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Solutions for 4D cadastre – with a case study on utility networks

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The increasing complexity and flexibility of modern land use requires that cadastres need to manage information on the third and temporal (fourth) dimension. This article considers the registration of legal space of utility networks in cadastre in this 3D + time (=4D) context. A requirement analysis in three countries that have methods to register utility networks complying with their legal, organizational and technical structure (Turkey, the Netherlands and Queensland, Australia) is the basis for three alternatives for 4D cadastre to register utility networks. The three alternatives are analysed with respect to legal, organizational and technical cadastral requirements. This article presents a case study and a prototype from the Netherlands. In this country by law utilities are considered to be real estate objects with obligatory registration of ownership and geometry. This study shows that the 3D space and separate temporal attributes approach (state-based model) is a very promising solution to maintain temporal changes of utility networks and that this approach is to be preferred above the current practice, where the 3D and temporal aspects are not considered when registering a network.

Keywords: cadastre; land administration; 4D cadastre; spatio-temporal data models; utility networks

1. Introduction

The use of land is always, at least implicitly, related to a certain amount of (3D) space and spans a certain amount of time (3D + time, or 4D). The latter is well illustrated by leasehold and time-shares. However, traditionally cadastres are based on a representation of the division of land in 2D (i.e. parcels) on a certain moment in time, obscuring the 3D and 4D aspects of land ownership in cadastral registers and maps (UN and FIG 1999, van der Molen 2003, Stoter 2004, van Oosterom *et al.* 2006). The currently registered 2D cadastral parcels are not suitable for organizing and modelling the information of complex commodities and interests in land (Bennett *et al.* 2008, Kalantari *et al.* 2008). Several researchers have discussed options for transition of 2D registers to 2D + time or 3D (Stoter 2004, Hespanha *et al*. 2006, van Oosterom *et al*. 2006). However, growing pressure on land and rising land values have caused an increasing need for 4D (including 3D) information in

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cadastral registers. This observation is especially true for underground utilities. These infrastructural objects are mostly located in a part of the parcel and may cross many parcel boundaries, although most of those parcels will be owned by parties other than the network manager. Furthermore, the utilities are often subsurface and have therefore a 3D characteristic. Finally, the cadastral registration of utility networks includes temporal aspects, which are (at a minimum) initial creation, changes during life time (including splitting and merging networks) and finally deletion.

Insufficient and unclear information about location and depth of underground utilities poses various problems, such as planning of surface and subsurface construction works. Lack of proper information is a major cause of damage to the utilities during excavation operations. The impact of this damage cannot be underestimated. For example, the economic loss of the damage to gas pipelines in Bursa, Turkey, was US $200,000 in 2005 (Karatas 2007). In Istanbul (with over 15 million inhabitants), some accidents during excavation operations resulted in damage to telecommunication networks and to a subway line, causing significant direct and indirect economic losses (Demir and Ozcelik 2007, Doner *et al*. 2008). In China an economic loss of up to US $200 million per year is estimated due to damage to underground utilities during the 1980s and the beginning of the 1990s (Du *et al.* 2006). In the Netherlands, 40,000 damage reports to infrastructures are reported on a yearly basis causing about €40 million direct loss and €80 million indirect loss (NEN 2004). Statistics in other countries (e.g. Roberts *et al*. 2002) reveal similar striking figures. Apart from the economic losses, damage inflicted to utilities even resulted in tragic accidents, such as the Ghislenghien disaster, the explosion of a high-pressure gas pipeline in Belgium that killed 24 and injured 132 persons (Aria 2009).

Furthermore, if utility services such as electricity and telecommunication are owned by private companies, utility networks will become a commodity. A clear registration of the legal situation of the utilities (ownership and other interests) is a condition for the transfer of the networks and establishment of mortgages.

Although the actual needs for 4D cadastre in relation to the costs should also be understood through market analysis, the research presented in this article explores the technical, organizational and legal implications of 3D and 4D cadastres. The use of the third dimension has proven to be especially relevant for the representation of the legal space around physical objects that cross above or below land parcels, such as tunnels (Figure 1, left), underground shopping malls and utility networks. In addition, the time dimension is required to be able to record how the legal status of land is changing in time. In most cadastral registers, the time dimension is represented by a versioning of the objects (the state-based model) represented

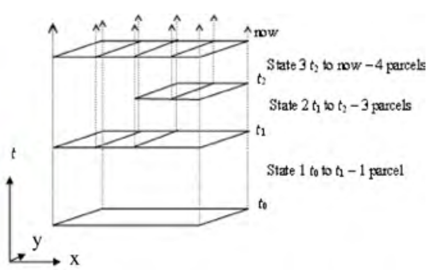


Figure 1 Left: Illustration of 3D (railway tunnel crosses several land parcels) and right: temporal concept (changes of state of a subdivision) in cadastral register.

by timestamps that indicate the creation and deletion of represented objects in the cadastral system, see Figure 1, right (van Oosterom 1997).

Establishing a 4D cadastre, which registers and provides access to (all required) 4D information of real estate, is not simple, because it comprises legal, organizational as well as technical issues. The research specifically focused on utility networks and consisted of several steps. First, conceptual bases of a 4D cadastre have been studied based on Land Administration Domain Model (LADM) (van Oosterom and Lemmen 2006, ISO/DIS 2010) for utility networks to explain the specifics of physical and legal representations. The LADM aims at standardization in cadastral domain, provides common definitions for land information and facilitates the effective use, understanding and automation of land-related data towards enhancing data sharing. The model gives a view of the relation between physical and legal objects.

