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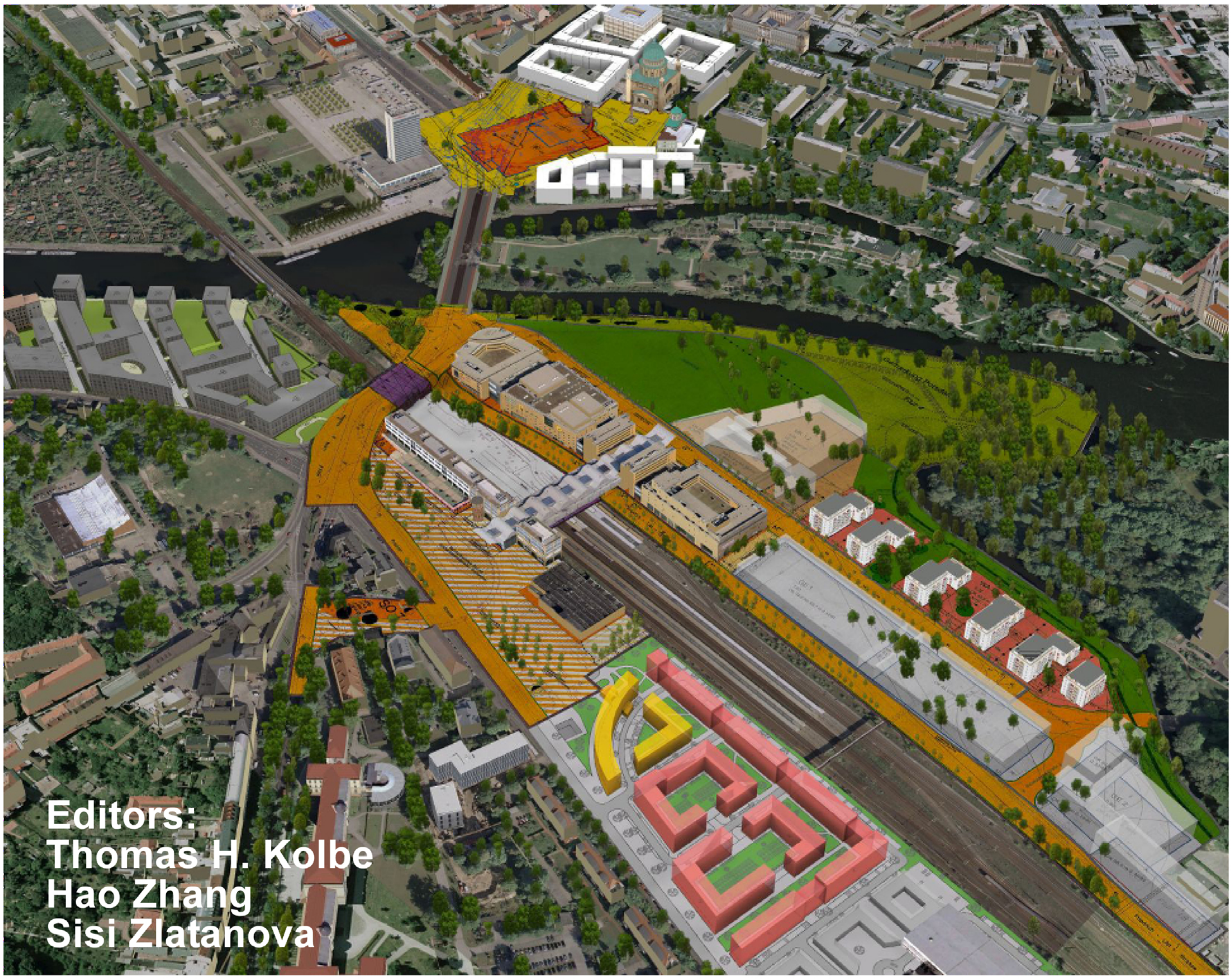

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SEEING THE UNSEEN: DELIVERING INTEGRATED UNDERGROUND UTILITY DATA IN THE UK

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KEY WORDS: Utility, spatial, integration, GIS, visualization, heterogeneity, semantic, schematic, syntactic

ABSTRACT:

In earlier work we proposed a framework to integrate heterogeneous geospatial utility data in the UK. This paper provides an update on the techniques used to resolve semantic and schematic heterogeneities in the UK utility domain. Approaches for data delivery are discussed, including descriptions of three pilot projects and domain specific visualization issues are considered. A number of practical considerations are discussed that will impact on how any implementation architecture is derived from the integration framework. Considerations of stability, security, currency, operational impact and response time can reveal a number of conflicting constraints. The impacts of these constraints are discussed in respect of either a virtual or materialised delivery system.

1. INTRODUCTION

Utility companies supply essential services to industry and homes throughout the world. Collateral information about other utility services in the same locality is essential for the safe, effective and efficient management and maintenance of utility assets. This is particularly important for those assets which are buried and therefore unseen. In addition there are a range of different third party users who pay for access to utility data. Many of these are for utility enquiries that underpin transactions in different market segments (for example conveyancing, insurance assessments, environmental impact assessments and planning applications). Furthermore, the effectively invisible underground assets owned by utility companies represent a significant health and safety hazard and mitigation problem to construction companies. This is particularly relevant to those working on brownfield sites or conducting major urban infrastructure projects (such as the Olympic village in London). Access to digital integrated utility data at the planning and construction stages can significantly reduce delays and improve health and safety conditions.

In the UK there are a range of different utility companies supplying services necessary to modern urbanism; gas, petrochemical, sewer, water, electricity and telecoms. Each company has a different approach to managing their asset network, although most store their data digitally and articulate it using Geographical Information Systems (GIS). The quality of the digital data can be variable: recently installed assets may have been well mapped, although, location and attribute data on older services can be very poor. Furthermore, the spatial inaccuracies of these data are unknown. For example, a utility company may be confident that it knows where 90% of its assets are, to a certain accuracy specification, but does not know where the 10% of unrecorded assets exist in its network. Marvin and Slater (1997) estimate that the location of only 50% of buried infrastructure is accurately known. In addition there is variable information pertaining to the third dimension (depth or elevation). Until recently only the sewer domain collected and stored depth and elevation data with any rigour. This is likely to change with the regularly use of GPS surveys. This variability in data quality can lead to uncertainty.

Prior to invasive works it is normally required that excavators should request and obtain record information from all relevant utilities to identify what is buried where. The current industry approach is based upon requesting paper based output, which can take weeks for delivery, or downloading raster outputs from a webGIS. Both of these approaches generalise the data attributes and require conversion to integrate the data with digital spatial decision support tools. Unfortunately, external companies (including competitor utilities, construction projects and highways authorities) tend to have a low level of access to the rich data held at source which results in a dilution of knowledge about the asset (NUAG, 2006). Some information held in utility records, e.g. installation details, maintenance history and physical properties of buried assets which are relevant to excavation works are not articulated. Knowledge sharing is hindered as each utility company employs their own methods for data recording and presentation and there is significant variability within each sector.

In summary the majority of utility companies have robust systems for managing their assets and facilities. However, the data can be imperfectly populated and has a range of spatial and attribute errors. The current approaches to sharing this data are time consuming and/or dilute the information resource. The core of the problem is that data consumers have insufficient and inadequate knowledge about what is where concerning buried assets. Furthermore, the available knowledge is not accessible in a timely manner. This is time, cost and process inefficient for utility companies (statutory undertakers) and those third party organisations that rely on utility data in their business.

We postulate that improving mechanisms of integrating and sharing knowledge on utility assets and the location of street works will lead to a reduction in the amount of works through better co-ordination and information quality. It is important to note that by quality we mean the modes and mechanisms in which information is shared and the harmonisation of structure and semantics as opposed to the underlying data quality.

This paper draws on the research undertaken by the School of Computing at the University of Leeds in both the Mapping The Underworld (MTU) and Visualizing integrated information on buried assets to reduce streetworks (VISTA) projects (www.comp.leeds.ac.uk/mtu). VISTA commenced in early 2006 and is a four year joint project with a consortium of academic and industry partners. UK water industry research (UKWIR) is the lead co-ordinating partner with Leeds and Nottingham Universities providing the research input. In addition, there are over 20 utility and other industrial organisations. VISTA builds on the pre-existing Engineering and Physical Sciences Research Council funded MTU project.

These projects have developed technology to enable underground asset data from multiple information sources to be integrated in a common format. The research is motivated in response to the market need for better and more timely access to information pertaining to underground utility apparatus. Although both projects have a UK focus, the problem has worldwide applicability. This paper discusses the nature of utility heterogeneity and the proposed integration framework which have both been discussed in previous publications. We then discuss techniques for delivering integrated data, the preliminary results of three pilot projects and potential implementation considerations.

2. UTILITY HETEROGENEITY

Each utility company has developed its own approach for managing the digital view of their asset network. The design is based upon each company's abstracted view of their infrastructure and their business model. Hence, when analysed at the sector or domain level, data is encoded in an uncoordinated way, without consideration of compatibility and interoperability with other utility systems. Overcoming these heterogeneities is an essential first step in achieving utility integration and a move towards domain interoperability.

In common with other organisations that hold geospatial data, heterogeneities in the utility domain can be broadly grouped into the three categories discussed by Bishr (1998): syntactic, schematic and semantic heterogeneity. Beck *et al.* (2008) discuss the range of heterogeneities expressed in the UK utility domain in greater detail.

Syntactic heterogeneity refers to the difference in data format. The most profound difference is in the storage paradigm: relational or object orientated. Partner utility companies rely on a range of storage solutions including Oracle, SQL server and ArcSDE. However, some utility companies are starting to make their data available in Open Geospatial Consortium (OGC) approved syntactically interoperable formats and services such as Geography Markup Language (GML) and Web Feature Service (WFS). Syntactically interoperable approaches underpin a number of geospatial integration frameworks currently under development based on Service Oriented Architectures (Donaubauer et al., 2007; Klien et al., 2007; Lemmens et al., 2007).

Schematic heterogeneity refers to the differences in data model between organisations. The database schema is designed at the conceptual modelling stage and reflects each company's abstracted view of their business and physical assets. Hence, different hierarchical and classification concepts are adopted by each company to refer to identical or similar real world objects.

Semantic heterogeneity refers to differences in naming conventions and conceptual groupings in different organisations. Naming mismatch arises when semantically identical data items are named differently or semantically different data items are named identically. Naming heterogeneities can be relatively easily reconciled with a thesaurus. Different companies, or utility domains, have subtly different cognitive views of the world which means that they describe similar real word objects from different perspectives. Cognitive semantics can be subtle, reflecting the domain of discourse. For example, a road is seen by the traffic management community as a link in a topological transportation network whereas in the utility industry it is seen as a surface with different engineering properties, reinstatement issues and access constraints (Aerts et al., 2006). Reconciling these cognitive heterogeneities is more difficult but is achievable through ontology mapping.

There are other utility domain specific heterogeneities that remain to be resolved. For example, different units and reference systems are a problem, although, this is reasonably constrained as all partner companies use the Ordnance Survey (OS) National Grid projection. However, the Positional Accuracy Improvement (PAI (OS, 2007)) programme, used to address accuracy issues in OS data that became apparent after using absolute positioning technologies (such as GPS), provides a 95% accuracy estimate of 1m in urban environments. The differences in precision and accuracy of relative and absolute positioning devices may increase data uncertainty.

Finally, though the literature is rich on techniques for resolving various heterogeneities, the assumption is that various metadata and documentation is available to assist integration work. This metadata is not always available: without good quality metadata some problems may be intractable (Bernard et al., 2003).

3. A FRAMEWORK FOR DATA INTEGRATION

The previous sections have introduced the nature of utility asset data in the UK and the range of heterogeneities that exist within the utility domain. In response to this, we have designed a conceptual framework which supports utility knowledge and data integration. This framework was reported by Beck *et al.* (2008), what follows is a summary of the salient points of the framework and a description of the current progress in resolving syntactic, schematic and semantic heterogeneities.

The framework is characterised by a number of features:

- The framework supports utility integration at two levels: the schema level and the data instance level. The schema level integration ensures that a single, unified interface is provided to access utility data in a consistent way, and to enable underground asset data from multiple utilities to be represented in a common format. The data level integration improves utility data quality by reducing semantic inconsistency, duplication and conflicts.
- A global schema (common data model) based architecture is adopted.
- A bottom up approach is employed to construct the global schema/model of utility data. This contrasts with many other domains, where shared, standard models/ontologies exist (Fu and Cohn, 2008a; 2008b).

As shown in Figure 1, the main components of the framework are the Schema Integration Manager, Data Integration Manager and Query Manager. The Schema Integration Manager is designed to support schema level integration, which is mostly performed as a pre-processing stage. It takes as input schema level knowledge, government legislation, codes of practice and users' knowledge as inputs, and produces the global schema mapping metadata between global and local schemas.

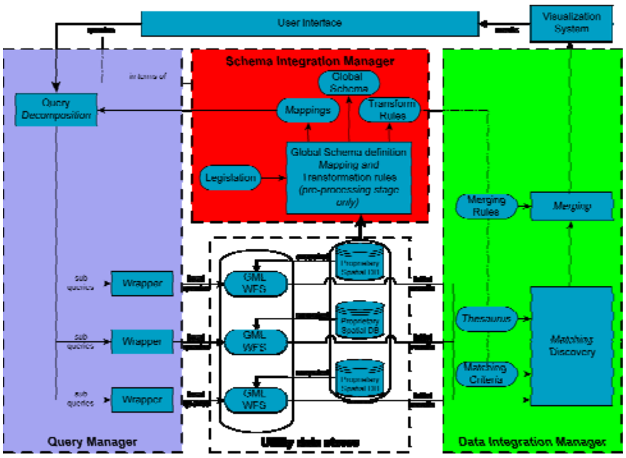

Figure 1, The proposed VISTA Framework for Utility Knowledge and Data Integration

The Data Integration Manager together with the Query Manager support run time integration activities. The query manager is necessary if a virtual integration approach is taken. All queries are specified in terms of the global schema. A query submitted to the utility integration system is first sent to the Query Manager. Based on the mappings generated by the Schema Integration Manager, the Query Manager decomposes the query into several local queries specified in terms of the underlying local schemas. These local queries are then forwarded to the appropriate utility datastore. These datastores are snapshots of the operational datastores. As they will form part of the business process for each utility company their refresh rates will be controlled by each individual organisation. The query results produced by the local datastores are integrated in the Data Integration Manager and then sent back to the user interface via a visualization system.

3.1 Syntactic Integration

It is worthwhile noting that during the proof of concept phases all data is held within an Oracle Spatial repository. Extract, Transform and Load (ETL) middleware was used to convert the range of supplied data into an Oracle Spatial format.

In a production environment it is envisaged that data would be accessed using an interoperable OGC compliant approach. When utility data was requested from the industrial partners it was asked if it could be provided using OGC compliant mechanisms. It was interesting to note that by early 2008 most partner organisation were able to produce GML files or were implementing WFS and cited the UK Traffic Management Act (NUAG, 2006) as one of the drivers.

3.2 Semantic Integration

Semantic heterogeneity can be resolved through the use of an ontology or thesaurus. Both techniques define a common vocabulary to reduce the semantic problems relating to data interoperability and integration. However, an ontology or thesauri does not in itself guarantee interoperability (Cai, 2007).

A thesaurus comprises of a collection of significant terms and the relationships between those terms in a domain knowledge space. A thesaurus has explicit concepts, relations, terminology and definitions (explicit specification) and reflects a consensual abstracted knowledge model for a domain (shared conceptualisation: Bernard et al., 2003; Deliiska, 2007; Studer et al., 1998).

An ontology is defined as a formal, explicit specification of a shared conceptualisation (Gruber, 1993). Hence, an ontology is essentially a machine readable (formal) thesaurus. Therefore an ontology allows sophisticated information processing, such as inferred properties, based on logical reasoning (Klien et al., 2007). For this reason an ontology is preferred over a thesauri approach. However, these are not competing techniques as an ontology is a richer conceptualisation of a thesaurus.

The VISTA project has built a thesaurus for the sewer, water and electricity utility domains using the 'MultiTes Pro' software (www.multites.com: Fu and Cohn, 2008a). The thesaurus maintains a controlled vocabulary describing utility asset feature types and related terms. The overall process of thesaurus development consists of 6 steps, namely Term Extraction, Relationship Derivation, Thesaurus Abstraction, Thesaurus Unification, Thesaurus Validation and Thesaurus Evaluation (cf. Ahmed et al., 2007; Deliiska, 2007; Pinto and Martins, 2004; Pundt, 2007). In addition Formal Concept Analysis has also been used for thesauri development (Fu and Cohn, 2008b). The resultant thesaurus has been used as a shared vocabulary to map utility asset type and subtype data.

The utility thesaurus acts as a shared vocabulary that is used to reconcile data value heterogeneities for fields in the Global Schema (including asset subtype, service type, and material type values: see Table 1). Mapping discovery, based on matching heuristics, identifies the relationship between the source utility value and the thesaurus terms. Values mapped to the same thesaurus term are considered to be equivalent or similar. The main information exploited here are value names, value definitions or descriptions and the relationship of one value to another. The mapping experiments were performed on 5 water datasets, 4 sewerage datasets and 2 electricity datasets. Validation of the mappings were conducted by relevant utility companies and feedback has been used to revise the mapping and utility thesauri (see Fu and Cohn (2008a) for more details).

3.3 Schema Integration

The two main problems in integrating heterogeneous utility data to a common data model are:

1. Defining the schema of the global model that is fit for purpose
2. Determining the mappings and transformations required to integrate source utility schemas to the global schema

Initially, automated and semi-automated techniques were employed to determine the global schema and its mappings. Unfortunately, the heterogeneities in the supplied data models meant that this approach was unsuccessful. Hence, the global schema was defined manually as described by Beck *et al.* (2008). This global schema, see Table 1, has been commented upon by utility partners and found to be robust for their purposes. Schema attributes have been placed into two categories: core and extended attributes. Core attributes are essential elements of the schema that are required by core end users (street workers, field engineers, back office planners).

Field Group	Global Schema Field	Short Definition	DataType	Total mappings
Asset	serviceType	Service type: the type of service that the asset is carrying	Lookup	6
Asset	assetType	Asset Type: type of asset i.e. duct, pipe	Lookup	3
Asset	materialType	Material Type: what is the asset made from	Lookup	11
Asset	assetUseStatus	asset Use Status: in use, abandoned, not commisioned, planned	Lookup	12
Asset	assetSubType	Asset Sub Type: trunk main, distribution main	Lookup	12
Dimension	assetProfile	Asset Profile	Lookup	
Dimension	horizontalDiameter	Horizontal Diameter in mm	Double	
Dimension	verticalDiameter	Vertical Diameter in mm	Double	
Dimension	nominalDiameter	Nominal Diameter: expressed in the units of the underlying data store	text	14
Domain	assetDomain	Asset Domain: the utility domain the asset belongs to	Text	
Domain	assetOwner	Asset Owner: who owns the asset	Lookup	6
GIS	assetGisLink	original GIS Link	text	10
Location	assetTopBuriedDepth	Asset Buried Depth (to top of asset): below surface	Double	10

Table 1, The Core Global Schema

In order to populate the Global Schema with data, the relationship between fields in the source table and fields in the global schema require articulating. Many of these mappings are simple source-field to destination-field transpositions. However, a significant number of the mappings correspond to data transformations. These transformations can represent simple scaling of data, such as conforming to a pre-defined unit specification. However, more complex transformations require the use of multiple fields to generate an appropriate destination result. For example, in every utility domain except sewer the term 'depth' refers to the 'depth of cover' (a measurement from the surface to the top external measurement of the asset). In the sewer domain the term 'depth' refers to "depth to invert" (a measurement from the surface to the bottom internal measurement of the asset). To compare sewer depths with other utility depths one also requires information on diameter (or profile depth for non-circular assets) and thickness (if available). Integration is further complicated by the fact that the source data fields are, at times, sparsely and imperfectly populated. Therefore, on-the-fly data validation during the transformation process is required to ensure data quality. The mappings, transformations and validation components represent metadata that allow bespoke utility data models to interoperate at a schematic level via a mediating global schema.

The mappings and transformations are generated in conjunction with a domain expert from each utility company and held within the 'Radius Studio' software package developed by 1Spatial (www.1spatial.com). Radius Studio provides a toolset which allowed the rapid generation of complex data mappings and transforms. In future, we will be examining ways to convert this metadata into XSL Transformations. The ability to share this metadata through the Radius Studio web interface has allowed the VISTA team to rapidly validate and enrich the global schema in collaboration with our industrial partners.

