 2018. *Best Practices 3D Cadastres*. Copenhagen, Denmark: International Federation of Surveyors.
- Paulsson, J. and Paasch, J.M., 2015. The Land Administration Domain Model – A literature survey. *Land Use Policy*, 49, 546–551.
- Rajabifard, A., Agunbiade, M., Kalantari, M., Yip, K.M., Atazadeh, B., Badiee, F., Isa, D.M.N. Bin, Adimin, M.K. Bin, Chan, K.L., Aien, A., Olfat, H., Shojaei, D., and Anaraki, M.R., 2018. An LADM-based Approach for Developing and Implementing a National 3D Cadastre – A Case Study of Malaysia. *In*: C. Lemmen and P. van Oosterom, eds. *7th International FIG Workshop on the Land Administration Domain Model*. Zagreb, Croatia, 47–66.
- Rajabifard, A., Atazadeh, B., and Kalantari, M., 2018. A Critical Evaluation of 3D Spatial Information Models for Managing Legal Arrangements of Multi Owned Developments in Victoria, Australia. *International Journal of Geographical Information Science*.
- Rajabifard, A., Atazadeh, B., and Kalantari, M., 2019. *BIM and Urban Land Administration*. Taylor & Francis, CRC Press.
- Stoter, J., Ploeger, H., Roes, R., Riet, E. van der, Biljecki, F., Ledoux, H., Kok, D., and Kim, S., 2017. Registration of Multi-Level Property Rights in 3D in The Netherlands: Two Cases and Next Steps in Further Implementation. *ISPRS International Journal of Geo-Information* .
- Vučić, N., Mađer, M., Roić, M., and Vranić, S., 2017. Towards a Croatian 3D cadastre based on the LADM. *In*: *4th International Workshop on Geoinformation Science: GeoAdvances 2017*. 399–409.
- Zulkifli, N.A., Abdul Rahman, A., Jamil, H., Teng, C.H., Tan, L.C., Looi, K.S., Chan, K.L., and Van Oosterom, P.J.M., 2014. Towards Malaysian LADM country profile for 2D and 3D cadastral registration system. *In*: *Proceedings of the 25th FIG Congress: Engaging the challenges, enhancing the relevance, Kuala Lumpur, Malaysia, June 16-21, 2014*. FIG International Federation of Surveyors.
- Zulkifli, N.A., Abdul Rahman, A., van Oosterom, P., Tan, L.C., Jamil, H., Teng, C.H.,

Looi, K.S., and Chan, K.L., 2015. The importance of Malaysian Land Administration Domain Model country profile in land policy. *Land Use Policy*, 49, 649–659.
- Zulkifli, N.A., Abdul Rahman, A., and Van Oosterom, P.J.M., 2014. 3D strata objectsregistration for Malaysia within the LADM framework. *In*: *Proceedings 4th International Workshop on 3D Cadastres, 9-11 November 2014, Dubai, United Arab Emirates*. International Federation of Surveyors (FIG).
- Zulkifli, N.A., Rahman, A.A., Jamil, H., and Hua, T.C., 2014. Development of a Prototype for the Assessment of the Malaysian LADM Country Profile.

BIOGRAPHICAL NOTES

Abbas Rajabifard is a professor in Geomatics Engineering and Director of the Centre for Spatial Data Infrastructures & Land Administration (CSDILA) at The University of Melbourne. He is also Chair of the United Nations Global Geospatial Information Management (UN-GGIM) Academic Network, which is a research and training strategic arm of UN-GGIM. Prof. Rajabifard has an active research interest in the areas of urban land administration, building information modeling, spatial enablement, 3D cadaster, and urban data analytics to support SDGs, resilience, and smart cities. He has spent his career researching, developing, applying, and teaching SDI, land administration, and spatial enablement to deliver benefits to governments, industry and wider society. He has widely consulted and published in these areas.

Behnam Atazadeh is a research fellow in the Centre for Spatial Data Infrastructures and Land Administration, Department of Infrastructure Engineering, The University of Melbourne. He has extensive experience in leveraging 3D spatial information environments and 3D digital technologies for advancing cadastral surveying and modernizing land administration systems. He has published several articles in reputable scientific journals and conferences in the domains of surveying and spatial information sciences. He also co-authored a new book titled 'BIM and Urban Land Administration' published by CRC Press, which provides the fundamental theory and practicality of intersecting BIM and land administration domains. He is a committee member of Standards Australia where he is involved in the development of building information modelling ISO standards.

CONTACTS

Abbas Rajabifard
Department of Infrastructure Engineering
University of Melbourne
Australia
Phone: +61-3- 8344 0234
E-mail: abbas.r@unimelb.edu.au
Website: www.csdila.unimelb.edu.au

Behnam Atazadeh
Department of Infrastructure Engineering, University of Melbourne
VIC 3010 AUSTRALIA
E-mail: behnam.atazadeh@unimelb.edu.au
Website: http://www.csdila.unimelb.edu.au/people/behnam-atazadeh.html