Second, an empirical case study was carried out in three countries: Turkey, the Netherlands and Queensland (Australia). These countries have different approaches to 4D cadastre requirements fitting within their legal, organizational and technical frameworks. Based on these three case studies, different alternatives for 4D cadastre are proposed and evaluated against legal, organizational and technical criteria in the next phase of our research to show how 4D requirements for utility networks in cadastral registrations may be met. A detailed case study with a prototype developed for Rotterdam, the Netherlands, implements the most advanced alternative to evaluate it in more detail.

The requirement analysis consisting of a study on the conceptual basis for 4D cadastre and on 4D cadastral needs is presented in Döner *et al*. (2010). The requirement analysis is the starting point of the alternative 4D cadastre solutions as studied in this article and therefore summarized in Section 2. As answer to the requirement analysis, three alternative 4D cadastre solutions are presented and discussed in Section 3. The detailed case study realizing the most advanced alternative is presented in Section 4. This article ends with conclusions in Section 5.

2. Requirements for registration of utility networks in 4D cadastre

As mentioned in the Introduction, the requirement analysis for 4D cadastre focused on the registration of utility networks in Turkey, the Netherlands and Queensland (Australia). This section starts with the background of the requirement analysis in Section 2.1 and then summarizes the main findings in Section 2.2.

2.1. Background of the requirement analysis

The reason to select the three countries for the requirement analysis is that they have fundamentally different ways to meet today's requirements (see Table 1) for 4D cadastral registration. Turkey was selected to describe the consequences for utility network registration if a land parcel-based system is kept unchanged and no legal registration exists for utility networks beyond what is needed to provide insight into the location of the physical objects. The Netherlands was selected because of the approach in which the utility networks are legally registered (independently from cadastral parcels in the cadastral registration) and in addition to that are separately included in a physical registration. Finally, in Queensland it is possible to establish 3D cadastral parcels without maintaining a physical registration or a complete network.

For the registration of utility networks, it is important to distinguish between legal and physical registration of networks, as these registrations meet different requirements. The

Table 1. Requirement analysis for 4D cadastre looking at utility network registration in three countries.

Land/question	Technical, legal or organizational	Turkey	The Netherlands	Queensland
Registration of legal ownership	L	By means of easement rights established on surface parcels	Owned by legitimate constructor	Owned by constructor
Real estate by law	L	No	Yes	Not usually. The cross-river tunnel and some sugar cane tramways are exceptions
Legal source[a] document contains 3D description	O	Yes, if limited rights are applied to certain part of the surface parcels, 2D descriptions can be shown on bases and make a right of easement on title deed	Yes, but not compulsory	Yes
Registration of physical network	O	Yes, but not complete	No single register exists, but information on underground networks is made available	No single register exists, but information on underground networks is made available
2D Visualization of physical network on cadastral map	T	No, but high-voltage power lines can be seen on cadastre map	No, but on a separate registered network map	Usually not. Part of some networks can be seen as collections of easements, but need not be complete. Also the purpose of an easement is not present in a cadastral map
2D Visualization of affected legal area on cadastral map	T	No, only as separate 2D drawing	No, only encumbrances	Yes, but not where the affected area is part of a road, watercourse or state land
3D Visualization of networks possible on the cadastral map	T	No	No	No
3D spatial queries	T	No	No	No
Ownership data queries	T	No	Yes	Yes
History data queries	T	Yes	Yes	Yes (for history created since 1997)
4D space/time partition concept	L	No	No	No
Measurements to guarantee 4D space time partition concept	O + T	No	No	No

Note: [a]A legal source document is required for the registration of ownership in relation to development, establishment, transaction or elimination of (parts of) networks.

physical registration requires detailed information on the location of networks and on the person/company managing the network. The legal registration should provide a clear overview of the property rights involved: rights on the network on one hand (e.g. ownership and mortgages) and rights on the land established for the benefit of the network on the other hand (e.g. easements, leases). Note that it is possible that the legal space has already been included in the cadastral registration, before the utility network has actually been constructed and included in the physical registration. The physical registration can support the legal registration by providing information on the location of networks, but one should note that the legal registration can be based on one moment in time of the physical registration. Therefore, the physical registration of utilities might be inconsistent with the legal registration of the same network, and as also shown in Döner *et al.* (2010), the legal registration cannot be used to ascertain the exact location of the network (e.g. to prevent physical damages by construction works in the land). Most optimally, in case of updates (i.e. changes) in the physical registration, a signal has to be sent to the legal system, which must then decide to move (or not) from the existing legal version of the utility network to a new version. In this scenario, identifiers and timestamps are of crucial importance (Groothedde *et al.* 2008).