Data is mapped or transformed using rules. A rule is a structured tree of hierarchical conditions, against which features can be tested. The rules are expressed in a form independent of any data store which means that rules can be easily re-used with different schema and data sources.

Rule formulation is best described with an example. Figure 2 is an artificial example used to attribute depth to a sewer pipe. The Global Schema field represents the average depth to the top of the asset. The source input polyline segment is 2d and has two attribute depths (upstream node and downstream node) and a diameter. The depth is measured in metres to the centre of the pipe and the diameter in mm. All source fields are sparsely populated. The example rule does the following:

- Checks if depth measurements have been populated.
- Calculates an average depth from the depth measurements and temporarily stores this value in AverageDepth.
- Divides the pipe diameter by 2, converts the units to metres and temporarily stores this value in PipeRadiusM.
- Populates the field GS_ASSETTOPBURIEDDEPTH with the value of 'AverageDepth – PipeRadiusM.

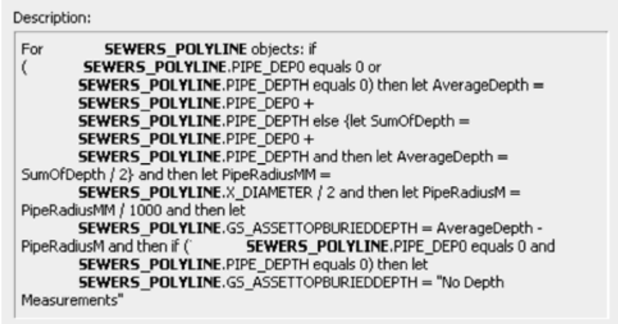
Description:
For **SEWERS_POLYLINE** objects: if
(**SEWERS_POLYLINE**.PIPE_DEP0 equals 0 or
SEWERS_POLYLINE.PIPE_DEPTH equals 0) then let AverageDepth =
SEWERS_POLYLINE.PIPE_DEP0 +
SEWERS_POLYLINE.PIPE_DEPTH else {let SumOfDepth =
SEWERS_POLYLINE.PIPE_DEP0 +
SEWERS_POLYLINE.PIPE_DEPTH and then let AverageDepth =
SumOfDepth / 2} and then let PipeRadiusMM =
SEWERS_POLYLINE.X_DIAMETER / 2 and then let PipeRadiusM =
PipeRadiusMM / 1000 and then let
SEWERS_POLYLINE.GS_ASSETTOPBURIEDDEPTH = AverageDepth -
PipeRadiusM and then if (**SEWERS_POLYLINE**.PIPE_DEP0 equals 0 and
SEWERS_POLYLINE.PIPE_DEPTH equals 0) then let
SEWERS_POLYLINE.GS_ASSETTOPBURIEDDEPTH = "No Depth
Measurements"

Figure 2, Text view of a rule in Radius Studio (details have been removed to preserve anonymity)

3.4 Bridging the gap between semantic and schematic integration

The semantic mappings are incorporated into the integrated utility data by simply replacing the original utility values with the thesaurus terms. This produced a unified representation of the utility data (i.e. asset subtype, service type, and material type data) which is heterogeneous across the different utility domains. Some harmonisation was performed in order to overcome granularity mismatch. For example, for the asset type 'water valve' one utility may have a subtype 'clockwise water check valve' and another may have a subtype 'water check valve': the two codes are unified to water check valve. This may results in generalising a specific asset type to a more generic one, e.g. clockwise water check valve to water check valve. This preserves the correctness of the semantics. However, this approach is lossy, as we no longer know which item is the 'clockwise water check valve'.

Radius Studio does allow the generation of validity rules in order to check the data conformance of the underlying data. These checks provide an overview of the underlying accuracy of a fully integrated dataset and insights into issues of spatial and attribute omissions and commissions. The Global Schema mapping has been undertaken and validated in collaboration with domain experts from each utility company. Hence, we consider that these mappings are valid at a company level for each sub-domain (gas, sewer, water etc.). However, we need to ensure that these mappings are still valid when conflated to the sub-domain and cross domain levels.

Validity at the sub-domain and cross domain levels means that all the integrated data from participating utility companies maintain semantic coherence and have a consistent degree of granularity. This will allow meaningful spatial and attribute queries to be articulated by the GIS or database without introducing errors of omission or commission from the Global Schema mapping process (or if these are introduced to ensure they are transparent to the end user). The ontology will be a significant tool for ensuring data validity at these levels.

3.5 The integration process

We have discussed the individual approaches for resolving each type of heterogeneity. Generic PL/SQL code was developed in Oracle to resolve the schematic and semantic heterogeneities. Figure 3 provides a high level view of the integration process.

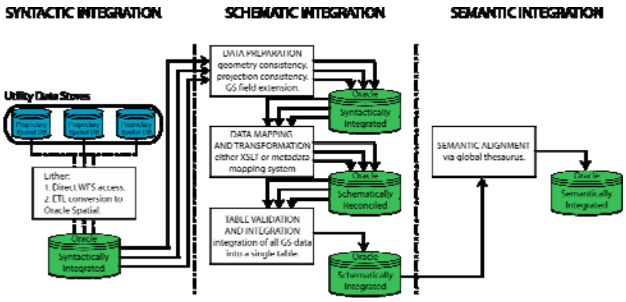

Figure 3, The proposed VISTA data integration flowline

The Oracle Spatial database is populated with source utility data. Each spatial table is checked for consistent geometry and the appropriate projection. Where problems are encountered these are automatically corrected. Each spatial table is extended with local copies of the Global Schema fields. These fields are then populated by invoking the Radius Studio web service to materialise the results of the metadata mappings. All the tables are then integrated into a single 3-d table. Any 2-d data is transformed into 3-d geometry on-the-fly. The semantic reconciliation procedures are then invoked.

3.6 Future developments for the integration framework

The work reported here represents the first steps towards generating an integrated framework for the delivery of utility data in the UK. It has 'proved the concept' that the dynamic integration of heterogeneous utility data sources is feasible. A cross-domain utility thesaurus has been developed and utilised to resolve semantic heterogeneities. Future research avenues will examine enriching the thesaurus and transforming it into an ontology. A robust cross domain ontology could have profound implications for the integration process itself. Instead of relying on a schema based integration process, an ontology driven integration process could be developed by mapping source data directly to the reference ontology using a bridge like D2RQ (Bizer and Cyganiak, 2007). This may offer further research potential for (semi)-automated matching and for visualizing semantic granularity (i.e. ontology based visualization). Once the ontology has been verified by the utility industry then the whole system will be modelled in UML. This may provide a framework for EU wide utility modelling under INSPIRE.

The ontology should allow the development of a lossless technique for resolving semantic heterogeneity. This would ultimately allow utility assets in different domains to be represented using the semantics and styling of any participating utility company. This moves closer to the interoperable framework discussed by Pundt (2008) employing the technologies described by van Harmelen (2008)

4. END-USER INFORMATION DELIVERY

The previous section has described the framework used to reconcile syntactic, semantic and schematic heterogeneities. The research programme also examined different techniques to deliver this integrated data to end-users. Two specific strands were pursued:

- Traditional webGIS delivery based upon deploying secure web services to established utility portals.
- Bespoke delivery using innovative end-user tailored visualisations.

There are also other delivery options. Two techniques that would require further evaluation are; direct access to WFS from a 'thick client' desktop CAD/GIS and an enhanced web-service to automatically process e-service requests (such as e-conveyancing: www1.landregistry.gov.uk/e-conveyancing). The former technique will provide back-office planners access to all the currently available utility data within their design and development platform of choice. This would allow conflicting utility location issues and risks to be evaluated and potentially mitigated during design. This has a range of obvious benefits.

4.1 Developing a utility web service

The VISTA consortium undertook 3 pilot projects. 2 using data from VISTA partners in the East Midlands (Lincolnshire, Nottinghamshire, Derbyshire, Leicestershire, Warwickshire, Northamptonshire and Rutland) and one, supported by the Scottish Executive, focussing on the Perth and Kinross region of Scotland (with data supplied by Scottish Water, Transport Scotland and Perth and Kinross Council).

A suite of Web Feature Services (WFSs) were deployed on a Leeds University server using the open source GeoServer package connecting to integrated utility data held in Oracle. Different materialized views were created in Oracle based upon data filters (utility data filtered by company or filtered by company *and* domain). Using this WFS infrastructure many different clients could consume integrated utility data from a single WFS environment.

A connection was established between the Leeds and client servers by IP filtering. The clients consume the WFS and render the output directly within their own WebGIS systems. All the pilot project systems have in-built authentication and security brokering. Although these pilots are on-going and have successfully implemented the technology, some problems were encountered.

Figure 4, Screen capture of a utility web service

Each consuming organisation used different software to access the WFS which resulted in connectivity and performance problems. Two organisations had problems connecting to the WFS. The former was because the service was password protected and the latter was due to strict XML parsing within the consuming software. These issues were subsequently resolved. The other organisation had no problem connecting to the WFS (see Figure 4) but there were problems in performance which are still under investigation.

In summary although WFS is a standard, different implementations exist. In time, the resulting problems are likely to be resolved.

4.2 Bespoke utility visualizations

Utility companies rely on their own GIS/CAD systems to produce maps for on-site and back office work. Current maps do not address specific representation issues such as dealing with uncertain information and complex multi-domain graphics. Our visualization work moves away from the 'one-map-fits-all' solution by developing data, user and task specific mapping (for example to address different accuracy requirements and levels of detail (Boukhelifa and Duke, 2007; 2009)).

4.2.1 Uncertainty visualization

As we have already discussed, utility data has a range of associated spatial and attribute uncertainties. VISTA has focussed on representing uncertainties associated with positional accuracy. Information on positional accuracy is particularly important for asset detection because it allows more informed decisions in the field. We used two popular visual variables to indicate the positional accuracy of assets: blur and colour. The choice of depiction method was driven by the need for simple methods and visual metaphors suitable for non-technical audiences

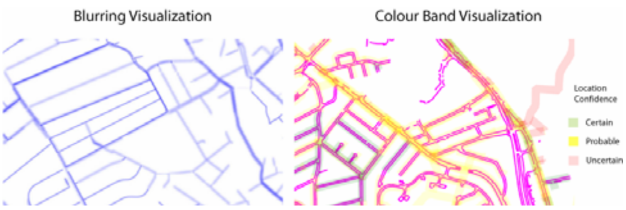

Figure 5, Uncertainty visualization using blur and colour

Blurring (Figure 5 left) provides users with qualitative information about spatial accuracy. The more blurred a polyline, the less accurate its position. Our second scheme is the "traffic lights" visualization (Figure 5 right). It uses a three-colour unified scheme to paint colour bands around utility pipes indicating the confidence in the location of assets.

We encountered a number of issues when implementing the blur method; (a) perceptual issues related to the number of levels that the user is able to distinguish and remember; (b) over-plotting in 2D can result in a number of certain lines looking less blurred or more certain than they are in reality; (c) blurred lines on printed plans may be associated with low quality printing rather than low quality information. The "traffic light" metaphor is intuitive but mapping different categorizations of confidence from various data sources inevitably introduces inaccuracies, i.e. uncertainty about uncertainty.

4.2.2 Clutter and visual complexity

Multi-service plans are typically complex drawings due to close geographical proximity between assets, line crossings and busy junctions, missing 3D information and overlaps between labels. The problem of clutter is complicated by the lack of standardisation in the utility industry; guidelines for recording and displaying information on assets do not cover methods to deal with detail. Sometimes, however, utility organizations adopt simplification or abstraction procedures manually to reduce clutter (e.g. Figure 6).

Figure 6, An example of simplification using hatching of a cluttered area of telecoms cables

Data integration should not lead to view confusion; our challenge is to find appropriate abstraction and simplification methods that improve visual understanding. We have considered clutter as an important factor in diminishing the aesthetics of the presented image. In our investigation to eliminate clutter in service plans, we took reductionist steps from graph drawing to measure clutter primitives such as proximity, bends, crosses and angles. We implemented proof-of-concept techniques to reduce clutter automatically by repackaging details and using aesthetics from information visualization. We argue that 'de-cluttering' does not mean loss of information, but rather repackaging details to make them more accessible.

5. PRACTICAL CONSIDERATIONS FOR IMPLEMENTATING A DATA INTEGRATION FRAMEWORK

The framework for integration described in the previous sections is an academic construct built in order to prove the concept that utility data integration is feasible. It was not designed to be exhaustive, nor was it expected to represent the range of delivery and integration solutions available. Integrating multiple datasets managed by different companies in different utility domains was expected to raise a number of practical problems. Recognition of these issues is considered important as they can frame the final architecture and may influence the approaches taken during implementation.

5.1 Data stability and operational impact

Previous experiments in integration have included either centralised database systems or organisationally independent systems based on the same data schema. Both of these options require a company to significantly change its data structure. Full harmonization of the underlying data models in this manner requires an unprecedented conceptual shift by participating utility companies which, given the costs involved and the fact that the models may not be suitable for their business processes, is highly unlikely. As stated by Lehto (2007) 'It can even be argued that an organization should not change its internal data model on the basis of outside requirements, as these external demands are inherently diverse, possibly contradictory, and change over time'. Thus, these approaches, although theoretically sound, have failed in practice. A number of our utility partners initially understood integration to mean the above.

In order to reduce barriers to acceptance and participation it is important that any system has a low operational impact on working practices. In particular it should not require participants to change the format or structure of their underlying asset database holdings. Where changes are proposed then these should have additional business benefits.

For example, syntactic interoperability is seen as a potential barrier to successful implementation. A number of techniques can be used to achieve syntactic interoperability such as the use of ETL middleware. However, a more appropriate approach would be to access OGC compliant syntactically interoperable data in the form GML either directly or via WFS.

The use of WFS or GML has a number of benefits:

- The utility company retains full autonomy of its primary data store.
- The underlying data store can be changed with only minimal impact on the framework.
- Operational activity is not directly affected.
- Only the attributes required by MTU/VISTA will be exported, ensuring the security of non-essential, but potentially sensitive, data.

WFS and GML technologies are already being used by some utility companies to provide in-field GIS updates to their engineers. When implemented these field packages offer bi-directional transactional updates between the field device and the corporate asset repository.

5.2 Data currency

In order to make well-informed decisions based on utility data one should be aware of the currency of the data being analysed. Although preferable, it is not necessary that the data is up-to-date. Rather, the currency of the data should be appropriate for the application (i.e. fit for the end-users purpose). Data currency requirements vary with different user groups. For example, data currency is more of an issue for street workers, who will be engaging with the physical assets in the short term, than for back-office planners who may be planning works which will be installed months, or even years, in the future.

It should also be recognised that corporate GIS servers do not reflect the actual state of the asset network at any one point in time. There is always some degree of time lag between remedial work or the laying of new assets and the time when these appear on the corporate GIS. This delay can vary from less than 24 hours in a fully digital data collection system to weeks or months.

The appropriate appreciation of time lag means that different integration strategies can be developed. This is, in part, dependent on how the integration framework is implemented. If a virtual approach to implementation is taken then the integrated results would have the same currency as the source utility data. However, if a materialised approach is implemented, in order to deliver large scale integrated data, then data source specific refresh cycles can be devised that would significantly reduce processing overhead. This refresh cycle may also be driven by the type of 'role' a querying user possesses.

5.3 Ramifications for the integration architecture

Some of these issues can be contradictory at implementation. For example, if one was integrating data on-the-fly then accessing individual source datasets and disseminating nationwide utility data within an hour is impractical. The software architecture which is generated from VISTA will in part be structured by these practical considerations. Ultimately the utility industry will choose the appropriate architecture and, unless there is a statutory requirement, each utility company will determine whether to make their data available through such a framework. However, in order to make this choice the industry needs to be made aware of the pros, cons, financial and organisational implications of any framework (see Table 2).

	Virtual	Materialised
Scale of Integration	Potentially Low	Full
Response Time	Delay	Real Time
Integration Overhead	Relatively Low	Very High: GRID
Data Currency	Current Snapshot	Almost Current Snapshot
Data Security	Data ***not*** Realised Locally	Data Realised Locally

Table 2, Comparison of Virtual and Material architectures

Two generic types of framework are postulated: Virtual and Materialised. The choice of either a Virtual or Materialised integration system has ramifications for the following issues:

1. Scale of integration: How much data can be sensibly integrated.
2. Response time: How long it takes for a user to get results.
3. Integration overhead: The processing resources required to integrate data.
4. Data currency.
5. Data security.

The strength of the virtual approach is that it reflects the data held in the source repositories at the time of querying (i.e. data currency) and that data need not be permanently stored (lower security risk). The weakness of this approach is that response time is relatively slow. The response time is dependent upon the quantity of data to be integrated, the data transfer speed and the data integration processing time. As a rule of thumb: the larger the spatial extent the longer the response time. Therefore, a virtual approach is potentially not appropriate where a significant quantity of data is required.

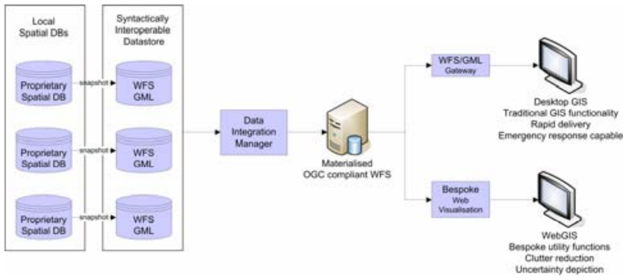

Figure 7, Materialised integration architecture

In the materialised approach data sources are merged into a single database, which is maintained centrally (see Figure 7). Queries are expressed against the integrated schema, but without directly accessing the local databases. The central database is periodically refreshed by globally updating all the source datasets at a periodic interval. The strength of the materialised approach is that it has very rapid response times and can deliver large datasets. The weaknesses of this approach are that the data is not always up-to-date, it is dependent upon the refresh cycle of the global update process, and all the source utility data will be permanently materialised on the server which may have security implications. Finally, in the materialised approach very large spatial datasets will be integrated. Efficiency gains might be realised by using GRID architecture.

There is, however, a third way which can combine the benefits of virtual and materialised architectures: GML "change only updates". Instead of synchronising distributed data sources by re-integrating the full dataset one could integrate only the data that has changed (new data, updates and deletions) since the last update. This significantly reduces the quantity of data that is transferred. The OS use this form of delivery for updating Mastermap.

6. CONCLUSIONS

This paper has outlined the approaches used by the VISTA and MTU projects to resolve syntactic, schematic and semantic heterogeneity in the UK utility domain. We have also examined how this integrated data could be delivered to end-users and some of the visualization issues that structure how integrated utility data is provided to consumers. In order to enhance the probability of successful implementation we have considered a range of factors that may influence implementation. This does not directly impact on the design of the integration tools that are under development, but it will impact on how they are configured. The utility industry will need to decide what access it requires to competitors' data (size of data, response time, data currency etc.). With this information it is possible to implement an appropriate virtual or materialised delivery architecture.

7. ACKNOWLEDGEMENTS

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USING 3D URBAN MODELS FOR PEDESTRIAN NAVIGATION SUPPORT

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KEY WORDS: pedestrian navigation, 3D city models, facade textures, urban space

ABSTRACT:

Mobile navigation is usually focused on car navigation which implies a limitation on a street network. Due to this, route instructions in most systems are based on distances and directions given by the underlying line graph. This type of navigation is not an optimal solution for pedestrians, as they are not necessarily bound to streets, walkways or other polylines to walk on. This paper suggests a concept that subdivides urban space into 'walkable', 'semi-walkable' and 'non-walkable' space that can be used by pedestrians to a certain extent. Advantages as well as shortcomings of this concept will be outlined and discussed. Due to the 'walkable space' concept the procedures of way-finding and route instructions need to be adapted because of the absence of an underlying line graph. In the presented approach instructions are going to be based on landmarks along the route that can be used by pedestrians for way-finding. The use of landmarks leads to a further concept that will be outlined in this paper: procedural façade texturing for 3D urban models. As pedestrians navigate using landmarks, respectively the appearance of the façades as the most prominent parts, flexible and adjustable building textures are needed to support intuitive navigation and orientation. Whereas this is a task-driven scenario models do not need to be photo-realistic and façades can be used to provide a mixture of realism and abstraction (e.g navigation hints or thematic information) along the route. A basic concept for procedural texturing will be presented and a brief discussion on technical capabilities on mobile devices will be provided.

1 INTRODUCTION

Navigation systems nowadays can be regarded as standard for cars, motorcycles and just recently Google has introduced their map application as a mobile version, which can be used by pedestrians. Nevertheless, navigation for pedestrians is still under development and there are some issues to be taken into account when it comes to pedestrian navigation in urban space. Using a "car navigation approach" for pedestrian navigation can result in certain shortcomings that the authors are going to discuss and present concepts addressing these problems.