For studying 4D cadastre solutions, it is important to understand the equivalent of the concepts 'legal' and 'physical' object in 2D. In 2D, a parcel is a legal object indicating the extent of property rights (ownership, leasehold, easements, limited real rights such as emphyteusis in civil law) of which the boundaries are not always easily traceable in the terrain. Only when overlaying the parcel boundaries maintained in the cadastral database with topography (i.e. representation of physical objects), the real estate objects can be located. In a full 3D cadastre, a volumetric parcel is also a conceptual (legal) object, not necessarily visible in reality and only indirectly related to physical objects. Therefore, it can also be used for other purposes than the registration of ownership of 3D physical objects, for example, to register the ownership of a safety zone for a tunnel or to register the ownership of some space to assure future view from a building. In most cases in 2D, parcels are related to physical objects because the ownership of a piece of land implies ownership of all physical objects that are attached to it, if located within the parcel boundaries. In the same way, the ownership of a 3D parcel implies the ownership of all physical objects that are located within the space, for example tunnel or utility network. To be able to treat a physical object as an entity and relate this to the corresponding object in the 4D cadastre would require establishing 4D parcels, described by integrated 3D space and time dimensions.

A 4D parcel is defined as the spatio-temporal unit against which (one or more) unique and homogeneous rights (e.g. ownership right or land use right), responsibilities or restrictions are associated to the whole entity, as included in a Land Administration system. Homogenous means that the same combination of rights equally apply within the whole 4D spatio-temporal unit. Unique means that this is the largest spatio-temporal unit for which this is true. Making the unit any larger (in 3D space or time) would result in the combination of rights not being homogenous. Making the unit smaller (in 3D space or time) would result in at least two neighbour 4D parcels with the same combinations of rights.

2.2. Main findings of the requirement analysis

From the results of the requirement analysis (summarized in Table 1), the following can be concluded. First, only the registration in the Netherlands provides the possibility to register the utility network in the cadastre as legal object as such, which means apart from (2D) parcels. When registering the network, the location of the network can be indicated with *x,y,z*-coordinates on the network map but this is not required. However, only few databases of utility network managers actually contain information on the *z*-coordinate. In addition because the cadastral map is in 2D, the third dimension will not be visible on the map. Although a 3D cadastral survey or other 3D description can be added to deeds, in practice only few networks are available in 3D, which are never shown as such on the cadastral map in the Netherlands. The situation in the Netherlands raises a fundamental question as currently only a registration exists for utility networks: Why not allow the legal registration of other physical objects such as a tunnel or an underground parking place?

Next to this 'legal registration' of the ownership rights and other interests in the utility network, the cadastre in the Netherlands makes it possible to get the information on the geometry (in 2D) of all known utilities on a certain spot: the 'physical registrations'. In this case the registration as such is not maintained by the cadastre, but kept by the utility companies in their databases. However, the cadastre plays a key role by being by law the central point for enquiries. Furthermore in near future, the cadastre is responsible to produce a single (digital) map to the applicant of the information that combines the information provided by the utility owners.

As the utility networks cannot be registered themselves, in the cadastres in both Turkey and Queensland, the network can only be traced through easements that may or may not have been established for the networks (see Figure 2 for a fictive, exemplary situation). Therefore, the cadastral map in both Queensland and Turkey will not give a complete overview of all utility networks, because it depends on a specific situation of how the ownership of the network is established. This may be even different for the same network.

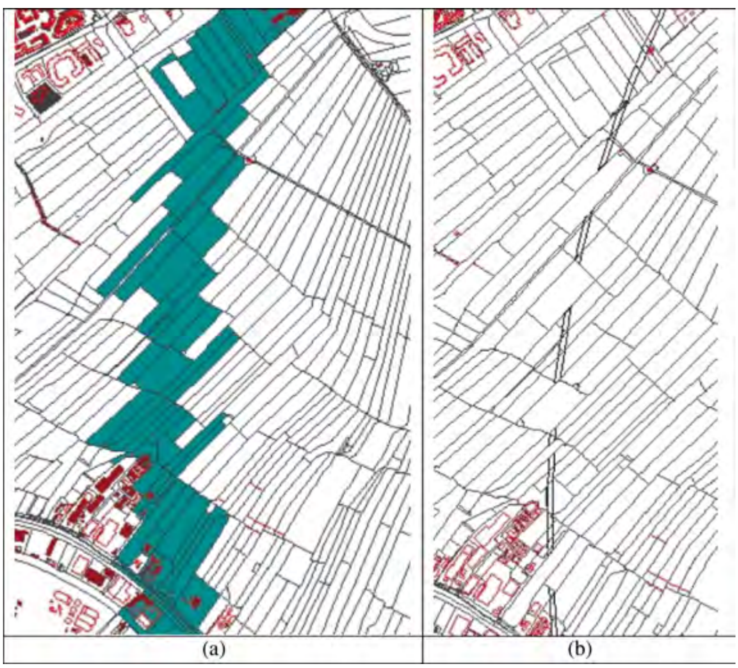


Figure 2 Rights for utility network are established on intersecting parcels (fictive situation). It depends per parcel on what kind of rights is established and therefore the cadastral map does not provide a clear overview. In (a) rights are established on complete parcels; in (b) some parcels have been subdivided to limit the rights for the utility network to the part of the parcel where the network is located.

Despite these limitations in Queensland, it is the only country of the three studied where it is possible to represent parcels in 3D, that is it is possible to provide the titles establishing the property rights (e.g. lease, easement) with a 3D survey plan, describing the legal space that is affected by the right. Volumetric survey plans have *z*-values on points that define parcels or easements (referred to as rl – reduced levels). Horizontal positions of parcels are only defined in relation to their adjoining parcels, and their metes and bounds are defined by the measurements (bearings and distances) of their edges. These then have to be transformed to fit into the 2D map of the digital cadastral database (DCDB). Despite the fact that 3D survey plans/parcels have legal status, the solution in Queensland is not a complete solution for 3D (nor 4D) cadastre. First, the interest parcel for a utility network must be located within a single base parcel and therefore cannot cross several parcels, and the network is only visible in the cadastre where it passes through (or above or below) non-government land. Thus, it is not possible to define the legal space of the whole network. Moreover, for objects within one parcel the Queensland solution has also limitations. As the 3D information is laid down on paper or scanned drawings as a 2D visualization, the 3D information cannot be interactively viewed. In addition, the 3D properties are only described on drawings, that is no 3D primitive is used. Therefore, it is not possible to check if a valid 3D parcel has been established; For example: Is the 3D parcel closed? Are the faces planar? Do any edges or faces intersect? Finally, two or more neighbouring parcels cannot be visualized in one view in 3D and it is also not possible to check how volumetric parcels spatially interact in 3D (overlap, touch, etc.).

Based on the insights obtained from this requirement analysis, showing that organizational, legal and technical aspects interact, the next section explores several 4D cadastral solutions.

3. Proposed solutions for a 4D cadastre

Three alternatives have been distinguished to register 3D and temporal aspects of utility networks in cadastre:

(1) Creating a link between the parcels and the documents containing 3D information as attribute when legal space is established for utility network;
(2) Copying 3D geometric description of the utilities into cadastre (i.e. the description of the physical objects), which can be used to create the legal object;
(3) Creating 3D legal space and referring from the cadastre system to the corresponding 3D descriptions in external registrations of representations of the physical utility networks.

This section evaluates the three alternatives against organizational, technical and legal criteria.

In the first alternative, the currently available utility information (survey plans or drawings) in the registration is attached to the cadastral parcel. This is often done to model individual objects in the cadastre by linking the units to the parcels as an attribute. Although simple, the method neglects the fact that these objects have their own geographic characteristics. The disadvantages of this alternative are that information is not available in vector format and in real world coordinates with related accuracies and that available information is limited to registered rights on intersected parcels. Therefore, it is not possible to represent the complete networks on the cadastral map, to query a network in the cadastral database or to integrate the geographic information of utility networks with geographic information of third parties.

The second alternative takes the geographic characteristic of the objects into consideration. In case of utility networks, a 3D geometric description of the physical object can be obtained from the network operator and the whole network can be copied and stored (registered) in the cadastre as an independent legal object. The represented physical object is equal to the represented legal object in this approach. This alternative is less simple than the first one, because it can be required to adjust the current system by organizing objects in two layers: one layer for surface parcels and the other layer for 3D objects (under, through or above the surface). The main advantage of such an approach is that it preserves also the current surface layer. It should be noted that the temporal aspect is still a problem because the geometry is a copy at a certain moment in time. Furthermore, handling changes in a part of the network is now 'solved' in a non-optimal manner, that is through static updates, because no dynamic link exists.

The third alternative requires the use of a geographic information infrastructure (GII) to access information on utility networks. The idea behind this alternative is that the cadastre can benefit from distributed registrations within a GII by dynamically linking information from utility networks maintained in different databases. In this approach, geometry of utilities can be maintained at their original source outside the responsibility of cadastre although this information can be accessed from cadastre any moment needed.

The advantage of the second and third alternatives is that the availability of the physical object (2D/3D) in the cadastre could improve the current situation of registration of utility networks. For example, in this way, 'gaps' in the registration where no rights are registered on the parcel could be avoided and traced (Stoter and Ploeger 2003). In addition, the physical network can be used for registration of legal space that encloses the physical network object (e.g. applying a buffer around the physical network). Consequently, the legal situation above, on and under land is better reflected in the cadastre.

The main difference between the second and the third alternatives is that the second copies the data (of physical objects), whereas in the third alternative the utility companies remain responsible to maintain the data and to provide a reference to the geometric description. In both solutions, a process should be implemented, which generates a legal object from the physical object. Therefore, the third alternative is the ideal solution because it supports sharing and multipurpose use of geographic data. In this context, the temporal aspect is a key aspect where one registration is referring to objects in another and not the other way around. The referred object may change over time (or even be removed). Therefore to keep the references correct and the systems consistent, one must be able to refer to a specific version in time that always has to be available. This is specifically important where the reference is used not only for querying but also to identify the spatial extent to which rights apply in the land administration.

4. Detailed 4D cadastre case study

To investigate the proposed 4D cadastral alternatives, a detailed case study has been conducted, including the development of a prototype. Underground utilities were organized into a spatial database then accessed, queried and visualized in 3D. The fourth dimension (time) is represented by timestamps, capturing state of spatial objects (Zaniolo *et al*. 1997, Guting and Schneider 2005). In fact this case study illustrates the second and third alternatives together, as it is not relevant in the prototype where the data are actually maintained. Data sets provided by the Municipality of Rotterdam are the underground utility networks (cables and pipelines), parcel boundaries, buildings with elevation information and terrain height points. Note that the buildings and pipelines should be considered as 3D legal objects/spaces in this case study (but it is true that the actual data in this case are taken from the physical objects). Section 4.1 describes the implementation of the prototype, Section 4.2 describes the editing and visualization of utility network-related data and Section 4.3 shows some database queries in the 4D cadastre prototype system.