Navigation systems normally provide route instructions based on a street network, respectively a line graph, because vehicles generally navigate on streets. This concept results in route instructions based on this line graph. The concept regarding navigation in such a network is to tell the user when to change directions and into which direction to turn next. Current navigation systems normally provide this information by a distance to the next relevant node on the graph and the direction in which to turn at this point. The current orientation of the user does not even have to be considered, as the assumption is that the vehicle only moves on the line graph, either forward or backwards. Therefore the degree of freedom in terms of probable moving directions is very restricted and simplifies the navigation instructions that are required in order to find the way to the target point. However, pedestrians do not tend to 'walk the line'. Normally pedestrians would navigate in a different way and would not necessarily navigate on a line graph, because they are not bound to navigate on a street, in contrast to cars. Pedestrians can use open spaces, like squares, parks, etc., where they can walk freely. They also use manifold ways of orientation, therefore they are not restricted to street names and other "vehicle based" concepts, like distances and directions on a street network. Pedestrians navigate using the environment they are surrounded by: urban space. When asking someone for the directions to a specific place, people would tend to describe a route based on landmarks and other prominent aspects along the way and hardly use street names or distances. They provide "visual" route instructions that describe the way. Pedestrians actually have the "right speed" in order to use these visual instructions as they have the time to find the specific landmarks and make a decision. For car drivers the direction/distance instruction is just the right information in order to make the next decision, besides all the other tasks that are involved driving a car. Therefore distances and directions seem not to be appropriate for pedestrian route instructions as they can hardly be related to a line graph, whereas visual route instructions might better support them in terms of way finding. The concept of visual route instructions might be backed-up by a line graph based data set, but other concepts might be possible. In section 2 the authors will outline situations regarding open spaces where vector based data sets might be inappropriate and other concepts have to be found for pedestrian navigation.

In order to better support visual navigation for pedestrians it would be useful to provide a digital 3D model on the mobile device. There are some approaches of navigation system manufacturers to include specific 3D landmarks into their navigation systems. Nevertheless, the navigation instructions are still based on the street graph providing distances and directions. In order to support a landmark based, visually oriented instruction approach, it would be necessary to provide all buildings along a route, not only the landmarks. This would make it easier for the user to compare the real world to the virtual model, locate his own position, use the visual hints and to follow the route instructions. In order to provide 3D city models on a mobile device, in contrast to just place landmarks, needs a very efficient way of data management and transmission. The focus in this paper will be on textures for 3D buildings as this data set is usually on of the largest. Another issue about façade textures is their flexibility. Normally 'static' photo images are used in order to produce façade textures. In a scenario where users navigate according to visual hints and landmark based route instructions it might be sensible to include these hints into the prominent façade textures in order to support the user. Including these hints would make it necessary to change the façade texture according to the calculated route. This might be very complicated using image based textures. In this paper the authors will outline a concept for procedurally created façade textures that are flexible enough to be adapted to the navigation context and the requirements in this scenario.

The remaining sections of this paper will be organized in the following way: Section 2 will discuss shortcomings of line graph based navigation for the pedestrian use case focusing on open spaces and will outline a possible concept to overcome these problems. Section 3 will introduce the concept of procedural façade textures for a 3D-model-based navigation approach and discuss the benefits of the developed concept. Section 4 will describe the MoNa3D project investigating the use of 3D city models for pedestrian navigation and section 5 will conclude the paper and give a brief outlook on future work.

2 ROUTING FOR PEDESTRIAN NAVIGATION

2.1 Car-based Approach

When we talk about navigation systems at the moment, car navigation systems in particular, the navigation concept of these systems is mainly similar. Navigation takes place on a street network. This concept is quite reasonable and straight forward, as cars mainly use streets. They are bound to the line graph as they are supposed to stay on the street. Therefore the orientation of the car is given too, it can only move forward or backward on the line segment. This restricted degree of freedom in terms of navigation only requires a minimal set of instructions in order to follow a route through the network. It is sufficient to provide instructions into which direction to turn at the next node of the network and in which distance this node is going to appear (see example in fig 1).

Figure 1: Navigation system example for car navigation [1]

This approach also seems to be beneficial for the scenario of car navigation, as the driver would hardly be able to observe more information as he needs to concentrate on many other things that are incorporated into the process of driving a car. Although there are several concepts integrating 3D buildings into these systems, using landmarks, half-transparent building blocks as well as more detailed textured 3D city models for city centres, these 3D representations are not part of route instructions yet.

[1] from http://www.navigon.com/, copyright Navigon AG

This 'graph-based' approach is also used for pedestrian route descriptions at the moment (see figure 2). One problem that can be recognized using this graph based approach is that the vector data for pedestrian foot paths, bridges, underpasses and other urban 'elements' that can be used by pedestrians are not entirely modelled in the graph(compare (Schilling et al., 2008)). And for open spaces like squares, parks, parking areas it might not be feasible to model these elements by line graphs, because they cannot define all possible paths a pedestrian can take. In the example in figure 2 the system suggests a route to the north entrance of the central station around the parking area. This parking area could be easily crossed by a pedestrian approaching the entrance directly.

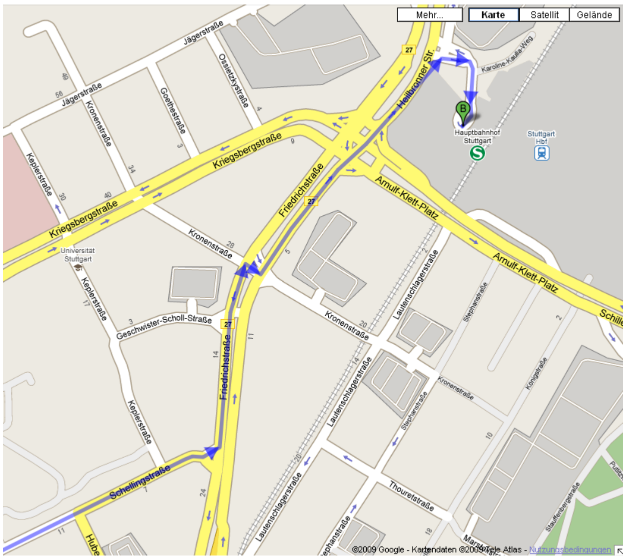


Figure 2: Pedestrian route from HFT Stuttgart to Stuttgart Main Station (from GoogleMaps)

Another issue would be that a local citizen would not cross the huge road intersection at the lower left corner of the parking area, as there are no pedestrian traffic lights (see figure 5). In contrast a local citizen would walk in south east direction and take another entrance of the main station building using a pedestrian crossing or underpass. Most of these aspects are not modelled in most of the current data sets which leads to route suggestions that pedestrian would hardly chose in a real scenario (e.g. main roads with no/limited sidewalks, no traffic lights, etc.). It might be complicated to model the missing data into the line graph and further investigations might have to be made in order to generate a data set that provides all the information relevant for pedestrian navigation in a suitable form.

2.2 Pedestrian Navigation Issues

When it comes to pedestrian navigation the concept of line graphs seems to be too restricted. One can find areas in urban space that are both accessible and comfortable for this user group in comparison to cars, e.g. squares, parks and other open spaces. But these open spaces represent urban elements that can hardly be covered by lines, because pedestrians not always 'walk the line'. As you can see in figure 3 an open space in GoogleMaps is approximated by certain vectors, but hardly any pedestrian would restrict himself to these options to cross the square if it is part of his route. This set of vectors is the attempt to cover the square with the 'car-based' approach, which is certainly not the optimal concept for pedestrian navigation.

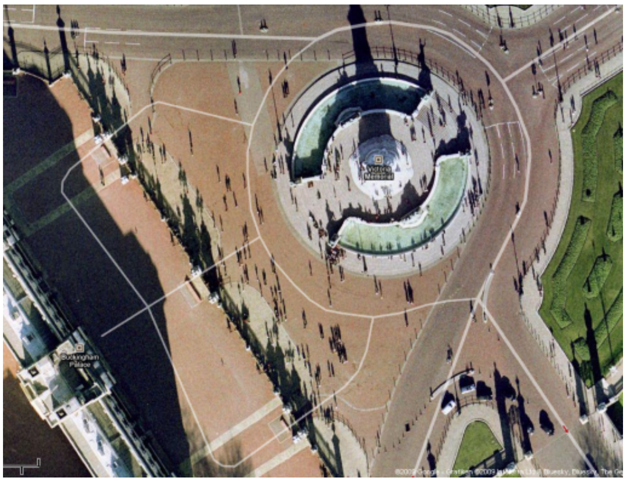


Figure 3: Street network example for open space in London (from GoogleMaps)

As the authors have tried to outline in the previous sections, a street network might not be the optimal basis for pedestrian navigation. And also route instructions based on distances, directions and street names (figure 4) might not be the optimum as pedestrians have a higher degree of freedom in terms of navigation compared to cars: they are not bound to the street network. Direction instructions like ”turn left” are also inaccurate as the orientation of the user is not given, as he does not necessarily align himself to a vector.

Fußweg nach/zu Schellingstraße 24, 70174 Stuttgart
1,0 km – ca. **13 Minuten**

Hauptbahnhof Stuttgart

1.	**Nordost** auf **Arnulf-Klett-Platz** Richtung **Karoline-Kaulla-Weg**	59 m
2.	**Links** halten bei **Kurt-Georg-Kiesinger-Platz**	13 m
3.	Nach **links** abbiegen, um auf **Kurt-Georg-Kiesinger-Platz** zu bleiben	29 m
4.	Bei **B27/Heilbronner Str. links** abbiegen Weiter auf B27	0,3 km
5.	Bei **Kronenstraße rechts** abbiegen	19 m
6.	Bei **B27/Friedrichstraße links** abbiegen	0,2 km
7.	Bei **Schellingstraße rechts** abbiegen Das Ziel befindet sich rechts	0,4 km

Schellingstraße 24
70174 Stuttgart

Figure 4: Pedestrian route instructions from HFT Stuttgart to Stuttgart Main Station (from GoogleMaps)

Having said that pedestrians do not navigate on lines, the authors would introduce the concept of people walking in zones. This is especially true for squares and other open spaces in the urban environment. These zones can basically be navigated freely taking into account certain restrictions. A basic classification into ”walkable”, ”semi-walkable” and ”non-walkable” space might be appropriate and could be refined in the future. In this approach it would be possible to subdivide open spaces into zones rather than approximating them by a path network. Investigations about navigable space in urban areas are also made by (Slingsby and Raper, 2007). Figure 5 shows two zones that would influence the route from the HFT Stuttgart to the main station. There is one ”non-walkable” zone at the road intersection. This zone would be avoided by pedestrians as there is a lot of traffic, no sidewalks and no pedestrian traffic lights. The second zone is ”semi-walkable” representing a parking area which can be crossed by pedestrians. This zone is defined as semi-walkable as for example a mother with a baby carriage or a person in a wheelchair would not preferably use it. Subdividing urban space into zones would also allow to overcome the split between indoor and outdoor navigation, as floor plans could also be subdivided into these zones. In this way the same data concept could be used for indoor and outdoor navigation. The need of connecting indoor and outdoor navigation is also addressed in (Becker et al., 2008)

Conceptually, the surface space is partitioned into a walkable space with obstacles of polygonal shape. Finding the shortest path here is similar to the well-known problem called ”Shortest path for a point robot” in computational geometry. The definition of the problem and an approach to solve it is given in (de Berg et al., 2000):”A point robot is moving among a set S of disjoint simple polygons in a plane. The polygons in S are called obstacles. Our goal is to compute a shortest collision-free path from p_{start} to p_{goal}”. Calculating this solution has the complexity $O(n^2 \log n)$. This concept can be extended to buildings as even in buildings, people walk on a surface with obstacle polygons. These surfaces in 3D space are usually connected by stairs, escalators etc.

Figure 5: Zones of ”non-walkable” (red) and ”semi-wakable” (yellow) space for the example from HFT Stuttgart to Stuttgart Main Station (own depiction based on GoogleMaps)

Another possible approach for way-finding in this zone based environment might be to use channel finding algorithms like the one described in (Kallmann, 2005). The computation of the shortest path through the channel might not need to be conducted as the user might find his way through the channel based on visual hints using a 3D city model (see section 3). If required by the scenario the shortest path can still be computed using concepts like the Funnel algorithm (Chazelle, 1982)(Lee and Preparata, 1984). This path can be additionally displayed in the 3D scene for user support. In contrast to the car-based approach, the user does not need to follow this line in order to understand the route instructions, it is more a visual guidance for the shortest path. In an open space, the user might also decide to use a different path to the next landmark. For identifying appropriate landmarks close to the channel this shortest path could be used for spatial requests deriving the closest landmarks to the channel that can be used as navigation points/hints. ”Non-walkable” space in urban areas could be defined as obstacles, for example the building footprints, which can be acquired from the land registry data set. As depicted in figure 6 the whole city would be subdivided in appropriate zones. The required triangulation could be pre computed as a basis for the way finding process. The described algorithm in (Kallmann, 2005) might need to be extended in order to take into account different path costs according to the classification of ”semi-walkabke” and ”walkable” space. As this paper only outlines a possible concept, further investigations are required and will be part of future work.

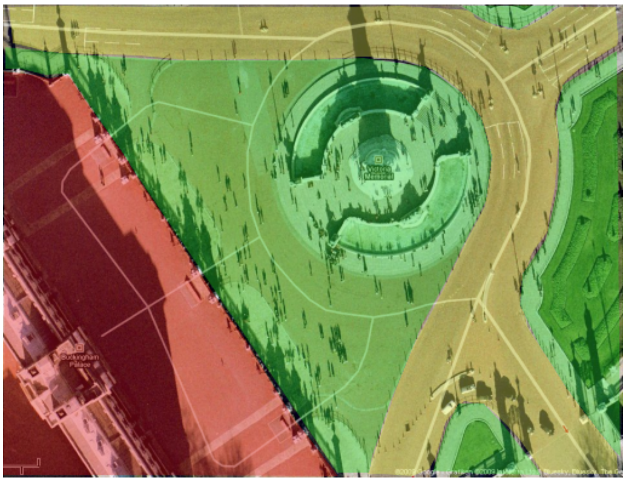


Figure 6: Zone definition for London examples (own depiction based on GoogleMaps)

As route instructions based on distances and directions would not work properly in this channel based routing scenario it will be necessary to find other ways of guiding the user through urban space. A landmark based approach (Coors et al., 2003) might be useful here and could guide the user appropriately using instructions that take the degree of freedom for pedestrians into account. By providing a 3D city model this landmark based approach can be realized in a very user friendly way, as the user can compare the real world to the 3D representation and orientate himself accordingly. This is basically possible, compared to the car scenario, because pedestrians have the time and the ’appropriate speed’ to use the 3D model as a navigation hint. Inaccuracy in positioning using GPS enabled smartphones for example can be compensated by the comparison of the virtual model with the real world. Nevertheless, limited resources on mobile devices make it necessary to provide light weight and efficient models. Limited screen size also makes some investigations necessary how visual navigation hints can be integrated into the 3D model. Highlighting of complete buildings using false colours might be a first step. However, in a dense urban environment and for pedestrians it could be necessary to provide more sophisticated visual hints, like highlighting the correct entrance to a big building or a building complex. In some scenarios it might also necessary to give exact visual hints in order not to confuse the user. With a textual instruction like ”pass the two university towers” it might be necessary to visually define if the landmark needs to be passed left, right or between the two buildings. This might be very important because passing the object on the wrong side would result in a position from which the user cannot see the next landmark, though the system would not recognize the slightly wrong position due to the inaccurate GPS position. Of course this could also be solved by enhancing the textual route instructions, nevertheless a visual hint should support the user in addition to the textual description. Other issues about the 3D model will be discussed in the next section, including considerations of how detailed or realistic the model needs to be.

3 PROCEDURAL TEXTURING APPROACH FOR PEDESTRIAN NAVIGATION

In order to give a visual aid for landmark-based navigation a 3D city model will be provided on the mobile user device. This 3D model should enable the user to orientate himself in his environment and find the specific landmarks that were identified by the system as suitable way points. The 3D city model in this scenario needs to be very efficient in terms of data model and data size, due to restricted system resources on the mobile device. Therefore, on the one hand a light-weight model needs to be provided which on the other hand can still provide a decent level of realism in order to support the user. In this paper the authors will focus on the façade textures as 1) textures consume a quite relevant amount of the overall data size and 2) building façades are the most prominent surfaces in urban space from a pedestrian perspective. Therefore this part of the data needs to be managed in an efficient way and needs to be flexible in terms of adding additional information. Integrating additional information into the façade texture might only be one approach of information visualization, but as the concept of landmark-based navigation introduces buildings as way points, the integration of information into the textures can be a feasible concept. This would also address the limited screen size and the restricted capabilities of integrating additional information by text boxes, billboards, etc.

The concept the authors are investigating is procedural creation of façade textures for 3D city models (compare (Coors, 2008)). In this concept not the original photo image is applied to the geometry in order to texture the building, but small tiles of the original texture. These tiles are arranged by a parameterized description in order to build the overall texture (figure 7). In that way the tiles can be arranged flexibly and according to user needs or context requirements. Using small pieces of the original texture taking into account repetitive and redundant elements of the façades this approach will also reduce the data size of the model.

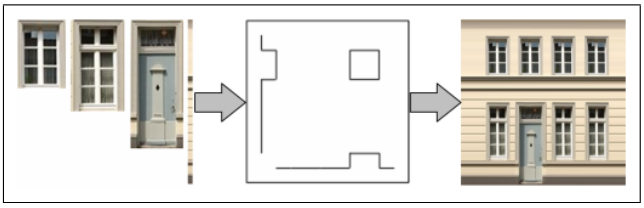


Figure 7: Procedural texture approach using tiles and a description in order to rebuild the overall façade texture

Basically the concept is built upon three components:

- **The programme:** this component implements the logic of the arrangement of the tiles in order to rebuild the façade texture. It reads the parameters of the description and arranges the tiles accordingly. The programme can support specific capabilities of the user’s device and hardware. For example, shaders could be used according to the effects the user wants to integrate into the visualization (e.g. thematic information, etc.).

- **The description:** the description is a set of parameters and definitions to describe for each façade how the tiles need to be arranged and if certain effects should be applied to specific tiles. The size for the tiles can be defined as well. In this way tiles can be scaled in order to fit into the overall façade reconstruction.

- **Texture tiles:** the tiles hold the actual texture information. The texture information is managed in small elements that are arranged in order to rebuild the façade. The texture information can be acquired from different sources, e.g. from a real world image but also managed in a texture library, which includes standard textures.

In the presented approach of procedural façade texturing the authors adapt the concept of (Parish and Müller, 2001) and extend it by further functionality in order to support different Levels of Realism (LoR) and the integration of additional information. These two aspects will be in focus as they are relevant for the navigation scenario outlined in the previous sections. The flexibility of the textures in terms of LoR seem to be useful as the 3D city model is not used for visualization only, where the aim is a maximum of realism. The navigation context is a task driven scenario where a specific LoR and an appropriate level of abstraction can be more beneficial for the user. The concept of adjusting realism to the task of the user is discussed in (Ferwerda, 2003).

In order to achieve this flexibility the procedural texture approach seem to be most appropriate. In the authors approach the aforementioned description is based on a 'pulse function' along the x- and y-axis. The pulses of both functions describe a zone in the texture area where they overlap and a predefined texture tile will be applied (see fig 8). These pulses can also be arranged in layers, where one layer includes one type of façade element. Therefore it is possible to decide which layers, respectively which content, to include into the façade. In that way it is possible to adjust the LoR according to the context and the user needs fulfilling the specific task.