4.1. Implementation of the prototype

For the prototype, *z*-values were assigned to the utility networks. Constant (relative) *z*-values were given to utility networks based on Dutch standards as 1.00 m depth for pipelines and 0.60 m depth for cables. It should be noted that many of the networks in the Rotterdam Municipality (e.g. in the area of Port Rotterdam) obtain absolute *z*-coordinates from GPS measurements before newly laid-out cables and pipes are buried.

Second, 3D coordinates were assigned to 2D parcels and buildings to relate the parcel and building data sets to the underground networks. For the buildings single height values for each building were provided by the Rotterdam Municipality. These values were maintained as attributes in the database and used to create the 3D extruded building (in geographic information systems (GIS) software). The *z*-coordinates of buildings' footprints and all the parcels were derived from the terrain elevation model generated from terrain point heights. In this implementation, all the data sets were represented with their absolute coordinates in the database.

After having the parcels, buildings and utility networks available in 3D, in the next step, these three data sets were imported in Oracle Spatial 11g. The geometry model (SDO_GEOMETRY) of Oracle Spatial was used to manage the spatial objects. This model has several primitive geometry types (and collections of them) such as point, point cluster, line string, polygon, multipolygon, arc line string, arc polygon, compound line string, compound polygon, circle and rectangle. Although the geometry model of Oracle Spatial supports 3D geometries, the topological model (e.g. for parcel boundaries) is still 2D (Oracle 2007).

To address the needs of storage and querying of 3D data, SDO_GEOMETRY data types have been enhanced by Oracle to store 3D data, and additional functionality for the efficient storage, query and management of such 3D data inside the database has been created by Oracle. Spatial queries can be performed either by using a spatial index and associated spatial operators or by using geometry processing functions, which are also referred to as spatial functions. For example, the SDO_RELATE identifies the spatial objects that have a particular spatial interaction with a given object, the SDO_WITHIN_DISTANCE operator determines if two spatial objects are within a specified distance of each other and the SDO_NN operator identifies the nearest neighbours for a spatial object (Kothuri *et al.* 2007). To have any operators considering all three dimensions, the dimension of the data must be specified in the PARAMETERS clause ('sdo_indx_dims=3') of the CREATE INDEX statement when the spatial index is created on a spatial table.

The information about utility networks (i.e. pipelines), buildings and cadastral parcels is stored in different tables in the spatial database. The content of pipeline table 'pipeline' in Oracle Spatial is given below as example (Table 2). In addition to tables, metadata are maintained in Oracle Spatial by describing the dimension, lower and upper bounds and tolerance in each dimension. Finally, spatial indexes (3D R-tree) are created on the tables to speed up spatial queries. Creation of spatial indices is necessary for efficient access to data after the data have been loaded into spatial tables.

Table 2. Content of pipeline table 'pipeline' in Oracle Spatial.

Column name	Data type	Description
IDBUIS	NUMBER(11)	Primary key
AANTAL	NUMBER(11)	Pipeline number
IDBEHEERDE	NUMBER(11)	Owner number
IDSPANNING	NUMBER(11)	Pressure
PIB	NUMBER(11)	Licence number
AANVULLEND	CHAR(50)	Additional
STEUNTEKST	CHAR(50)	Support text
TYPE	ENUMERATION	Type of network
STATUS	NUMBER(11)	Status of network
BELOWSURFACE	BOOLEAN	Underground or not
DANGEROUS	BOOLEAN	Dangerous or not
MATERIALTYPE	NUMBER(11)	Material type
DIAMETER	NUMBER(11)	Diameter
TMIN	Date	Installation date
TMAX	Date	Deletion date
GEOM	MDSYS.SDO_GEOMETRY	Gtype = 3002 (3D line)

The implementation of time (4D) in this case study adopts the technical solution of 3D data types with separate temporal attributes. Two different approaches can be chosen: event- and state-based modelling (Guting and Schneider 2005). In event-based modelling, transactions are modelled as separate entities within the system (with their own identity and set of attributes). When the start state is known and all events are known, it is possible to reconstruct every state in the past by traversing the whole chain of events. In state-based modelling, the states (i.e. the results) are modelled explicitly: every object gets (at least) two dates/times. Through the comparison of two succeeding states, it is possible to reconstruct what happened as a result of one specific event. It is very easy to obtain the state at a given moment in time, by selecting the object based on this moment being within the time interval (Lemmen and van Oosterom 2006). Therefore, the state-based model has been applied in this case study to model the time dimension. Two dates are attached to spatial objects (utility networks) to indicate the time interval during which these objects are valid: the start and end dates. The end date is unspecified if the object is currently still valid. Time information for parcels and buildings was readily available in the cadastre data. Since 1997, the Netherlands Cadastre keeps track of change per spatial object with two attributes tmin and tmax (Tijssen *et al.* 2001, van Oosterom and Lemmen 2001). Rotterdam Municipality maintains records of the time a utility network has been laid down and these were used to represent the fourth dimension for utility networks.

4.2. Editing and visualization of utility data

The database management system (DBMS) only provides a solution for data management (storage, query, analysis) and a front-end tool is required for visualizing the information stored in the DBMS so that a user can better understand the meaning of the information (see Figure 3). The 3D spatial data are stored in the spatial columns within the DBMS, and a connection needs to be built so that a display tool may access the spatial column and retrieve the data for 3D visualization (Khuan *et al.* 2008).

Many front-end applications (GIS/computer-aided design (CAD)) can be used to access, to query, to visualize and to edit the spatial data stored in the DBMS. In this research two

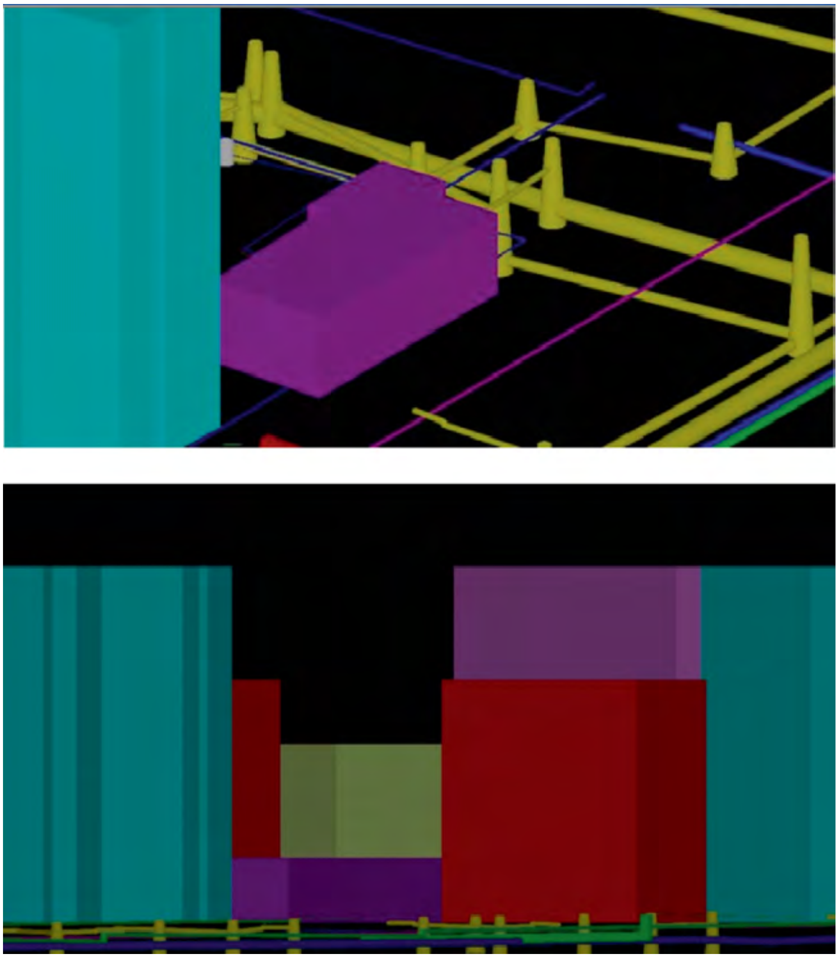


Figure 3 3D visualization of pipelines using cylinders and rectangular pipelines (Du *et al*. 2006).

commercial mainstream software packages have been used, one of which is CAD (Bentley's Microstation v8) and the other is a GIS application (ESRI's ArcGIS 9.2). The solution of accessing data with a CAD system offers many possibilities such as flexible tools for 3D editing, adaptable, user-friendly graphic user interfaces, advanced means for realistic rendering and navigation through 3D models, creating animations, different views and export data in various formats (Breunig and Zlatanova 2006). To visualize data, the user has to connect to Oracle Spatial database. Then, CAD application checks the Oracle metadata table for the name of the table(s) and corresponding columns that contain spatial data. Using extensibility options of the CAD systems, it is even possible to create on the fly 3D cylindrical or rectangular pipes for more realistic visualization (see Du *et al*. 2006). The GIS application, on the contrary, provides tools for 2D query of spatial data as well as 3D visualization (Zlatanova and Stoter 2006).

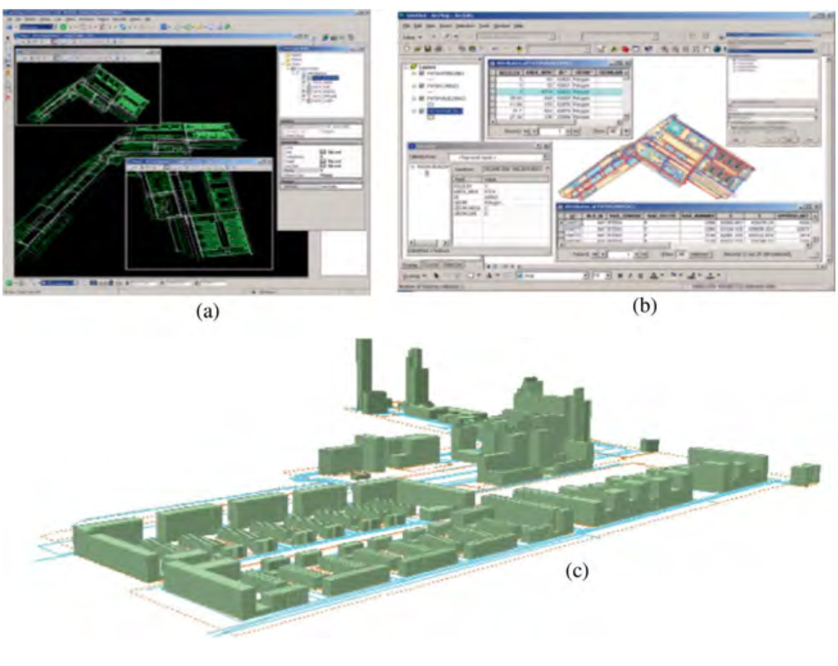
The steps needed to access the data stored in spatial database with the GIS application are described in Stoter and Zlatanova (2003). The difference between the CAD and GIS application is that GIS packages usually support (only) 2D editing, analysis and visualization and also provides 2.5D functionality. The CAD packages on the contrary usually support 3D editing and visualization, but are limited with respect to analysis of geographic information. Figure 4 shows screenshots of CAD and GIS application for accessing, editing, querying and visualization of 3D utility data.