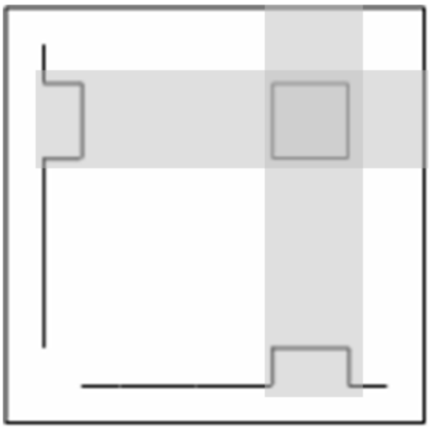
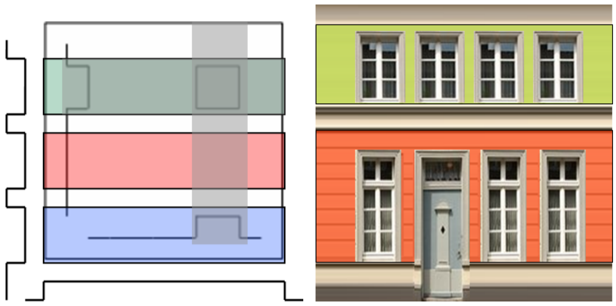


Figure 8: Pulse function concept for procedural texturing of façades

Another possibility of this approach would be to define additional layers with further information besides the 'real world' elements. In that way thematic data can be added into the façade texture. For example, if the use of the specific floors is given it would be possible to define pulses that are linked to a colour code. The pulses can represent the thematic data of the floors and it would be possible to generate a mixture of realistic appearance and abstracted thematic representation (see fig 9(a) and 9(b)).

For the navigation context these additional layers and pulses can also be used to give users visual hints in order to support them in navigating urban space. Using 3D city models the pedestrian navigation system would have to be a server-client application. Therefore it would be possible to generate the navigation hints on the server dynamically according to the computed route. By



(a) Example for thematic pulses (b) An abstracted façade representation

Figure 9: Including thematic information into the procedural façade

computing the shortest path in the determined channel (compare section 2.2 and (Kallmann, 2005)) it would be possible to detect the relevant landmarks. If specific landmarks are close to the route it would be possible to find out where the route passes them and because of the flexible texture concept a change in the appropriate façade textures would be possible (see fig 10).

Figure 10: An abstracted façade indicating a route instruction passing the landmark on the left side.

All in all the procedural concept seems promising in terms of reduction of data size which is a major issue when it comes to mobile applications. It also provides a flexible way of generating façade texture content according to the application scenario. This approach is quite innovative in terms of 3D city models as textures nowadays mostly consist of static image based textures. These textures only allow one fixed representation of the façade, which is sufficient for realistic visualizations. For task driven applications using 3D models as a part of the application concept and probably as a part of the user interface, a more flexible approach is required. Procedural textures appear to be a good concept towards a more sophisticated use of 3D models in task driven scenarios beyond pure visualization purposes.

4 MONA3D PROJECT - 3D CITY MODELS FOR PEDESTRIAN NAVIGATION

MoNa3D is the abbreviation for "Mobile Navigation in 3D" which focuses on pedestrian navigation with support by 3D city models. This project is conducted in cooperation between the HFT

Stuttgart, the University of Applied Sciences Mainz and several partners from the navigation systems and location based services industry. The aim of the project is the development of a navigation system that provides 3D city models on the mobile client in order to support pedestrians navigating urban space. As the authors have already outlined in the previous sections the concept of using 3D models for navigation is beneficial for pedestrians when using landmark-based route instructions. The MoNa3D project will investigate most of the aforementioned issues like procedural textures, detection and specification of landmarks as well as implementation of a prototype navigation system for future field tests. The concept of "walkable", "semi-walkable" and "non-walkable" space is not part of the MoNa3D project, although it is considered as part of future work. The computation of the route is still based on a street network. Nevertheless, route instructions based on landmarks and procedural texturing for the 3D buildings is part of the research conducted in MoNa3D. The following sections will describe the general architecture and concept of the MoNa3D project.

4.1 Client-Server Concept

The MoNa3D architecture is basically a client-server environment as it would not be feasible to store the 3D model and the street network on the mobile device. Therefore the system has got server-side components and the main part of the communication is based on Open Geospatial Consortium (OGC) standard interfaces. The server side system provides an OpenLS service (Open Geospatial Consortium, 2008), a Web 3D Service (Udo Quadt, 2005), a Catalogue Server and many more in order to fulfil the task included in the workflow. A 'mediator service' coordinates all the actions among the different services providing only one interface towards the client device. This prevents the client application to coordinate these actions and to cache intermediate results. Basically the 'mediator layer' is responsible to query the route for a given start- and endpoint from the OpenLS service and to provide the returned route to the Web 3D Service. The semantic route service will also identify the relevant landmarks and provide information about them (e.g. IDs). On the 3D server the appropriate 3D model will be loaded. As there is information about the landmarks available it should be possible to generate procedural textures according to the route geometry, which include navigation hints and additional information relevant for the navigation task (see section 3). The output of the Web 3D Service will then be transmitted to the 'mediator service' which will forward the 3D scene including the navigation instructions to the client. Optionally a compression of the data can take place in order to optimise transmission. The format of the 'mediator' response depends on the client. It would be possible to use standard formats like X3D (ISO/IEC FDIS 19775-1:2008, Extensible 3D (X3D), 2007) or proprietary formats and custom viewers. The rendering of the 3D model and procedural textures will be discussed in the next section.

4.2 Rendering on Mobile Platforms

The rendering of the procedural textures using hardware shaders is an open issue at the time of writing this paper. Currently there are no smartphones, PDAs or other mobile devices on the market that support shaders with their graphics hardware. The final goal would be to rearrange the texture tiles on the client device using the programmable rendering pipeline. This would completely exploit the benefits of using small tiles in terms of data size, because the final texture is built during the rendering process. Due to the absence of the appropriate hardware the texture is rebuilt by the client application and the complete texture is kept in memory for rendering. For clients that require a data format that does not

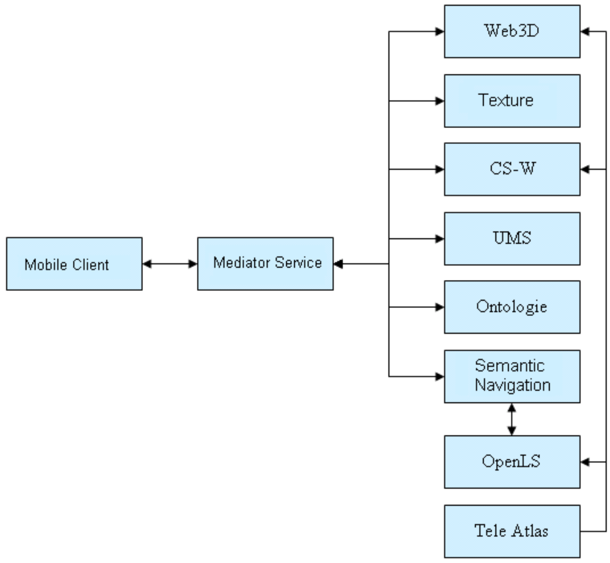


Figure 11: The MoNa3D System Architecture

support the transmission of shader code or cannot provide functionality of analysing the description for procedural textures, the textures could also be rebuilt on the server side, thus transmitting the complete texture to the client. This would also allow including navigation hints and additional information into the texture, as these are computed on server side. However, dynamic changes to textures in a context sensitive manner would only be possible on client side, otherwise too much traffic would be generated. A small advantages would remain even when the textures are rebuilt on the server. Although the complete textures would be transmitted the system would only have to store and load the texture tiles from the database. This results in less data that has to be stored in the database and the amount of data transmitted between the DBMS and the server application.

5 CONCLUSIONS AND FUTURE WORK

This paper has outlined a possible concept for pedestrian navigation that is not based on a street network like in today's navigation systems. The described concept is based on navigable zones that are classified according to their suitability for pedestrians. A more fine grained classification can be introduced according to the specific scenario. These zones can be navigated freely by the user, who is not restricted to walking on a street/path network, which is especially true for open spaces like squares, parks, etc. These open spaces can only be approximated when using a line graph and would probably not provide a convenient navigation experience for the user. Because of the fact that this concept does not work on a street network anymore route instructions based on distances and directions are also not appropriate anymore as pedestrian users would find it complicated to orientate themselves as they are not necessarily aligned to a line and find it hard to understand in which direction to turn. The authors have suggested to navigate the aforementioned zones according to landmarks and to support the user by a digital 3D city model. This model needs to be efficient and light-weight in order to be usable on a mobile device. Nevertheless, the model should also be flexible in terms of appearance and LoR in order to be adaptable to the user's scenario and the navigation scenario in general. The procedural texture approach outlined in section 3 seems to be promising in both terms, reducing data and providing the required flexibility. The landmark based navigation concept and the approach of procedural texturing on mobile devices are investigated by the MoNa3D project presented in section 4. At the moment the focus is on data management of the procedural texture on server side and the identification of suitable landmarks. First promising prototypes have been implemented and test were conducted, both in the specific domains. In the future work the main focus is to integrate the components to form the overall system and to start with first field tests as soon as the system prototype is working. Although these field tests can only investigate the feasibility of the system and the involved concepts as well as a general evaluation of acceptance of the identified landmarks for navigation. A detailed comparison between traditional navigation and the use of landmarks in 3D city models in terms of human perception and Human-Computer-Interaction needs more detailed research which is out of scope of this project at the moment.

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SIMILARITY AMONG MULTIPLE GEOGRAPHIC REPRESENTATIONS

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Commission II/2

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ABSTRACT:

A key ingredient of systems aiming to cope with multiple representations of geographic features is some method for assessing the correspondence and similarity of such representations. In other words, given two objects from two different data sources, one must be able to tell whether they model the same real world object and, in this case, measure their degree of similarity. This paper proposes an adaptation of the Equivalents Rectangles Method (ERM) to quantify the average distance between ambiguous cartographic representations and uses the Cartographic Similarity Index (CSI) – an index based on areal distances – to evaluate how much a given geometric representation resembles another. To validate the proposal, a prototype system was implemented and experiments were conducted on two geographic databases from two different institutions responsible for mapping the city of Rio de Janeiro. These were first matched using feature names in order to independently establish object correspondence. Then, the *ERM* and *CSI* of 159 districts that make up the city were computed. Results show that 157 districts have an *Adapted ERM* lower than 100.00 m and a CSI of 70% or greater. The method was thus able to detect 2 districts with significant dissimilarity, and these conflicts were later confirmed visually, indicating survey errors. In summary, while the proposed method is being used in a larger framework for *ad hoc* querying geographic data with multiple sources, it is also useful in other circumstances, such as in a preprocessing stage for data source integration or for assessment of data source quality.

1 INTRODUCTION

In many countries, geographic surveys of the same area are frequently developed by different agencies or companies. As a result, the results may differ significantly, even when the employed methodology is similar. It is also common for the *post-processed* geospatial data to be made available via web, meaning that, in principle, any interested party may access it. If two or more surveys of the same feature are available, one must, as a rule, either choose one of them or spend significant effort in integrating these data sources into one unambiguous data set. In other words, geographic databases assume that data about a given feature is unique, correct, and representative of physical reality (see Fig. 1.a).

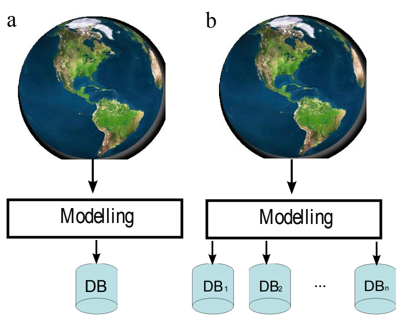

Figure 1: Single and multiple representation

A related problem arises when a given producer employs a given cartographic methodology for surveying a certain theme, but this must later be matched against data pertaining to another theme which was created using some other methodology. This can generate sliver polygons and can easily lead features over other incompatible features, like roads lying inside lakes.

In a nutshell, the current paradigm for modeling and querying geographic databases requires error-free and unique representations. This is a well established concept and was well summarized by Spinoza:

> "There can not exist in nature two or more substances with the same property or attribute"(de Spinoza, 2005).

Of course, this fact is, rationally, readily understood and accepted by human intuition.

To achieve this paradigm, one has to avoid the conflict between data from different producers. Several approaches are common for obtaining a database with no conflicts by data integration. Some of these are the use of Digital Libraries (Pazinato et al., 2002), the Clearinghouse (Goodchild et al., 2007) and the Data Curation approaches (Beargrie, 2006), (Charlesworth, 2006) and (Lord et al., 2008). But, there are some other like a manual schema integration (Kokla, 2006), an extensial determination of schema transformation rules (Volz, 2005), a data matching approaches for different data sets (Mustière, 2006) and a semantic integration (Sester et al., 2007).

Unfortunately, any approach for integrating data sources may lead to information loss. Whereas a given producer tends to favor one aspect of the real world, another producer will, perhaps, lend more detail to some other aspect. When both sources are integrated into a unique data set, some detail may be lost in the process.

In our research, we propose delaying the solution of these conflicts by integrating query answers rather than data sources. Let

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us assume that a certain aspect of the real world has been modeled by different surveyors resulting in several distinct data sources DB_i (see Fig. 1.b). In practice, if a user queries $Q(DB_i)$ each data sources separately, he or she will obtain answers A_i which may or may not be identical (see Fig. 2). In other words, it is possible to have

$$Q(DB_i) \neq Q(DB_j),\ i \neq j\ \vee\ Q(DB_i) = Q(DB_j),\ i \neq j.$$

If all answers A_i agree with each other, then we must concur that no data integration was needed. Otherwise, we may have different kinds and amounts of discrepancy, which, however, may be resolved in a simpler way. For instance, we may find that most data sources produce identical results whereas a single data source may be regarded as an outlier. It seems reasonable that presenting this duly categorized information to the user will lead to safer decisions being made than simply discarding the outlier, even when it really contains erroneous information. One may easily imagine a scenario where the outlier is correct and all other sources are wrong.

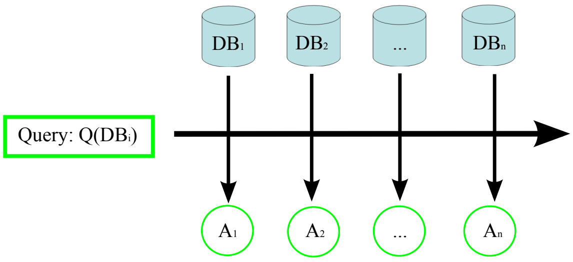

Figure 2: Different answers for different queries

It stands to reason, however, that any process whereby answers must be categorized will require previous knowledge about discrepancies among the sources. In this research we focus on a methodology for analyzing data sources which represent the same set of features in order to establish similarity measures. In particular, we describe an adaptation of the Equivalent Rectangles Method (ERM) (Ferreira da Silva, 1998), a linear discrepancy measure originally proposed for polygonal lines, extended to closed polygons. Furthermore, we use the Cartographic Similarity Index (CSI), an approach for measuring similarity among geographic data sources.

To validate the proposed methods, district boundary databases for the city of Rio de Janeiro, as prepared by two Brazilian institutions, are compared. In this case, databases are represented as a set of closed polygons (not necessarily convex).

The rest of this paper is organized as follows. Section 2 presents the original ERM and shows how it can be adapted to polygons. Section 3 describes the CI, CoI and CSI indexes, and discusses its applicability. Section 4 describes the data sets, methodology used in the experiments, and presents a comparison results. In Section 5, we present our final remarks and suggestions for future work.

2 EQUIVALENT RECTANGLES METHOD (ERM) AND VARIANTS

2.1 Classical *ERM*

The *ERM* methodology was developed to assess the discrepancy between linear representations – polylines, in practice – of the same feature (Ferreira da Silva, 1998). In other words, it tries to measure an average distance between two representations of the same geographic feature. It should be stressed that the methodology can only be used if it is known that both geometric representations are related to same real world feature. So, the *ERM* is very useful in evaluating the quality of data sources.

The approach is based on the well-known formula (Eq. 1)

$$x^2 + S \cdot x + P = 0, \tag{1}$$

taking into account a “discrepancy polygon” obtained by connecting the initial and final points of the polylines and generating an equivalent rectangle (see Fig. 3). The coefficients assume the values of half the perimeter *P* and area *S* of this discrepancy polygon. Using the formula of Baskara (Eq. 2) two roots for Equation 1 can be determined .

$$\begin{cases} x_1 = \frac{-S+\sqrt{S^2-4 \cdot P}}{2} \\ x_2 = \frac{-S-\sqrt{S^2-4 \cdot P}}{2} \end{cases} \tag{2}$$

The absolute value of the first root $|x_1|$ measures an average distance between the representations while the second absolute value $|x_2|$ measures the mean semi-perimeter of the representations (Ferreira da Silva, 1998).

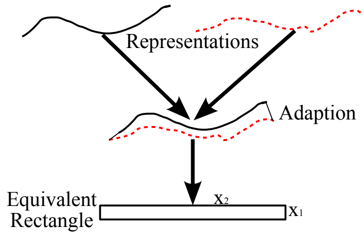

Figure 3: Two line representations and the rectangle used for computing the *ERM*

Incidentally, although the *ERM* has been developed for linear features only, it has been extended to cope with Digital Elevation Models (DEM), having received the name of Equivalent Parallelepiped Method (EPM) (da Rocha Gomes, 2006). In this case, the measure considers the volume, lateral area and perimeter of the generated parallelepiped.

2.2 Polygon *ERM* adaptation

In this work, we propose another extension of the *ERM* so that it can be used for polygonal representations. To obtain this extension, we first observe that a polygon corresponds to a closed polygonal line (see Fig. 4). By analogy with the original *ERM*, a discrepancy polygon can be obtained by computing the difference between the union and the intersection of both polygons. This is then processed in the same way as in the original ERM. Notice that there is no need for joining endpoints.

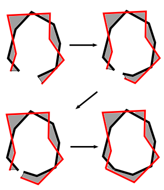

Figure 4: *ERM* adaptation for a pair of polygonal representations

So, is P_i the polygon representing the feature area *A* in the data sources DB_i (Eq. 3). In this case, the coefficient *P*, for the semi-perimeter, and the coefficient *S*, for the area, have value as those obtained by Equations 4 and 5.

$$P_i = DB_i|Polygon(A),\ i = 1, 2 \quad (3)$$

$$P = perimeter((P_1) + perimeter(P_2) \quad (4)$$

$$S = area(P_1 \cup P_2) - area(P_1 \cap P_2) \quad (5)$$

Time complexity of the algorithm for intersection (Žalik, 2000) and union polygonal procedure (Agarwal et al., 2002) is too high. But, it is essential to measure the *CSI* and the *CI* (Sester et al., 2007). Obviously, the quantity of polygon vertices and the number of intersection points are directly related to time complexity of the algorithm. As it was exposed by (Žalik, 2000), an optimal intersection algorithm has a complexity given by $O((k+I) \cdot log_2(k+I))$, where I is the number of intersection points and k is the sum between the number of the input polygon vertices ($k = n + m$). The union operation has a higher complexity. In this case, there are many algorithms, such as, (Agarwal et al., 2002) and (Varadhan and Manocha, 2006). But all of them require non-convex polygons to be decomposed into convex pieces. In this work, we used the algorithm proposed by (Varadhan and Manocha, 2006) to process the union operation and the algorithm proposed by (Žalik, 2000) to produce an intersection polygon.

3 SIMILARITY, COMPLETENESS AND COVERAGE INDICES

When a user considers data from different sources, ambiguities are likely to occur. Measuring the severity of an ambiguity occurrence is not straightforward. Also, it is not clear how to determine the degree of similarity. As a rule, ambiguities may arise in two different scenarios. The first possibility occurs when a single data source has an ambiguous representation. In this case, it is an error of the producer, and a supervised and rigorous inspection on the data source is sufficient to pinpoint this situation and allow it to be corrected. The second case appears when the user has processed data from different producers. This type of ambiguities is a common occurrence because "errors in geographic databases cannot be avoided" (Ali, 2001).

An easy way to identify potentially ambiguous representations is by using metadata. Unfortunately, metadata cannot identify ambiguities in many cases, since it may also be incorrect or ambiguous. A saner approach, then, is to analyze the relevant geometric representations in order to extract information about their similarity. In this work, we use the term **Cartographic Similarity Index** (CSI) to refer to the complement of the *areal distance* (Ali, 2001), a measure originally used to evaluate the "distance" *d* between two sets of polygons. In other words, let P_A and P_B be two polygons, then the relation between CSI and distance *d* is expressed by Equation 6.

$$\begin{aligned} CSI(P_A, P_B) &= 100 \cdot (1 - d(P_A, P_B)) \\ &= 100 - 100 \cdot (1 - \tfrac{area(P_A \cap P_B)}{area(P_A \cup P_B)}) \\ &= 100 \cdot \tfrac{area(P_A \cap P_B)}{area(P_A \cup P_B)}. \end{aligned} \quad (6)$$

Notice that the CSI is expressed as a percentage. Thus, two representations are considered identical ($CSI = 100\%$) if they occupy exactly the same locus. Conversely, two disjoint representations have $CSI = 0\%$.