4.3. Queries in DBMS realizing 4D cadastre prototype

Apart from editing and visualization in 3D, it is important to perform spatial queries on the data to obtain information from the 4D cadastre prototype. The examples provided below are executed on the table 'pipeline' (as presented in Table 2), table 'building' (i.e. 3D buildings) and the table 'parcel' (i.e. 3D cadastral parcels). In the context of the ISO 19152 LADM, these tables would then represent three levels (LA_Level) with LA_SpatialUnits: the 'parcel' table corresponds to the open 3D columns and the 'pipeline' and 'building' tables correspond to closed 3D parcels/spaces, which have to be subtracted from the columns. Below a number of example queries illustrate how these different levels can be combined in various manners.

The following query selects pipelines within a 100-m distance of a specific building (with id = 57) together with their installation dates. Results were limited to the pipelines installed before 2005.

```
SELECT p.IDBUIS, p.TMIN
FROM building b, pipeline p
WHERE b.id = '57'
AND SDO_WITHIN_DISTANCE
```

(a) (b) (c)

Figure 4 Accessing, editing, querying and visualizing the data by means of CAD and GIS applications: (a) accessing and editing of 3D data with a CAD application; 2D querying (b) and 3D visualization (c) with GIS application.

(b.GEOM, p.GEOM, 'DISTANCE=100') = 'TRUE' AND p.TMIN<date '2005-01-01';
This query returns following result:

```
IDBUIS  PIPELINE_
------- ---------
 72573  25-JUL-04
125994  25-JUL-04
125995  25-JUL-04
 72572  25-JUL-04
...
13 rows selected.
```

Using the spatial functions and operators, queries about the depth of the pipelines, which can be formulated as 'what is the vertical distance between a parcel and pipeline' or 'is a pipeline at a particular distance from a cadastral parcel', can be performed. The SDO_GEOM.SDO_DISTANCE function was used in the following Oracle SQL statement to compute the 3D distance between a surface parcel (e.g. having a number 6451) and a specific pipeline (e.g. having an id = 73,560) under that parcel. Please note that the assumption here is that all data sets are inside one DBMS.

SELECT SDO_GEOM.SDO_DISTANCE (pa.GEOM, p.GEOM, 0.005)
Distance3D_parcel_to_pipeline
FROM parcel pa, pipeline p
WHERE pa.kad_nummer = '6451' AND p.idbuis = '73560';
Result of this query:

```
DISTANCE3D_PARCEL_TO_PIPELINE
-----------------------------
                   5.44526788
```

Figure 5 shows the representation of the underground pipeline as being used in the query together with the representations of surface parcels. Surface of the parcel, in this query, is defined by assigning *x,y,z*-coordinates to vertices describing the parcel boundaries (a polygon in 3D space).

In most application scenarios for utilities, spatial relationships of geometries such as 'nearest to' or 'within a specified radius from' are needed. The next example shows how to query the nearest buildings and their distances to a specific pipeline (e.g. with id = 73,570) in spatial database. The SDO_NN operator of Oracle Spatial was used to perform this query. The number of the geometries returned was limited to four by using the sdo_num_res keyword:

SELECT b.id Building_ID,
SDO_GEOM.SDO_DISTANCE(b.GEOM, p.GEOM,0.5,'UNIT=M') Distance
FROM building b, pipeline p
WHERE p.idbuis='73570'
AND SDO_NN(b.GEOM, p.GEOM,'sdo_num_res=4')='TRUE'
ORDER BY Distance;
This query returns the following result:

```
BUILDING_ID  DISTANCE
-----------  ---------
      63319  6.46961534
      63181    6.575846
```

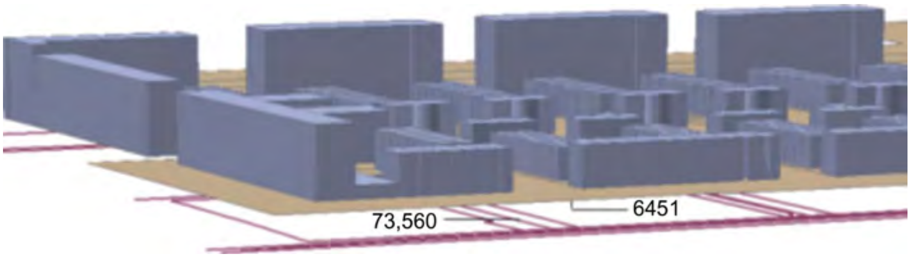


Figure 5 Underground pipeline used in the query together with surface parcels and buildings.

```
  63183  6.58915516
  63227  6.68007334
4 rows selected.
```