Another useful measure is the so-called **Completeness Index** (*CI*) – (Ali, 2001) and (Kieler et al., 2007) – which tries to establish how much of a given representation P_A agrees with another representation P_B, and is given by Equation 7.

$$CI(P_A, P_B) = 100 \cdot \frac{area(P_A \cap P_B)}{area(P_A)}. \quad (7)$$

We may also define the **Coverage Index** (*CoI*), expressed by

$$CoI(P_A, P_B) = 100 \cdot \frac{area(P_A)}{area(P_A \cup P_B)}, \quad (8)$$

which can be interpreted as a measure of how much a given representation P_A covers points which may actually belong to a feature, given that this feature is estimated by polygons P_A and P_B.

We notice that measures CI and CoI are not symmetric, i.e., in general,

$$CI(P_A, P_B) \neq CI(P_B, P_A) \wedge CoI(P_A, P_B) \neq CoI(P_B, P_A).$$

Notice also, that the CSI, a symmetric measure is related to CI and CoI by

$$CSI(P_A, P_B) = \frac{CI(P_A, P_B) \cdot CoI(P_A, P_B)}{100}.$$

Although the CI, the CoI and the CSI were presented as pairwise operators, they can easily be generalized as n-way operators:

$$CI(P_A, \ldots, P_n) = 100 \cdot \frac{area(P_A \cap \ldots \cap P_n)}{area(P_A)}$$

$$CoI(P_A, \ldots, P_n) = 100 \cdot \frac{area(P_A)}{area(P_A \cup \ldots \cup P_n)}$$

$$CSI(P_A, \ldots, P_n) = 100 \cdot \frac{area(P_A \cap \ldots \cap P_n)}{area(P_A \cup \ldots \cup P_n)}$$

4 EXPERIMENTS

In order to investigate the usefulness of the *Adapted ERM* and the *CSI*, a prototype system was used to compare two data sources for the district partitioning of the city of Rio de Janeiro. The prototype exhibits both data sources graphically, thus allowing a visual inspection of ambiguities. It also computes the *Adapted ERM* and *CSI* values for the different polygons. In this case, each polygon represents one of the 159 districts of the city of Rio de Janeiro. The data was obtained from two sources in the same scale (1 : 10.000): **Pereira Passos Institute** (IPP in Portuguese), a municipal institution responsible for mapping the city, and the **Brazilian Institute of Geography and Statistics** (IBGE in Portuguese), an entity responsible for the systematic mapping of the country. In fact, the two data sources are, visually, quite similar, but not identical (see Fig. 5).

The data was, initially, acquired in *shapefile* format (ESRI, 1998), but was converted to Geography Markup Language (GML) format (OGC, 2001) using GDAL tools (GDAL, 2008). All subsequent processing was made in *GML* format.

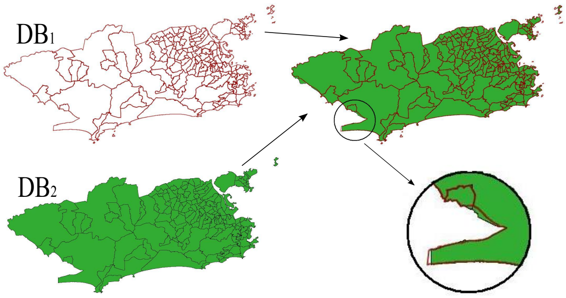

Figure 5: Districts ambiguities

In general, we are interested in performing a procedure to establish matching representations of the same features according to two data sources, say, DB_1 and DB_2. For simplicity, we assume that a data source is comprised solely of two columns, one for the geometric data, and another for the non-geometric information which identifies the table row , which we call "feature name" (see Table 1).

feature name	geometric data
district D_1	list of coordinates
district D_2	list of coordinates
...	...
district D_n	list of coordinates

Table 1: Data source example

The detection of matches consisted of checking all possible pairings between polygons (features) of both data sources. For each pair (P_i, R_j), where P_i is a polygon from the IPP data source and R_j is a polygon from the IBGE data source, both the *Adapted ERM* and the *CSI* were computed. It should be noted that both sets have the same cardinality, but this needs not be the case in general.

The intention was to evaluate the occurence of *matches* between two specific representations by analyzing index values. So, let $ERM_{min}(P_i)$ denote the minimum value for the Adapted ERM among all pairs (P_i, R_j). Then, R_k is considered the candidate match for P_i if $ERM(P_i, R_k) = ERM_{min}(P_i)$. Similarly, let CSI_{max} denote the maximum value for the CSI among all possible pairs (P_i, R_j). Then, R_k is considered the candidate match for P_i if $CSI(P_i, R_k) = CSI_{max}(P_i)$. Notice that the matching functions are not symmetric, i.e., R_j being considered the candidate match for P_i does not imply that P_i is considered a candidate match for R_j.

Within this framework, it is reasonable to suppose that any given feature is represented in both data sources, i.e., there is a multiple representation. One may even call these representations "ambiguous", in the sense that a feature has, thus, two representations. This benign occurrence corresponds to the case where the candidate match (using either index) for P_i is R_j and vice-versa.

Another important consideration is the match between feature names. What happens if a match detected geometrically does not concur with their respective feature names? Conversely, what does it mean to have identical feature names associated with non-matching geometric representations? Clearly, a *true* match must only be considered if geometric representations match each other (according to both index metrics), *and* their feature names also agree. This is expressed in Equation 9, where $FN(x)$ stands for the feature name for polygon x:

$$P_i \; matches \; R_j \Leftrightarrow ERM(P_i, R_j) = ERM_{min}(P_i) \wedge CSI(P_i, R_j) = CSI_{max}(P_i) \wedge FN(P_i) = FN(R_j). \quad (9)$$

4.1 Matching problem

After processing the district data sources, the candidate matches obtained using both indices were exactly the same. In other words, the *Adapted ERM* and the *CSI*, produce the same result. However, the use of feature names reveal that only 158 of the 159 matches were "true" according to Eq. 9. In particular, only one district was not identified correctly. For both data sources, the candidate match for the district named "Parque Columbia" was another district named "Pavuna". In other words, let P_c denote a polygon in the first data source for which $FN(P_c)$ is "Parque Columbia", and P_p denote a polygon for which $FN(P_p)$ is "Pavuna". Let R_c and R_p analogously denote the polygons of "Parque Columbia" and "Pavuna" in the second data source. Then, it was found that $ERM_(P_c, R_p) = ERM_{min}(P_c)$, and, similarly, $CSI_(P_c, R_p) = CSI_{max}(P_c)$. Notice that the district of "Pavuna" was correctly matched, i.e., $ERM(P_p, R_p) = ERM_{min}(P_p)$ and $CSI(P_p, R_p) = CSI_{max}(P_p)$.

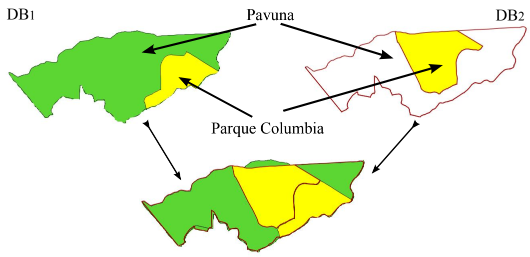

Figure 6: An indefinition example – "Parque Columbia"

In that case, there are indefinitions about the boundaries of the districts. As it is shown in Fig. 6, IPP and IBGE do not agree about the geographic position of "Parque Columbia". These specific districts return the values shown in Table 2.

Correlation	*Adapted ERM (m)*	*CSI (%)*
$P_p \times R_p$	232.50	54.16
$P_p \times P_c$	708.22	0.00
$P_p \times R_c$	415.08	21.32
$R_p \times P_c$	457.20	31.60
$R_p \times R_c$	859.13	0.00
$P_c \times R_c$	680.19	0.00

Table 2: "Pavuna" and "Parque Columbia" comparison

4.2 ERM Analysis

We notice that the values obtained with the ERM_{min} index were fairly high both for the district of "Pavuna" and for the district of "Parque Columbia", but generally low for the other districts, rarely surpassing $40m$, as shown in Table 3.

Incidentally, Brazilian law tries to establish standards to assess the quality of the systematic mapping of the country, called the Cartographic Accuracy Standard (Brasil, 1984). In this case, the standard prescribes that a class A map should have 95% of field samples lying within $5m$ of the corresponding map feature in mapping scale. Thus, using the ERM index, it is possible to affirm that at least one data source used in the experiments would not pass said standard.

ERM_{min} range (m)	number of districts
$0 \leq 10$	2
$10 \leq 20$	67
$20 \leq 30$	60
$30 \leq 40$	18
$40 \leq 50$	4
$50 \leq 60$	4
$60 \leq 80$	0
$80 \leq 100$	2
$100 \leq 250$	1
$250 \leq 500$	1

Table 3: ERM range analysis

Another curious aspect of the *ERM* index is that it sometimes yields non-intuitive similarities. For instance, the match for the district of "Oswaldo Cruz" yields

$$ERM_{min}(P_o) = ERM_{min}(R_o) = ERM(P_o, R_o) = 9.10m,$$

the lowest among all ERM values. Looking, however, at the next best candidates for matching that district, i.e., the next 5 lowest values of $ERM(P_o, \ldots)$, we do not find neighboring districts as can be seen on Figure 7 and Table 4, instead of the highest CSI values, as can be seen in Table 5.

$FN(R_j)$	$ERM(P_o, R_j)$	$CSI(P_o, R_j)$
Oswaldo Cruz	9.10	97.00
Cosme Velho	421.70	0.0
Santa Teresa	431.75	0.0
Paquetá	437.49	0.0
Urca	447.29	0.0

Table 4: Lowest ERM values for matching P_o, the district of "Oswaldo Cruz"

$FN(R_j)$	$ERM(P_o, R_j)$	$CSI(P_o, R_j)$
Oswaldo Cruz	9.10	97.00
Bento Ribeiro	728.15	0.19
Madureira	784.79	0.02
Turiaçú	597.36	0.01
Campinho	575.03	0.01

Table 5: Highest CSI values for matching P_o, the district of "Oswaldo Cruz"

4.3 CSI Analysis

It is also useful to look at the highest value for the CSI among all pairs, which corresponds to the district of "Bangu". A table with the next highest CSI values for that district are shown in Table 6. As can be seen in Figure 8, these correspond to districts neighboring "Bangu", as expected.

We also ranked the matches obtained with the CSI in increasing order, as shown in Table 8. As expected, the two lowest values are associated with the districts of "Parque Columbia" and "Pavuna", whereas all other districts yielded CSI values bigger than 70%. Thus, a cut-off value of 70% would be enough to pinpoint matching problems, even in the absence of feature name information.

In Figure 9, it is possible to observe the *CSI* distribution with respect to geographic locations. Districts with *CSI* lower than 70% are painted in red, districts between 70% and 90% in yellow, and above 90% in green. We notice that smaller values usually correspond to districts with smaller areas. This is understandable since errors are more likely to occur on district boundaries.

Our tests indicate that the *Adapted ERM* and *CSI* tend to detect the same matches. However, the *Adapted ERM* is not as sensitive

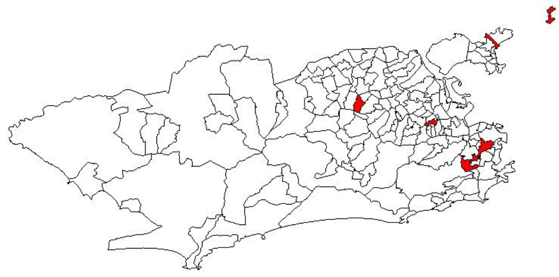

Figure 7: Districts yielding the 5 lowest values of ERM with respect to the "Oswaldo Cruz" district

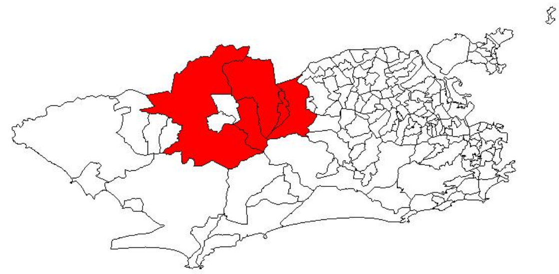

Figure 8: Districts yielding the 5 highest values of CSI with respect to the "Bangu" district

as the *CSI*. The former produces a large dispersion in the results when compared to the latter, as shown by Table 3 and 8. Thus, the identification of ambiguities is probably easier when the *CSI* is used. The advantage of the *Adapted ERM* lies on its yielding measures in distance units. On the other hand, the *CSI* is more adequate for quantifying similarity.

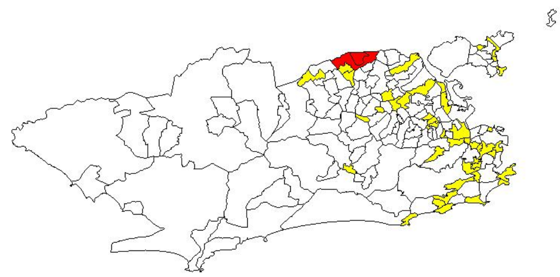

Figure 9: Similarity distribution on Rio de Janeiro city

5 CONCLUSIONS AND FUTURE WORK

This work is part of a doctoral thesis that proposes a methodology to enable an user to obtain any information from a query to multiple data sources. The next step of the research will be to use the *CSI* as a qualifier of ambiguities and facilitate the integration of responses. The main idea is to shy away from *a priori* integration of data sources in favor of an *a posteriori* treatment of answers obtained by querying these data sources separately. Thus, given a *query* applied to any multiple representation, it is necessary to process the multiple responses in order to provide support for decisions. This, also, helps quantifying the certainty, coverage and completeness of the query answers.

To reach this goal, this work proposed, initially, an extension of *ERM*, and then proposed a new use for a known index, the *CSI*. The idea was to seek a way to identify possible ambiguities, in order to facilitate a further integration of responses. It can also

$FN(R_j)$	$ERM(P_b, R_j)$	$CSI(P_b, R_j)$
Bangu	20.98	98.32
Padre Miguel	2081.72	0.24
Campo Grande	2789.99	0.11
Senador Camará	2273.43	0.09
Realengo	2292.59	0.03

Table 6: Highest CSI values for matching P_b, the district of "Bangu"

$FN(R_j)$	$ERM(P_o, R_j)$	$CSI(P_o, R_j)$
Bangu	20.98	98.32
Santa Teresa	1690.78	0.0
Barra de Guaratiba	1907.89	0.0
Cidade Universitária	1913.72	0.0
Centro	1934.76	0.0

Table 7: Lowest ERM values for matching P_o, the district of "Bangu"

be observed that the proposed index serves as a certifier of geographic data to be used in digital curation. Identifying ambiguous representations and offering them a value of similarity is essential to obtain the largest possible amount of information. It is our belief that this approach will help making ready use of *web* data sources without incurring the costly effort of integrating them in a single database.

CSI_{max} range	number of districts
$0 \leq 70$	2
$70 \leq 80$	6
$80 \leq 90$	36
$90 \leq 95$	72
$95 \leq 100$	43

Table 8: CSI range analysis

The admittedly small experimental evidence shown in this paper indicates that the *CSI* is more sensitive to the identification of possible ambiguities than the *Adapted ERM*. Nevertheless, the latter, being able to return distances rather than correlations, may be of use in queries involving metric reasoning.

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ROOF PLANE EXTRACTION IN GRIDDED DIGITAL SURFACE MODELS

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KEY WORDS: Algorithms, LIDAR, Modeling, City, Detection, Reconstruction

ABSTRACT:

With the rapid improvement of LIDAR systems regarding point density and accuracy in relation to the (application dependent) requirements, robustness, efficiency and automation of the modeling process are becoming more important than achieving the highest possible accuracy and modeling detail from the available LIDAR data. Therefore we opt for development of a 2D grid based LIDAR data analysis approach. An important step is detection and parameterization of planar surfaces (roof elements). The paper reviews four methods, based on analysis of gradients, principal components, least squares and hough transforms, respectively. It introduces a series of improvements to the standard usage of each of those methods and shows results from synthetic and real data.

1. INTRODUCTION

In nowadays information society a growing need for 3D information of the urban landscape is observed. Producers as well as consumers of geoinformation recognize the attractiveness of representing the urban environment by 3-dimensional models rather than 2D maps. Growing needs for efficient exploitation of the scarcely available urban space requires more careful and detailed spatial modeling than 2D information allows for. Examples can be found in urban planning and architecture, and in simulation and modeling of noise and pollution caused by traffic and industry. An interesting, new and fully 3-dimensional application is modeling the urban climate, with all its micro-climate phenomena. But also in consumer-oriented applications, such as real-estate advertising, portable and in-car navigation systems, and even Google Earth, 3D is becoming common practice.

With the increasing availability of airborne LIDAR data, full automation of 3D city modeling from those data has become a challenging and relevant research topic. In the algorithms to be applied a choice has to be made whether to regard the data as a 3D point cloud or as a 2D (often termed 2.5D) surface model, in which the elevation z is a function of the planimetric location (x,y). Furthermore, in both cases the data can be regarded as vector points with explicit coordinates, or be discretized in a regular grid with implicit raster coordinates. These choices lead to voxel representations in 3D or to pixel representations in 2D, where the elevations are stored in the pixel values.

Traditionally the goal of 3D modeling has been to obtain the best possible detail given the available data. For this reason vector representations are often considered superior over gridded ones, despite the advantages of the latter concerning efficiency and convenience. With the rapid improvement of LIDAR systems regarding point density and accuracy, however, the data are no longer the limiting factor, but robustness, efficiency and automation of data analysis have become more important instead. Therefore we opted for development of a 2D grid based approach for 3D modeling. An important step in the approach is detection and parameterization of planar surfaces (roof elements).

Irrespective of the chosen input data structure, the first phase of 3D building reconstruction can be described as a segmentation problem. It is necessary to subdivide the input point set into subsets corresponding to objects of interest, where objects are for example (depending on the required amount of detail) entire buildings of elements of building roofs. Subsequently (or simultaneously) the geometric characteristics (the shapes) of the objects are reconstructed on the basis of the coordinates of the participating points.

A choice to be made is whether the segmentation should be complete, meaning that every point is assigned to an object, or whether we are only looking for buildings, whereby points on vegetation and cars, or even on the ground, may be discarded as ‘not of interest’. In the latter case the entire issue is largely covered by the capability to detect planar regions above a certain height in a normalized DSM (which is a DSM where the terrain has $z=0$). Points below that height as well as those not belonging to planes are discarded. There are issues remaining, for example caused by non-planar roof elements, tall trees over buildings, roof gardens and trucks. Moreover, vertical building elements (walls) are not present in LIDAR point sets, but they have to be inferred from the data by recognizing surface discontinuities.

The remainder of the paper concerns detection, delineation and parameterization of planes. It reviews a number of methods in Section 2, with the purpose of combining these into a novel local Hough transform in section 3. Section 4 will show experimental results on synthetic and on real data, followed by conclusions and an outlook in Section 5.

2. PLANE DETECTION

Generally, plane detection can be performed using global or local methods. Global plane detection looks ‘at once’ at the entire data set or at a large subset, which is perhaps bounded by algorithm capacity or by prior knowledge concerning the maximum extends of a plane [Oude Elberink and Vosselman, 2006]. As a result, planes are entirely detected ‘at once’ as well. A popular global plane detection method is the Hough transform described below (Section 2.1). Local methods, at the other hand, attempt to decide for each point, or small group of nearby points, whether it might be part of a planar surface, and if so, what would be the surface parameters (Section 2.2). The decision is based on a neighborhood of the point or point group.

2.1 Hough Transforms

'Hough transform' is the collective name of a class of algorithms for detecting parameterized shapes in 2D or 3D data sets. The most popular example is detection of thin lines in two-dimensional binary images. The object pixels are supposed to belong to those lines, but there are also 'noise' object pixels, whereas the lines have gaps. The problem is to find the parameters of the lines, and the solution starts by parameterizing the set of image lines passing through an object pixel with coordinates (x, y) as (for example):

$$y = ax + b \quad (1)$$

In a parameter space with axes a and b this collection corresponds to a line

$$b = -xa + y \quad (2)$$

Therefore, a point in image space corresponds to a line in the parameter space. For a set of collinear image points the corresponding lines in parameter space intersect at a single point (a, b) representing the image line $y=ax + b$ that passes though all image points. Thus the problem of finding collinear points in image space is reduced to finding intersections of lines in parameter space (Figure 1). These intersections are easily found by discretizing the parameter space into a 2D accumulator array: an image where lines are constructed one by one, by adding the value 1 to all cells of the line. When all lines are done, each cell value represents the number of lines passing through this cell, and the location (a, b) of the cell denotes an image line passing through that many image points.

This principle is easily extended to finding planes

$$z = ax + by + c \quad (3)$$

in a set of 3D points (x,y,z), such as a LIDAR point cloud. Each 'image' point now corresponds to a plane

$$c = -xa - yb + z \quad (4)$$

in a (a,b,c) parameter space, and a point (a,b,c) where N planes intersect corresponds to a plane in image space containing N image points.

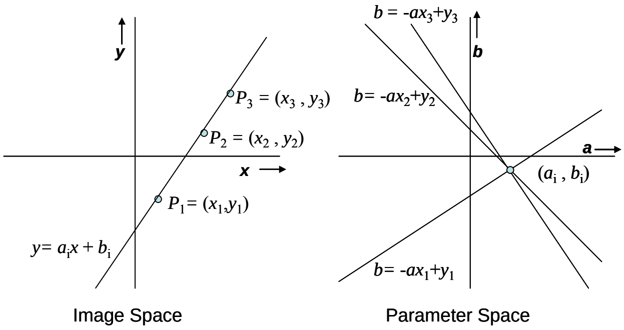


Figure 1. Hough transform for lines in 2D

Note: The above parameter spaces become unbounded when having vertical lines, resp. planes in the data. This is not a major problem in case of airborne LIDAR.

2.2 Local Plane Detection

Local planed detection methods analyze a small neighborhood of points at a time to decide about co-planarity of those points. Neighborhoods can be defined in two or in three dimensions. In 2D, a point near the edge on the roof of a high building and a point near to the wall on the ground may be in the same neighborhood, whereas in the 3D case they would not be.

It can be based, for example, on analysis of gradients (Section 2.2.1), least squares adjustment (2.2.2) or principal component analysis (2.2.3). At a later stage adjacent candidate points with similar surface parameter values are combined into larger planes, for example by region growing [Rottensteiner and Briese, 2001] (see Section 2.2.4), The performance of segmentation largely depends on the results of plane parameter estimation, which is the motivation of studying these closely.

The methods considered below can be described in terms of estimating parameters a, b and c of equation (3).

2.2.1 Gradient analysis

In a vector approach, plane parameters can be derived for each triangle after a Delaunay triangulation by using a voting mechanism similar to the one in Hough transforms, in order to construct larger segments from adjacent triangles with similar parameter estimates [Lohani and Singh, 2007]. [Gorte, 2002] presented a TIN-based region merging algorithm.

In a grid based approach, plane parameters a and b are derived straightforwardly as the image gradients in column and row direction, respectively, while taking the spatial resolution of the dataset into account. The value of the Laplacian, as estimated by a 3x3 filter in the same window, provides a measure for the planarity of the 3x3 neighborhood.

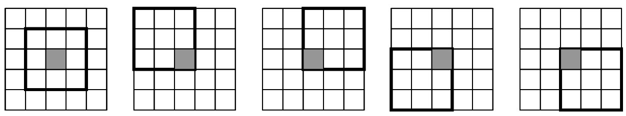


Figure 3. 3x3 subwindows in a 5x5 window

The main disadvantage of using gradients is that they are computed by subtracting neighboring z-values. Especially when point spacing (or grid spacing) is small compared to the measurement noise, gradients are getting quite noisy. In a grid-approach, the use of larger kernels reduces noise, but creates a wider zone near to the edges of planes where the results are unreliable.

Adaptive Gradient Filtering

An interesting way to reduce this edge effect is to consider different subwindows within the window around a pixel under consideration, as in Figure 2. This will be called adaptive gradient filtering. It is inspired by the Nagao type of edge-preserving smoothing [Nagao an Matsuyama, 1979], where the central pixel is assigned the average value of the subwindow with the smallest variance. Now, we assign the gradient from the subwindow with the smallest value for the laplacian. The same idea can be applied in a 9 x 9 window, using 5x5 subwindows. Figure 4 shows two of five cases.

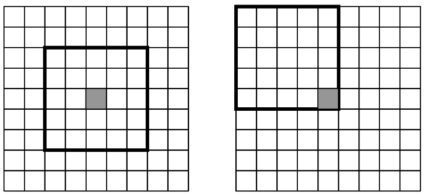


Figure 4.Two 5x5 subwindows in a 9x9 window

2.2.2 Least squares adjustment

A straightforward way of obtaining a plane through a number of non-collinear points is to perform a least squares estimation of the plane parameters. The RMS error provides a measure of the quality of the estimates, which is favorable since the estimates are severely contaminated if the plane does not fit well, as it happens near the edges of a plane, or in case of outliers in the points.

The method is easily implemented in a grid and extended in the same Nagao fashion as in the gradient method above, which we will call adaptive least squares filtering. window sizes are possible, for example using 7x7 subwindows in a 13x13 window, or 9x9 in 17x17. In each case the parameter estimates are obtained from the subwindow with the smallest RMS error.

2.2.3 Principal component analysis

When regarding a number ($N \geq 3$) of (x,y,z) points as a collection of simultaneous observations of variables *x, y* and *z* it is allowed to compute the 3x3 variance-covariance matrix *C* of these observations. Co-planarity of the points is signaled by the smallest eigenvalue of this matrix being (close to) zero, whereas the other two eigenvalues are significantly different from zero [Guru et al 2004]. The smallest eigenvalue can be used as a measure of co-planarity of the points. The eigenvectors belonging to the other two eigenvalues are orthogonal to each other and to the normal vector of the plane, and provide the plane parameter estimates.

Also now the extension to the distinction between different subwindows within a window under consideration is easily made. This can be called adaptive principal component filtering. Plane parameters are taken from the subwindow where the smallest eigenvalues is smallest (!).

It should be noted that the principal component method is equivalent to the least squares method of Section 2.2.2. Also computationally there is no clear advantage for either method.

2.2.4 Image segmentation

After plane parameters and co-planarity measures have been obtained by one of the local methods of Sections 2.2.1 tot 2.2.3, groups of adjacent points with similar parameters should be grouped in segments, corresponding to planar objects. It should be noted that all three plane parameters should be considered; using only the gradients *a* and *b* is not sufficient, for example, when two flat roofs with different heights (and different *c* values) are adjacent.

Popular image segmentation methods such as region growing and region merging rely on thresholds to determine whether adjacent pixels or regions are similar enough to be combined into a single segment. The performance of segmentation largely depends on the input, i.e. on the results of plane parameter estimation.

3. LOCAL HOUGH TRANSFORM

Hough transform, being a global method, is particularly suitable for detecting (and estimating parameters of) large structures, such as long lines in 2d or 3d, or big planes in 3d, that are sparsely represented by points in noisy images and point clouds. Its parameter estimation is quite insensitive to outliers. At the downside there is an element of chance in the detection because a parameter space resolution has to be chosen.

Moreover, the method does not consider adjacency of points being assigned to a plane (in the 3d case), Therefore a rather large threshold has to be set for the minimum plane size (i.e. the value in the accumulator array), or otherwise many arbitrary planes are generated from points that happen to be coplanar, but are spread all over the scene. Consequently, planes that are smaller than this threshold will not be detected. Sometimes this is solved by using prior knowledge, for example from 2D map data, to constrain the process to the interior of a single building ground plan, or even to a rectangle that is obtained by further subdividing a ground plan [Vosselman and Dijkman, 2001].

Another problem of Hough transforms in 3D is the computational cost. Having millions of points, belonging to hundreds of planes in a LIDAR data set, millions of planes need to be constructed in the parameter space. This space needs to have a resolution that allows hundreds of local maxima at the plane intersections to be represented and detected accurately.

Also here it helps to use prior knowledge to pre-segment the data, but a more general way out is to reduce the dimensionality of the problem. [Rabbani and van den Heuvel] for example managed to bring down the dimensionality of 5D cylinder parameter estimation by splitting the process into a 2D, followed by a 3D stage.

Combining these observations with the results of Section 2 inspired development of a local grid based Hough transform. Its purpose is to find the plane that passes through as many points as possible in a k x k window, including the point represented by the central pixel. The points are expressed in a local (x,y,z) coordinate system having the origin at the central pixel. The x and y coordinates of the other points are given by the row and column positions within the window, taking the spatial resolution into account, and the z value of each pixel is obtained by subtracting the central value from the pixel value.

The fact that (0,0,0) has to be part of the plane reduces the number of parameters from 3 to 2, since only planes

$$z = ax + by \qquad (5)$$

need to be considered. For each of the k x k - 1 remaining points a line is constructed in an (a,b)-accumulator by:

$$b = z/y - ax/y \qquad (6)$$

The maximum value in the accumulator determines the number of points, beside the central point, belonging to a single plane, whereas the position of this maximum in the accumulator gives an estimate for the corresponding plane parameters *a* and *b*. These are valid in the original coordinate system as well. Again, the remaining parameter *c* can be computed using equation (3). However, provided that sufficiently many points participate, a better estimate of all three parameters is obtained by a least squares fit of a plane through these points. Here, the absence of outliers in the set of participating points is of great benefit – the resulting RMS errors are expected to be much smaller than those obtained in Section 2.2.3.

4. EXPERIMENTS

The methods to estimate plane parameters from gridded DSMs described in section 3 are applied to three data sets:

1. a synthetic DSM of a simple house
2. a synthetic DSM of the same house with added noise
3. a FLI-MAP 400 dataset of an urban scene

The synthetic house was generated by sampling a point cloud from an "ideal" grid model with 10 cm resolution. The point cloud was then rotated over an angle of 28 degrees, and converted back to a 10 cm grid. Values of grid cells without points were interpolated form their neighbors by using a local average filter. The resulting DSM is shown in Figure 5.

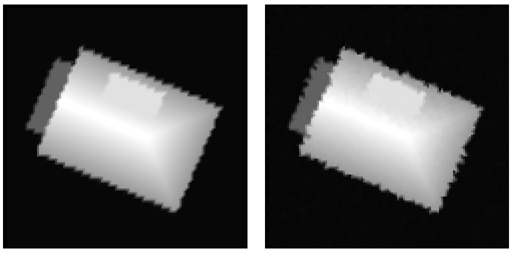


Figure 5.Synthetic DSM of a house with and without noise

Figures 6 and 7 illustrate the gradient methods described in Section 2.2.1. Standard 3x3 image gradients in x and y direction, corresponding to estimates of the *a* and *b* plane parameters are shown (Figure 6), as well as adaptive gradient filters (only for the parameter *a*, Figure 7). It is clearly visible that the effect at the edges is drastically reduced in the latter case, and also noise is reduced significantly.

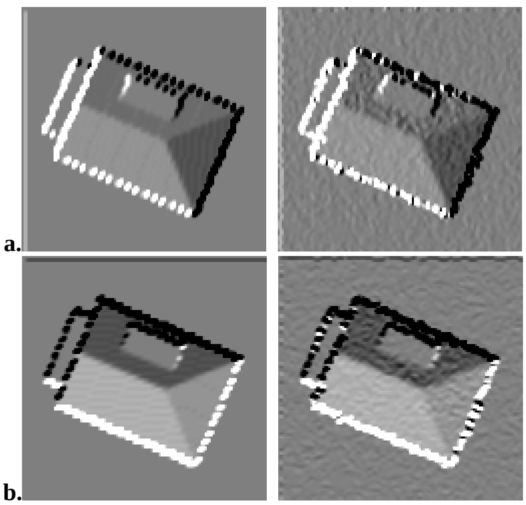


Figure 6. Gradient filtering.
a: image gradient in x direction without and with noise,
b: image gradient in y direction

The results of least squares methods is shown in figures 8 and 9. Figure 8 shows the estimates of the plane parameter *a* obtained by least squares filtering in a fixed 5x5 window and in an adaptive filtering in a 9x9 window with 5x5 subwindows, both for ideal and noisy images. Also the RMS errors of both situations are shown (Figure 9).

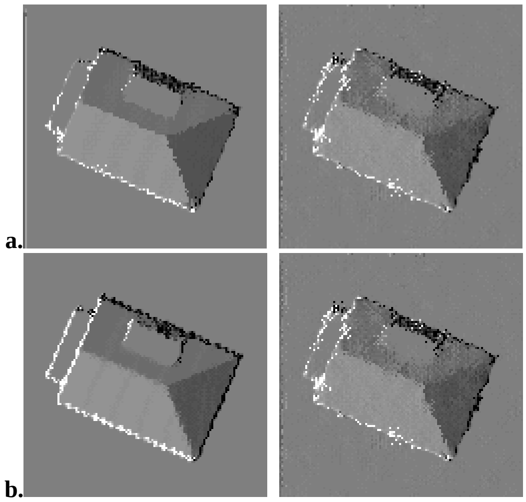


Figure 7. Adaptive gradient filtering.
a: 5x5 with 3x3 subwindows, without and with noise
b: 9x9 with 5x5 subwindows

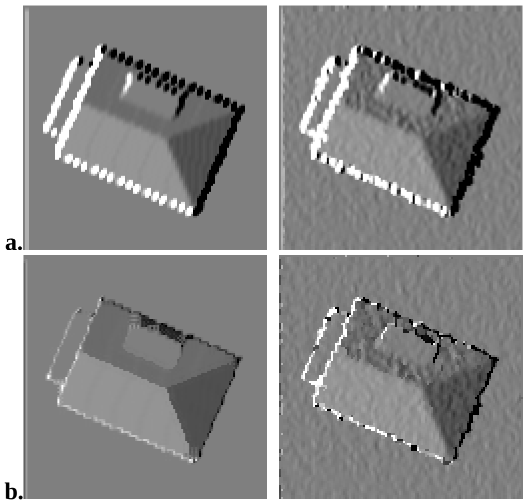


Figure 8.. Least squares filtering in ideal and noisy data
a: in 5x5 window, b: adaptive 5x5 in 9x9 window

The next experiment concerns local Hough transforms where the *a* and *b* plane parameters are estimated directly from the positions of the maxima in the accumulator (only parameter *a* is shown). We show the results of different window sizes, again for ideal and noisy input data (Figure 10). It appears possible to apply large window sizes, resulting in effective noise reduction (outlier removal) without loosing spatial detail.

The final experiment on synthetic data concerns local Hough transform with simultaneous least squares plane parameter estimation. See Figure 11, where all parameter estimates are illustrated, as well as the RMS of least squares estimation. A 21x21 window size was used. It appears that the parameter estimates do not differ much from those directly obtained from local Hough transform with the same size and without least squares estimation (Figure 10d.). It should be noted that the RMS of the least squares estimates is very small compared to those in Figure 9, where the same mapping from RMS values to gray levels has been used.

Last but not least, a result from real data is shown in Figures 13.

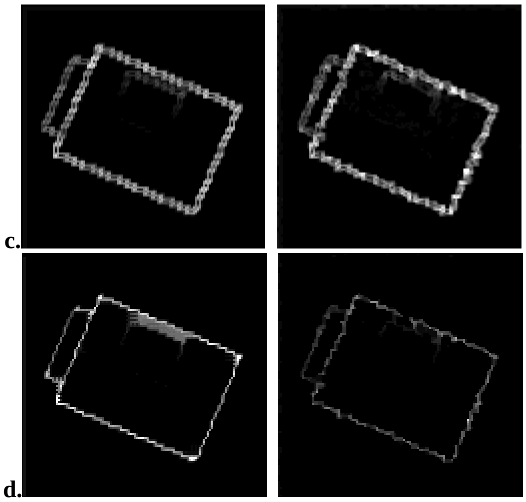
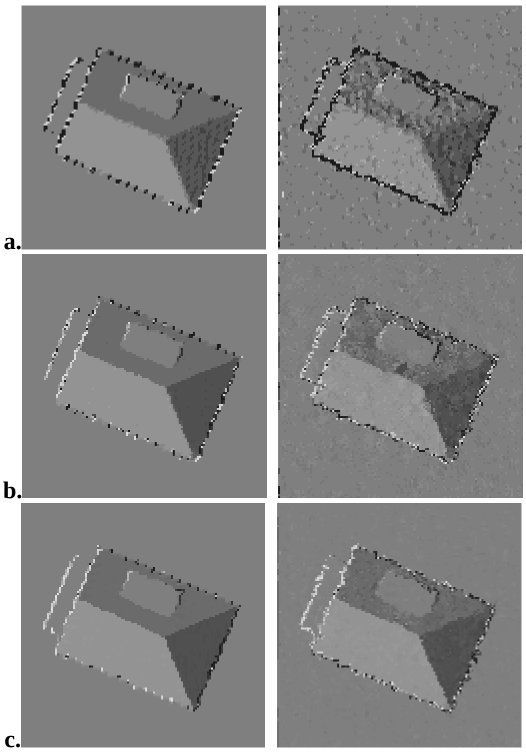


Figure 9.. Least squares filtering.
c: RMS of image 8a, d: RMS of image 8b.



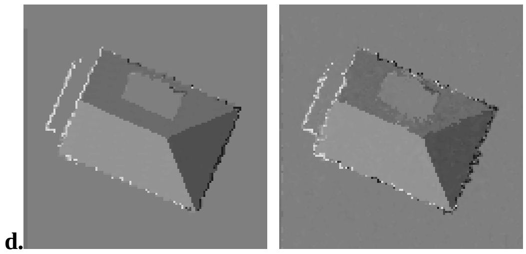


Figure 10. Local Hough transform in ideal and noisy data
a: in 3 x 3 window, b: 7 x 7 c: 13 x 13, d: 21 x 21

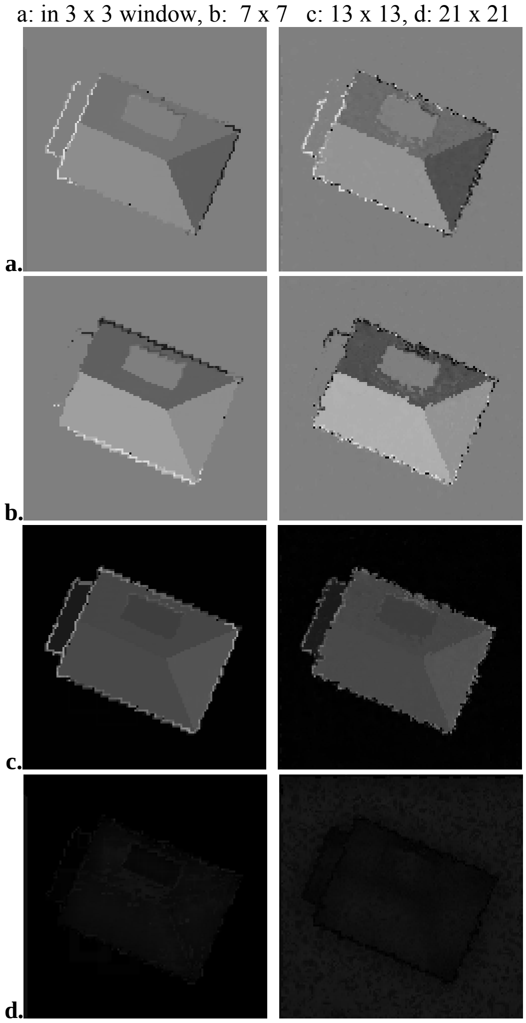


Figure 11. Local Hough transform with least squares plane parameter estimation of *a, b* and *c* in 21 x 21 windows.
d. shows the RMS of the least squares fit.

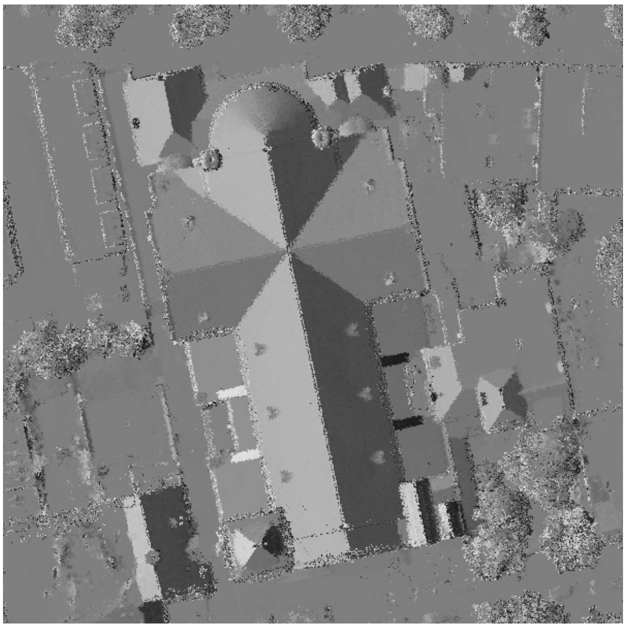


Figure 12: Plane parameter *a* estimated from FLI-MAP 400 data in Rotterdam (NL) using a 21x21 local Hough transform.