A frequently needed query is finding all underground networks in a given region. The SDO_RELATE operator of Oracle Spatial was used to identify the underground cables that have a particular spatial interaction with an area of interest given. Here, this area of interest is a query window defined by a rectangle with lower-left and upper-right coordinates in national reference system. The mask keyword identifies a specific type of interaction such as intersection, touching the boundaries, being completely inside and so on.

```
SELECT p.idbui CableID
FROM pipeline p
WHERE SDO_RELATE(p.GEOM,
SDO_GEOMETRY(2003, 28992, NULL,
SDO_ELEM_INFO_ARRAY(1,1003,3),
SDO_ORDINATE_ARRAY(94000,435800, 94030,435810)),
'mask=anyinteract') = 'TRUE' ORDER BY CableID;
Result of this query:
CABLE_ID
---------
   80834
   81777
  282543
  284282
  284302
  286122
  289123
7 rows selected.
```

The query is on both the 2D (area of interest) and on the 3D (cable) object. In this case the SDO_RELATE operator ignores the *z*-coordinate of the 3D object. It should be noticed that a similar query can be used to find all the cables that cross a certain parcel (i.e. the geometry of the parcel should be given instead of the area of interest). Queries presented here are just a few examples among others addressing requirements given in Table 1.

The selected system architecture based on integration of DBMS for management and spatial querying of the data with front-end applications for access and visualization of the data is a promising option to improve registration of utilities in current practice. In this way, the geometry of utilities remains at its original source whereas this information can be accessed from cadastre to register the legal space of these physical utility objects. By representing the whole network in cadastre, spatial analyses within the network can be performed together with other cadastral data sets. The approach can also represent safety areas of physical objects when included for registration, for example space around antennas and high-voltage power lines.

5. Conclusions

Because of the complex management tasks, modelling dynamic and multidimensional spatial information has become one of the challenging topics in cadastres. Because utility networks are typical objects with 4D characteristics in a cadastre, the current physical and legal registration of utilities in three countries (Turkey, the Netherlands and Queensland, Australia) was the starting point to study three different 4D cadastre alternatives. A 4D cadastre alternative for GII-based management of physical and legal networks has been proposed. The analysis and the tests (Rotterdam prototype) have shown that the 4D (=3D space + time) cadastre is possible from legal, organizational and technical perspective.

5.1. Legal

An approach to improve the current registrations of utility networks could be to keep the geometry of physical utility networks in the databases of utility companies and dynamically refer to this information from the cadastre. The legal objects for utility networks can then be generated in a controlled (regulated) manner from the 3D descriptions of the physical objects. Because of the permanent link, the legal registration can be better maintained. This fits well in the LADM (van Oosterom and Lemmen 2006, ISO/DIS 2010). LADM distinguishes between physical representation of the spatial object (outside the scope of the LADM) and a legal registration of the space (within the scope of the LADM) needed by the physical objects. Concerning the legal aspect of a 4D cadastre, it can be concluded that the spatial (3D) aspect of a cadastre will only be relevant against a legal background that recognizes the possibility of a stratification of land ownership, although the time aspect as such will be relevant for any system of land administration.

5.2. Organizational

The organizational aspect on which the best (i.e. third) alternative is based relies heavily on the use of the GII and accessing remote data maintained by another organization. Besides the technical aspects, this also requires organizational agreements. With this approach, it becomes possible to detect (unwanted) differences between the 3D physical objects itself and the property rights. The registered legal objects may not necessarily coincide with physical objects. For example, the rights on the land in which the utility is constructed may give not only the ownership to the utility, but also the rights to a certain space, a 'buffer' around the utility. However, a link between a physical registration and a legal registration within the GII enables efficient checking of the consistency between the two. Organizational arrangements have to be made to resolve the differences and to make sure that after changes at the side of the physical networks also the legal counterpart is updated (of course in a controlled/regulated procedure). Probably the preferred approach would be to first arrange the legal space and then perform the actual construction of the physical networks (within the legal spaces).

5.3. Technical

The proposed solution for 4D registrations of utilities in the cadastre is based on 3D geometry data types and separate temporal attributes. In the prototype environment (DBMS and GIS), the 3D geometric description of utilities, buildings and parcels was organized in a spatial database and tested with a case study in Rotterdam (the Netherlands). In this environment, the relationships between utility networks and other cadastral objects are visible. In addition, a spatial analysis within the network and between other data sets is possible in the DBMS. Furthermore, 4D utility and cadastral data can be effectively managed in a database whereas processes on networks such as editing and visualization can be performed by using standard functionality of the front-end software.

The 4D cadastre solutions as studied in this article are more sustainable regarding 4D than observed practice, where the 3D and temporal aspects are not considered when registering a network. Specifically, the third alternative where the physical registration of utility companies is dynamically linked with the cadastral registration within a GII looks promising. From our case study, we can conclude that the 3D space and separate temporal attributes approach (state-based model) is sufficient to model temporal changes of utility networks. However, it should be noted that the 4D integrated data type is necessary to model dynamic objects such as parcel boundaries that follow the movements of natural features such as coastlines or river borders. This requires further study. Another important issue is availability and quality of 3D data. Height information of future utilities (also for other 3D objects such as apartment buildings) should be provided in an absolute manner instead of relative heights with respect to surface (as used in our case study) because absolute coordinates are more stable and they provide unambiguous definitions of the 3D objects.

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