5. CONCLUSIONS AND OUTLOOK

The paper describes theoretical considerations leading to the development of a local Hough transform method for detecting planes in a gridded surface DSM, while estimating the plane parameters. The method was expected to deal effectively with noise and to behave well near the edges of plane, which is confirmed by experiments on synthetic data with and without noise, and appears to apply to real high-density LIDAR data in a complex urban scene as well.

The next step in the development of robust, fully automatic 3d city model generation will be the delineation of roof planes, both at the intersections of neighboring planes as well as at surface discontinuities where walls have to be reconstructed.

Acknowledgement: The FLI-MAP 400 data were collected by Fugro for the municipality of Rotterdam, and were made available for research purposes.

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GENERALIZATION OF SEMANTICALLY ENHANCED 3D CITY MODELS

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KEY WORDS: Generalization, City Models, 3D, Semantics

ABSTRACT:

With the rapid advances in sensor – especially laser scanner – technology and the development of increasingly more sophisticated algorithms for the extraction of features from the data sets produced by those sensors, very detailed digital models are going to be produced for a large number of urban areas. In order to make these models available for different applications, concepts for the generalization of these models have to be developed to reduce the size and semantic complexity of the models to a degree that can be handled by the application without losing information that is relevant for the task at hand. Postulating a stricter separation and modularization of the processes of feature extraction and generalization, we present a workflow for the generalization of semantically enhanced models with a hierarchical structure and describe how such models can be used to integrate different algorithms for the generalization of special constellations of features.

1. INTRODUCTION

1.1 Motivation

With the growing availability of increasingly more detailed 3D city models, the demand for approaches towards their generalization can be expected to rise significantly in the next few years. This trend is going to be supported by an increasing number of applications that will also change the current practice of producing these models mainly for visualization purposes. An example for this trend are the 3D models that have to be used to calculate noise levels for urban areas according to recent EU regulations.

In the context of the German grid computing initiative (D-Grid), the GDI-Grid project is concerned with using grid technology for spatial data infrastructures. Within this project, one task is the development of generic generalization service for 3D city models.

In order to use 3D city models beyond the task for which they were produced, a generalization step is often necessary. Two main reasons can be identified for the necessity of generalization: The size of the data sets is too large to be processed in the application or there is information in the data that is not needed or cannot be handled by the application.

The main purpose of generalization is therefore to reduce the complexity of a data set with respect to its size and semantic content while retaining the pieces of information that are relevant to the task at hand – removing or rearranging those aspects that cannot be handled by the application.

With the concept of “relevant information” being inherently a semantic one, approaches towards generalization that do not (or only marginally) rely on semantic information yield satisfying results only for special applications. One of those cases is, however, the most popular one: (more or less) photorealistic visualization. For this application, the most important criteria for the importance of a feature are its size and reflection properties rather than specifically semantic information – with the term “*semantic information*” referring to the type of the feature and the values of parameters specific to the feature’s type and the application.

In cartography, semantics are modeled through specific feature classes and thematic layers. In the generalization process, semantics were initially introduced by using different mostly geometric operators – like the Douglas-Peucker or Jenk’s algorithm for line features – for different kinds of features. In recent years, however, the relevance of semantic enhancement by structure recognition has been emphasized, and a growing number of specific generalization algorithms have been developed like the one presented in Heinzle and Anders (2007) for road networks.

In the context of the generalization of 3D city models, this is even more necessary because in three-dimensional models there are often constraints that are extremely difficult to ensure on a purely geometrical basis.

A parameter giving the maximum tolerable inaccuracy for a feature is introduced to control the generalization process. This parameter will be referred to as the target resolution assigned to a feature. One way of introducing semantic criteria in the generalization process is to set different target resolutions for different features according to semantic conditions.

An important goal of this work is to make it possible to define the process of generalization in as natural a way as possible. For this purpose, semantics-based generalization approaches are an essential tool. A description like “at a given resolution, a Mansard roof is simplified to a gabled roof of equal height” is much more intuitive – and far less error-prone – than a description like “if there are four roof planes in a certain constellation (Mansard roof) then transform them to a pair of planes (gabled roof) at a given resolution.” Unfortunately, few models with a sufficient level of semantic information to directly apply a rule like the one described in the first example are available at the moment.

For this reason, most approaches towards the generalization of 3D city models that have been presented so far remind rather of the second example: Because they have to use models that contain mostly geometric and comparatively little semantic information, a feature recognition step is introduced implicitly in the algorithms.

This implicit combination of generalization and feature extraction has several important drawbacks: Such algorithms can usually only be used for specific geometrical representations of (conceptually) the same situation (like walls having to be represented as one surface); there are two independent sources for problems; many approaches concerned with generalization end up having spent considerably more effort on feature extraction (structure recognition) than the original task

of generalization – which is not surprising considering the fact that feature extraction is a wide field of research in its own right. In our opinion, it is therefore necessary to introduce a stricter separation between the processes of generalization and feature extraction.
An additional improvement of the separation of the steps is the fact that existing feature extraction solutions can be used. Milde et al. (2008) and Ripperda (2008), for example, present projects concerned with the extraction of detailed roof and façade structures from mostly geometric data. Models provided by these approaches contain a high level of semantic information and are therefore promising for semantics-based generalization.
Some generalization operators like typification are defined for groups of features. In order to use these operators in the generalization of data sets in which such group features are not labeled explicitly, algorithms for the detection of recurring or symmetric structures like the one presented in (Bokeloh, 2009) – for laser scanner data – have to be employed before these operators can be used.

1.2 Related Work

The approach of using hierarchical models for generalization has been introduced in (Lal, 2005) in his distinction between micro, meso and macro models for generalization. There are, however, only these three fixed levels in his hierarchy; it is therefore not possible to extend the model towards larger or more fine-grained structures. He also stresses the necessity of a stronger separation of the processes of feature extraction and generalization. The focus of his work is, however, on feature extraction and the specific generalization operation of aggregation.
M. Kada (2007) uses the wall surfaces of a building complex to detect structural parts (cells) of an ensemble of building components. He introduces parametric primitives for roof forms. Using the different roof primitives, regular patterns of roofs can be detected in order to apply the generalization operator of typification. For the general structure of the building complexes, the selection operator is used: If a cell is too small to be retained after the generalization process, it is removed from the model. The generalization approach works on geometric models and consists to a great part of a feature extraction component. It is limited to building models that consist of wall and roof surfaces.
Döllner and Buchholz (2005) introduce the concept of Continuous-Level-of-Quality buildings that allows the user to model buildings with custom granularity according to the task at hand. They do, however, not provide concepts for the automatic generalization of such models. The concepts for generalization introduced in Buchholz (2006) are mostly concerned with visualization issues, especially the treatment of textures.
H. Fan (2009) introduces an approach to extract the exterior shells of building models that contain interior and exterior surfaces for walls and roofs – with the generalization step consisting of replacing the original geometry by the exterior shell. Additionally, different strategies for the generalization of (regular arrays of) windows are evaluated.
There are lots of techniques for the reduction of polygon meshes for visualization from the computer graphics community. These approaches are, however, not designed to make sure that resulting models fulfill semantic constraints. For this reason, employing such models for the generalization of city models often results in mostly geometry-based approaches with semantic constraints introduced implicitly. An example for such an algorithm is the approach of Rau et al. (2006) in which rules for the detection of protrusions are introduced implicitly in rules for the collapsing of walls.
Thiemann and Sester (2004) also present an approach towards the generalization of 3D city models: The roof and wall planes in the model are used to derive a CSG representation of the building. The generalization step is a selection that is employed by removing those primitives from the representation that are too small for the given resolution.

2. A GENERIC GENERALIZATION SERVICE

2.1 A Workflow for the Generalization of 3D City Models

In the development of a generic generalization service, it is impossible to predict all requirements and peculiarities an application may introduce – especially if the purpose is not only visualization. In a flooding application, for example, it is possible that upright surfaces (like walls) cannot be used directly in FEM-based simulation software.

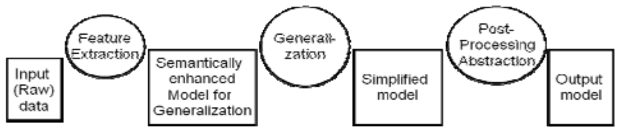

Figure 1: Generalization workflow

In a typical generalization scenario, the three different steps shown in Figure 1 can be identified: Feature extraction (possibly from different sources), the generalization step itself, and a post processing step to adjust the output data to the application.
In this context, the term *feature extraction* refers to the process of deriving information that was not explicitly modeled in the input.
A great increase in reusability can be gained through the modularization of different concepts in the fields of feature extraction and generalization. One interesting scenario in this context could, for example, be to use the algorithm for the extraction of the exterior shells from Fan et al. (2009) in order to prepare models for the partitioning into cells introduced by Kada (2007).
Feature extraction and generalization are very closely related, and in order to enhance the quality of the output of the generalization process, it can be reasonable to introduce further feature extraction steps – especially for the identification of patterns.
Such a nested feature extraction step can, for example, make sense in the context of an arrangement of similar but slightly different features in a regular pattern. At maximum resolution, these numerous small differences can make it problematic to model these features as a group. At lower resolutions, however, the differences may be irrelevant and to collect the features in a pattern offers new possibilities for generalization (like typification).
Such cases are, however, not arguments against the separation and modularization of the different generalization and feature extraction strategies but rather in favor of this because only atomic services can be combined with the necessary flexibility.

2.2 Usability

For a wide range of users, standard feature types and generalization strategies with the possibility to request special features at different resolutions depending on application data will be sufficient for most feature types. For this reason, the framework is going to provide a standard feature model with configurable generalization options.

A generic service can, however, not predict which influence the values of application-specific variables have on the importance of a feature.

For this reason, the user can configure the generalization process using semantic and spatial criteria. An example for such a generalization query could be "Give me all features within 1000m of the river with the name 'Mississippi' at a resolution of 2m, the bed of the river at 1m, and the rest of the model at 5m resolution". If the data does not contain the required amount of detail, the user has to choose between either using the most detailed version available or aborting the process. In the simple standard case, a uniform resolution is set for all features.

Due to the modular approach in the design of the generalization process, the user can also choose between different generalization approaches for different features that could be mapped (if appropriate) to the different features in the same way as the different resolutions.

Unfortunately, there are features of special importance for different applications that can require custom generalization procedures. In order to deal with this problem, a third party is necessary: The developer of application-specific generalization components. In order to support the development of specific feature types and generalization procedures, the framework offers a standard model with the possibility of inheritance. A dike may, for example, be defined as a special type of ridge with parameters describing the construction and the pattern of breakwaters. The user can then, for example, choose between the dike generalization algorithms of developers A and B.

3. A SEMANTICALLY ENHANCED BUILDING MODEL FOR GENERALIZATION

3.1 Explicit and Parametric Modeling of Geometry

To represent geometric information explicitly in a model has the advantage that it is easy to extract this information without knowledge of the more specific semantics of the model. For this reason, the explicit modeling of geometry is popular with exchange formats. In many cases, however, the explicit modeling of geometry obscures semantic information. Two planes in a building model may, for example, form a gabled roof or be two opposite walls in the body of the building.

The CityGML model presented in (Kolbe et al., 2005) uses a semantics-based feature hierarchy with an explicit representation of geometry in the leaf features. This may lead to the inconsistencies introduced above if the modeler does not take care to avoid them.

If (geometrically relevant) semantic and explicit geometric information are combined in a model they can be redundant – with the ensuing problem of possible inconsistencies. If, for example, a roof is stored labeled as a gabled roof and the geometry corresponds to a flat roof, the semantic and geometric information are inconsistent.

The advantage of the parametric modeling of geometry is that operations on the geometry can be described in a more abstract way using semantic concepts and that constraints can be satisfied implicitly. This reduces the complexity of the generalization process and of ensuing integrity tests considerably. For this reason, parametric representations have been chosen for most feature types in the reference model. It is, however, possible to use both ways of representing geometry in the model.

Depending on the application, different geometric representations can be derived from the same model – a wall that is known to have certain thickness can, for example, be instantiated as a solid, as its two visible faces or as a single face.

Geometrical tests like intersection tests for the detection of conflicts introduced by overlapping features can never be avoided completely but the goal of using the parametric model is to reduce their number and complexity as far as possible.

3.2 A Hierarchical Feature Model

In order to deal with the complexity of 3D city models and the necessity to give users the possibility to extend the model by their own types, the reference model is organized hierarchically with a parent-child relation meaning that the child is part of the parent feature.

This makes it possible to deal with features of different granularity and to ensure constraints implicitly. Another advantage is the fact that the effects of the introduction of additional feature types can be limited to specific parts of the feature hierarchy.

For each feature in the hierarchy, a bounding box and a transform are stored – when a new child is added to a feature, its bounding box is updated to make sure that all children are enclosed in its bounding box. Using this information, the feature hierarchy offers possibilities of a scene graph like using local coordinate systems for the description of a feature and of the R-Tree data structure because search queries can be pruned if a feature's bounding box (and through the containment relation, all of its subfeatures) does not intersect with the search interval.

For the detection of overlaps of features in the process of the identification of conflicts during generalization, these bounding boxes can also be used for quick tests whether conflicts can occur and to define areas occupied by a certain set of features that must not be intersected by others in order to avoid conflicts.

As in cartographic models, thematic layers for features from different thematic fields can be introduced. In the CityGML model, for example, there are layers for water bodies, buildings, traffic objects and vegetation features. The current version of the proof-of-concept prototype consists only of building-related features. It is, however, planned to incorporate traffic objects like roads in one of the next steps.

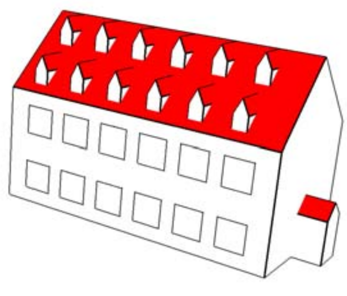

Figure 2: Example of a building model

Figure 2 shows a simple model of a building; the structure of this model is shown in Figure 3. The top level feature is a BuildingPart object with a gabled roof and an annex (modeled as another BuildingPart object) attached to one of its sides. There is an array containing two rows of windows with six windows in each row attached to one of the walls (the first one with index 0) and an array of six by two dormers attached to the roof. Both of these arrays are represented by the same 2DArray class with different template features for the windows and dormers and subjected to the same generalization procedure of typification in the generalization process.

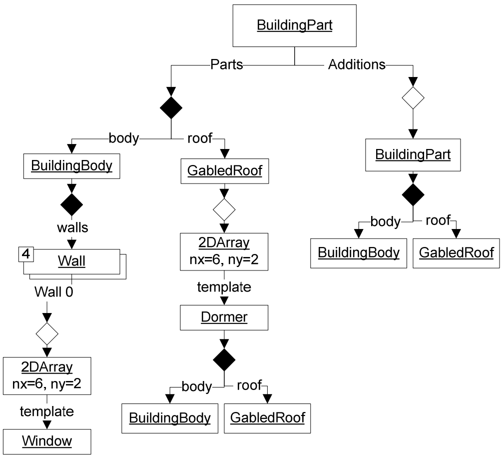

Figure 3: Structure of the model in Figure 2

The rhomboid shapes in Figure 3 symbolize the two different kinds of subfeatures a feature can have: The filled rhomboid stands for the essential parts of the feature, the empty ones for non-essential additions. This distinction is important for the generalization of the model because necessary parts of a feature should not be removed from the generalized model if the parent feature has been decided to be kept. In special features that represent arrangements of features, template features are used to model the features that appear in the different cells. As for all other features, the treatment of these special features in the generalization process depends on the application. In a typification strategy, for example, they would be emphasized to match the current resolution.

This notation was chosen to remind of the UML notation for the aggregation and composition relations because it has a similar meaning. It does, however, work in the opposite direction: In the UML definition, an aggregation relation is a composition if the parts do not make sense without the whole while in the model the whole is not valid without the essential parts.

Figure 3 shows another characteristic property of the model: The structure of the model represents an interpretation of the situation. One example with direct impact on the generalization process is the arrangement of the features in group or array features. The arrays of windows or dormers may as well have been represented as two independent rows – meaning that they are being considered independently in the standard generalization process which would lead to their being removed from the generalized model at much earlier steps. Such restructurings can be used in the harmonization and optimization steps in order to resolve conflicts or enhance the result of the generalization.

4. WORKFLOW FOR THE GENERALIZATION OF HIERARCHICAL CITY MODELS

4.1 Overview

The generalization process is implemented as a depth-first traversal of the feature hierarchy according to the process model shown in Figure 4.

In the first selection process, the feature is tested if it qualifies to be retained in the generalized version of the model. If this is not the case, the process terminates and nothing is returned. Common criteria are the size and type of the feature: Usually, a minimum size is given for a feature depending on a target resolution. This minimum size may vary for different types of features; additionally, special types of features can be excluded if they are not relevant for the purpose for which the generalized model is produced and other types of features can be enforced to be kept if they are of special relevance.

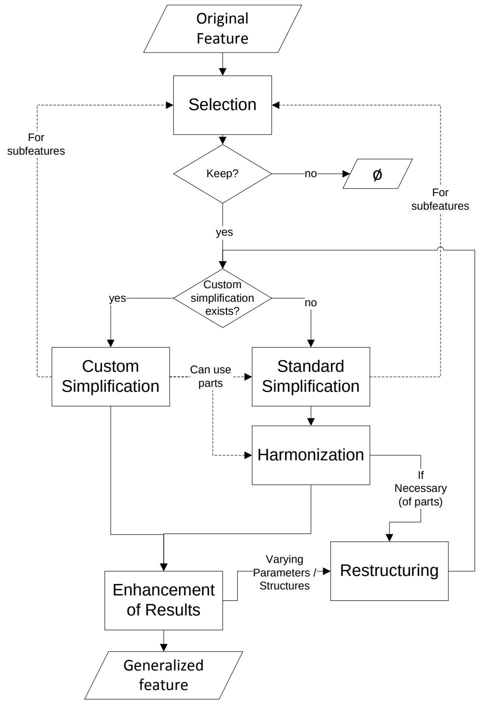

Figure 4: Process model for the generalization traversal

If a feature is an essential part of a feature that has already been decided to be kept, it is retained without having to pass the selection test.

In the first pass, the restructuring unit is not going to change the model. In the following processes, however, it may turn out that using a structurally slightly different (but semantically equivalent) representation of the situation described by the model yields considerably better results – or may be necessary to get a valid result at all: The restructuring step includes, for example, the setting of annotations that prevent special simplification steps that have been discovered to lead to inconsistencies in the model. A more detailed description of the restructuring step can be found in section 4.2 of this paper.

In the next step, it is tested whether custom simplification procedures exist for the current feature. If no such procedure is found, the standard simplification is applied: In the first step, the general structure of the generalized feature is constructed by applying the whole process recursively to the essential parts of the current feature – with the selection decision always being positive – and reassembling them to form the new one. After that, the additions are also subjected to the process and attached to the new feature – if they have been decided to be kept in the selection step.

Because the different parts are generalized independently, conflicts can occur that have to be resolved by the harmonization component. Such a harmonization step can require – possibly repeated – partial restructurings of the model with the subsequent new simplifications.

Custom simplification procedures can be defined for individual features – which is, of course, a very laborious thing to do for all features but can make sense for special features like buildings of very unusual architectural design – or for classes of features. Generally, the most specific simplification procedure is applied: If there is one for the individual feature, it takes precedence over all others; procedures for the class of the feature are applied before procedures of superclasses are considered. For features with different superclasses – or more than one implemented interface – the precedence can be defined in the selection component.

In principle, a custom simplification procedure has complete control over the way it generates the generalized feature. It is, however, possible to use components from the standard simplification. This is especially useful in order to deal with additions: Only in rare cases will a developer of a custom generalization procedure have to deal with all possible additions to a feature – especially as anyone might define a new feature class and want to use an instance of it as an addition to a feature of the class for which the custom simplification procedure is developed. For this reason, it makes sense to reuse the standard simplification approach of independent simplification and harmonization at least for the rest of the feature's additions for which no specific treatment has been specified.

In order to achieve better results, the whole process can be embedded into an optimization step. In such an optimization process, different restructurings of the model and different parameters for all parts of the simplification process can be tested and evaluated against each other.

Usually, a trade-off has to be found between the desired quality of the generalized model and the amount of processing resources available. In order to cover as many application scenarios as possible, a configurable system like the blackboard approach or a formal grammar is going to be used in the prototype.

4.2 Restructuring

The same situation in the real world can be described by different building or city models. Such models will be called *semantically equivalent* while identical models are not only semantically but also *structurally equivalent.*

Especially for constellations of similar features, different semantically equivalent models can be defined in which these features are grouped in different patterns or hierarchical structures.

Because the structure of the model is essential for its generalization, using a structurally different (but semantically equivalent) version of a feature can significantly enhance the result of the generalization – it may, for example, be possible to collect features in a regular array if they are similar enough after their simplification.

As indicated in the process model shown in Figure 4, such restructuring operations can be employed for two different reasons: To resolve conflicts that occur due to the independent generalization of sibling features (from the harmonization step) and in order to find the interpretation of the original model that yields the best results after generalization (in the optimization step).

As a simple case, restructuring operations can also be used to exclude certain generalization operations. Such measures can be necessary if, for example, a gabled roof has a group of dormers: It makes sense to prevent it from being generalized to a flat roof if the dormers have been decided to be kept at the given resolution.

Finding semantically equivalent but structurally different versions of a model is a graph rewriting problem: Parts of the feature tree defined by the current feature that can replaced by other features have to identified and replaced by the appropriate new features.

Unfortunately, the general graph rewriting problem is NP-complete. It is therefore not a promising approach to try all possible sets of structurally different representations of a detailed city model that may contain a lot of features.

For this reason, restructuring steps are used only over limited parts of the feature tree; mostly only between the direct children of the current feature. For nested patterns like the more sophisticated facade model introduced in (Ripperda, 2008), it can be useful to descend deeper in the feature hierarchy to get better results.

A substantial alleviation of the general complexity of the problem is the fact that – usually – only patterns of features have to be considered that start directly below the current feature in the hierarchy.

As mentioned in section 2.1, one way to find different interpretations of a model is to employ feature extraction algorithms from different sources on a collection of already simplified subfeatures in order to find patterns that were obscured by slight differences between the features in the original model.

Another approach is to directly define valid transformations for special constellations of nodes in the feature tree.

4.3 Pattern Features

In order to make the generalization process more transparent, pattern features can be introduced to explicitly model characteristic constellations of features.

Using these patterns, operators from cartographic generalization like typification can be defined as simplifications of pattern features.

A special kind of these pattern features are group features in which similar features are arranged in a more or less regular distribution along a line or in a grid. For those features, the cartographic operator of typification can be introduced as a simplification procedure.

In the current prototype, a class representing a regular array of features is included. Features of this class have a template feature that is copied to all cells in the reconstruction of the geometry. Additionally, the number of features and their distance in x and y direction on a virtual canvas are given; the height offset of the features is associated to a virtual height field defined over the canvas. This is necessary because otherwise dormers might, for example, end up below the roof surface.

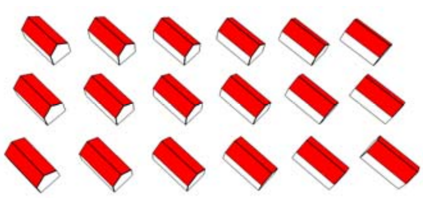

Figure 5. Regular array of rotated buildings

It is possible to specify a transformation for the template feature that is applied after the feature has been moved to its place in the grid defined by the array feature. Such a transformation can be used, for example, to model features – like the buildings shown in Figure 5 – that are arranged in patterns but rotated or otherwise not aligned with the main axes of the distribution defined by the pattern.

For “letter” patterns like “I”, “T”, “E”, etc. – for example of buildings in a block as introduced in (Rainsford and Mackaness, 2002) –, the different parts of the letters can be defined as essential parts which may be simplified but not omitted outside of a specific simplification procedure.

4.4 Models in Scale Space

So far, only point queries in scale space have been described in this paper: It was assumed that one value of the resolution parameter was specified for each feature.

There are, however, applications for which it can be expected that different distributions of resolution values over the features will be needed.

A typical example of such a scenario is the derivation of models for visualization: According to the position and orientation of the camera, different features will have to be represented at different levels of detail. Especially in this case, generating a generalized model on the fly – especially if harmonization and optimization backtracking steps are necessary – is going to lead to unacceptable delays.

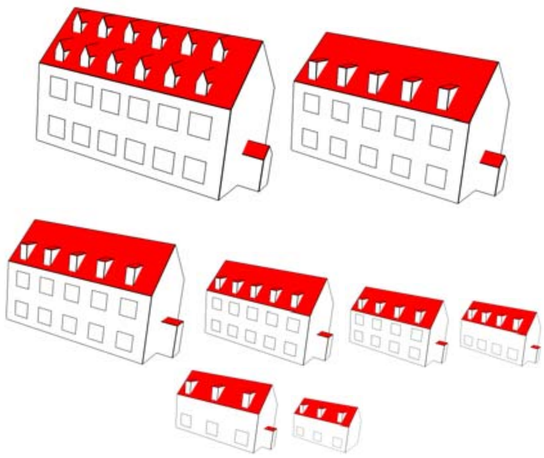

Figure 6: Steps in the generalization of a building model

As long as a uniform resolution is chosen for the whole model, such models with “precompiled” generalization levels can simply be stored as a sequence of generalization steps – with the resolution at which they occurred – inverted to a refinement series; this approach is similar to the “streaming generalization” introduced in (Sester and Brenner, 2009).

Figure 6 shows such a generalization sequence for the model introduced in chapter 3.2. The development of the incremental model is a sequence of events in the reverse order of those that occur in the generalization sequence with the first representation being the least detailed model – in this case, with a gabled roof, three windows and three dormers. If a more detailed representation is required, details are added until the desired accuracy is reached. In the example, the second step is to restore the small annex followed by the appearance of a fourth element in the rows of dormers and windows. In the succeeding steps, elements are added incrementally to the arrays of windows and dormers and the flat roofs of the smaller structures are replaced by the original gabled ones. If the requested accuracy is higher than the one associated with the first generalization (last refinement) step, the original model is returned.

If non-uniform resolutions are required, the problem becomes more difficult because very complex conflicts can arise in this case – especially if the difference in the required accuracy is motivated by the semantics of the model rather than visualization and there are close relations between parts that are needed in more and less detail.

4.5 Harmonization

There are two classes of problems that have to be resolved by the harmonization component: general and feature(type)-specific problems.

Most general problems are the result of the fact that features can change their shape in the generalization process.

In the course of such changes – especially in the context of typifications –, features may be moved or emphasized with the result that they cover areas on which they had no impact before. If there is a feature in such an area with which the generalized feature is not supposed to have a non-empty intersection, there is an overlap problem. Such a problem can be solved in several different ways: According to the relative relevance of the features, one of them may be moved, reduced in size (if possible) or omitted. Another approach is to restart the generalization of the feature of less importance with a constraint defining “no-go areas” in those locations that are occupied by parts of the more important ones. Combinations of these approaches and new ones can be tested in the optimization step or implemented directly for special situations.

Parent-induced problems occur if changes in the shape of the parent feature affect one of its child features. If a roof, for example, changes its shape from a mansard roof to a gabled roof, a dormer attached to it might end up “dangling” in the air. In other cases, it might be “drowned” below a “rising” roof surface. These problems can often be solved by a displacement of the child feature.

There are, however, cases that are more specific to special feature types: it may, for example, not be desired to keep dormers if a previously sloped roof is simplified to flat roof. In such a case, it must be decided in the harmonization step if the critical simplification step is not executed or the affected features can be changed or omitted. In order to deal with these specific conflicts, individual rules have to be specified in the harmonization component.

Difficult problems can occur if closely related features are required at different resolutions, especially if a subfeature is needed at a higher degree of accuracy than its parent feature – for example, special architectural details like gargoyles on the eaves of a cathedral’s roof. In order to resolve such conflicts, more complex measures may have to be taken. It can be necessary to retain those parts of the less detailed features that are in conflict with the more detailed one at the same level of detail.

In the further course of our research, representations for such “precompiled” models with the option of non-uniform resolutions are going to be developed together with strategies for their automatic construction from a given more detailed model.

5. CUSTOMIZATION

There are several different ways in which the model and the generalization process can be customized to meet the demands of an application.

The model can be extended by the definition of application-specific attributes for existing features. It is also possible to introduce user-defined feature classes either as subclasses of existing ones or as independent classes.

There are different ways in which all parts of the generalization process can be customized. The easiest way is to define varying target accuracies according to the relevance of the different features. For the distribution of resolutions over the features, a query language similar to the XQuery specification is going to be developed that allows the user to address parts of the feature tree – with the possibility to define filters based on features types, application data and geometrical relationships – and assign a target resolution to the features in the selection. This includes the possibility to force a set of features to be omitted or kept in the generalization process.

In principle, all parts of the generalization workflow can be changed to be better suited for a given application. In the course of the development of the model and the generalization components, the focus will be on the implementation of frameworks with configurable default procedures and the possibility to define custom procedures for those parts of the model or generalization where the application demands it – offering the developer the possibility to fall back on existing components at every step. Using such a mechanism, a developer may, for example, develop generalization processes for the generalization of building ensembles leaving the generalization procedures for features below the level of individual walls and above the one of building blocks to the standard component – or one developed by a colleague.

Additionally, different approaches for the control components of harmonization and optimization can be implemented and evaluated for different applications.

6. CONCLUSIONS AND OUTLOOK

In this paper, a process model for the generalization of semantically enhanced city models has been presented. In a proof-of-concept prototype, parts of the feature hierarchy and the process model for generalization have been implemented.

It has been motivated that rather because of than despite the potential for different interpretations of the same situation, explicitly semantics-based approaches are considerably more promising for generalization than more or less geometry-centered ones. For this reason, a stricter separation of the processes of feature extraction and generalization is postulated in order to facilitate the development of generalization algorithms that do not depend on specific geometrical representations of a model and to allow researchers to concentrate on generalization rather than feature extraction.

In the next steps, a default model for a wider range of feature types is going to be developed. For this model, the implementation of the process model is going to be extended to cover all components proposed in this paper.

7. ACHKNOWLEDGEMENT

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EXTENDING A PEDESTRIAN SIMULATION MODEL TO REAL-WORLD APPLICATIONS

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ABSTRACT:

Although recent advances in sensor technologies draw our attention to indoor spaces, no fully functional indoor 3D models are available as of now. Researchers in 3D modeling field have focused on representing 3D volumes using B-rep method and suggested different theoretical types of topological relationships. However, very few of them are related with explicit implementations for indoor spaces. Pedestrian evacuation simulation has been an active topic that targets scientific investigation of crowd behaviors in indoor areas. However, most simulations found in the related literature have been carried out using experimental settings without being linked to real-world applications. The purpose of our study is to propose a method to extend a pedestrian model to real world applications. First, we suggest a simplified 3D model that can be efficiently applied to indoor simulation and show how to build the model using a spatial DBMS. Then, we show a process to perform a pedestrian simulation using the proposed 3D model of a real campus building.

1. INTRODUCTION

While GPS-based outdoor LBS applications are becoming mature solutions, localization sensors such as RFID and UWB are drawing our attention to indoor spaces for navigation and facility management. However, compared to different technologies discussed widely for indoor applications, no fully functional implementations are available as of now. The primary reason is that indoor model is much more complex than outdoor model and indoor model has not been fully established yet.

Another reason is that indoor-related research efforts have been taken place in different academic communities. Pedestrian simulation (or crowd simulation) modeling area is a typical example that have not integrated with data modeling or real-world applications. The researchers in this area seek to investigate pedestrian behaviors in indoor environments. They are mostly devoted to developing scientific models that better explain pedestrian behaviors. Although there are some commercial evacuation simulators (e.g, EXODUS, SIMULEX), they are not related with real-time environment using indoor sensors.

In this study, we present a framework to extend pedestrian simulation models to real-world applications. For this, we see two problems as the most important factors that need to be resolved first; one is, we need proper indoor data model for simulation. Most data shown in pedestrian research are simple polygon types drawn either artificially or by CAD floor plans. To be able to use semantic information as shown in the outdoor LBS applications, we need similar topological data model for indoor spaces that can store semantic attributes. The other is, the data for indoor applications should be geo-referenced and stored in databases. Current commercial packages mostly use proprietary file-based data types. Such file-based data may suffice for the purpose of simulation or visualization in a single building. However, in order to deal with many buildings and communicate with real-time indoor localization sensors, building data should be stored in databases with real coordinates.

In this paper, we suggest a solution to above two problems. We propose a 3D indoor data model that can be adapted to pedestrian simulation models. The proposed model is less complex than those in theoretical 3D model research while retaining topological properties for semantic queries and computations. We show the process to build the data in a spatial database and apply it to a pedestrian simulation model. The simulation is illustrated using a campus building.

2. RELATED WORKS

Pedestrian navigation or evacuation problems in indoor spaces have been dealt with in different contexts and frameworks. Examples include those areas as architecture, cognitive science, robot navigation, indoor sensors and pedestrian behavior simulation. We will discuss them here in two viewpoints; data modeling and crowd simulation.

Indoor models are dealt with in different contexts in the recent studies (Becker et al. 2008, Hillier 1996, Kwan et al. 2005, Lorenz et al. 2006, Meijers et al. 2005, Pu et al. 2005, Tsetsos et al. 2005). While proposing the space syntax theory, Hillier (1996) used a linear structure called 'axial line' for computing indoor accessibility. Lorenz *et al*. (2006) suggested a hierarchically structured graph to support wayfinding. Tsetsos *et al*. (2005) introduced ontological concepts into the wayfinding and also used hierarchical graph. Becker *et al*. (2008) related their indoor model with sensor network by introducing connections between topographic and sensor layers. Some researchers (Kwan *et al*. 2005, Meijers *et al*. 2005, Pu *et al*. 2005) who are devoted to 3D data modelling applied indoor network structure to evacuation. With some variations, these studies shares similar properties in that they model indoor 3D spaces using reduced dimension for representing relationships and connectivity between spaces. For example, 3D rooms are represented using 2D polygons or cells, and then, they are reduced to one dimension graphs for the connection of those cells.

Although these models mentioned above are more focused on data models than on pedestrian behaviors, they can be largely categorized into macroscopic models in the perspective of behavior science. They primarily use node-link-based graphs as the data format. They consider pedestrians as a homogeneous group to be assigned to nodes or links for movements and do not take into account the individual interactions during the movement. Microscopic models emphasize individual agent's movement and their responses to other agents and physical environment such as walls and obstacles. Microscopic models are mainly based on simulation and use fine-grained grid cells as the base format for simulation. They have been used by experts in different domains including architectural design for the analytical purposes of the structural implications on the human movement especially in emergency situations.

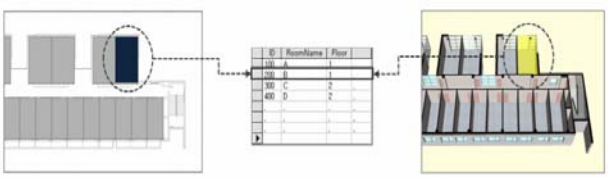
Different micro-simulation models have been proposed over the last decades (Schreckenberg 2001) and there is a growing interest to use cellular automata as the base of micro-simulation (Blue *et al*. 1999, Klupfel *et al*. 2002). Kirchner and colleagues (Kirchner *et al*. 2002) have proposed CA-based floor field model, where two kinds of fields—static and dynamic—are introduced to represent interactions of agents. The floor field model uses grid cells as the data structure and computes movement of an agent at each time step choosing the next destination among adjacent cells. This makes computer simulation very effective. In this paper, using Kirchner's model as our base model, we show how we applied our DBMS-based 3D data structure to cell-based pedestrian simulation.

3. FLOOR-BASED 3D INDOOR MODEL

In pedestrian simulation models, movements taking place on the floor surfaces in the building are concerned. Along with the floor surface geometry, some semantic information contained in exits and rooms are needed in computing simulation parameters which will be described in the next section. Thus, instead of using the complex topological relationships found in 3D data model literature, we can focus on the 2D floor surfaces with semantic information of them. 2D topological data structure has been already developed and become a well-known standard GIS format.

In our previous study (Park *et al*. 2007) we had proposed a file-based 2D-3D hybrid data model in order to realize both 2D topology and 3D visualization functionalities. We used two separate models, 2D GIS layers and 3D models, and combined them using a database table as the means of linkage.

First, we created 2D GIS layers (shapefiles) using CAD building floor plans. A 2D building floor was then decomposed into separated compartments and assigned IDs. Then, the IDs of layer's room polygons along with other attribute values such as owner's name and status of use are stored in a database table.



(a) 2D layer model (b) DB table (c) 3D model

Figure 1. Integrating a 2D-GIS floor layer and a 3D model

While polygons in GIS layers are inherently divided separately and topological relationships are defined between them, most 3D models used for the visualization of a building are not constructed such way.

Thus, we first had to model a 3D building by creating isolated spaces. Not only floors but all rooms in a floor are explicitly divided into individual spaces. Then, the same ID values of spaces as those corresponding spaces in the 2D GIS layer are assigned. Once both models are constructed following the process described in the above, each space from the two models now shares the identical IDs. Through the shared data table, spatial objects from both sides are synchronized together (Figure 1). Using this method, we were able to perform analyses and queries using the semantic information stored in 2D layers along with 3D visualization. Figure 2 shows a test routing simulation under a fire situation. The routing results computed from 2D layer attributes avoiding the fire spot are displayed in 2D and 3D.

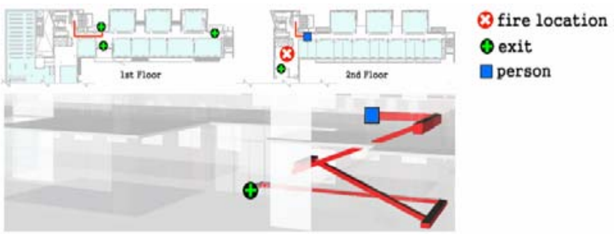


Figure 2. Evacuation routing simulation under emergency

Although this file-based approach was satisfactory in incorporating semantic and topological functionality into a 3D model, it has some drawbacks. First, two models are created separately and need additional table for linkage, which makes consistent maintenance difficult. Second, building a 3D model by separating compartments requires additional time and cost. Finally, such file-based models are not easy to store many buildings and, most importantly, they cannot be integrated with client/server applications such as sensor systems (i.e. RFID, UWB, thermal sensors).

To solve these problems in our previous study, we proposed a new approach in this study that uses a DBMS instead of files. Because semantic information is now extracted from database tables and used for analyses and 2D/3D visualization, the new model does not require an additional table for linkage. This data model has a multi-layered structure based on 2D building floor plans as the previous file-based model. It retains 2D topology because building floor plans are converted into 2D GIS layers (shapefiles) and then are stored in a spatial database. Thus, it is possible to perform topology-based analyses and operations provided by the DBMS. Also, all records containing geometries can be visualized for 2D and 3D.

Most simulations in pedestrian behavior research are carried out using simple 2D rectangles for the validation of models. However, in order to extend pedestrian simulation models to real-world 3D data, we also need a means to represent the connections between floors through stairs. Indoor navigation studies which were discussed in the previous section use graph structure for representing stairs. However, for the pedestrian simulation, stairs should also be treated as same grid cells as other room compartments. Figure 3 illustrates a simplified situation taken place in a 3D environment.

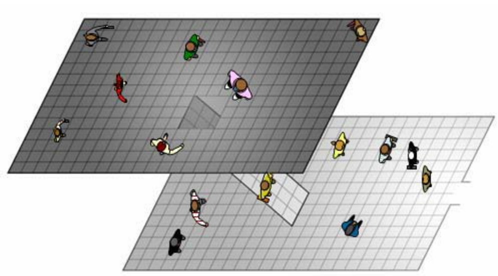


Figure 3. Pedestrian movement on 3D floor surfaces

For the connection of floors, we also converted the stairs to a simple set of connected polygons and then stored in the DBMS. Figure 4 illustrates the process for storing indoor objects in a database. This shows that we used only the bottom part of a room polyhedron.

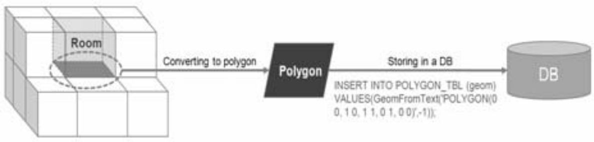


Figure 4. An example of storing rooms floors in a spatial DB

This approach can well fit in DBMS-based applications due to less complex and simplified data construction process. Using a DBMS against file format gives many merits including data sharing, management, security, back-up and speed. It is also possible to integrate with sensor systems by storing the sensor information in the database. In this study, we used PostgreSQL/PostGIS for the DBMS. PostgreSQL is an open source object-relational database system, freely downloadable. To display indoor objects in 3D stored in the database, we used OpenGL library and it also interacts with the PostGIS database for the data retrieval and visualization (Figure 5).

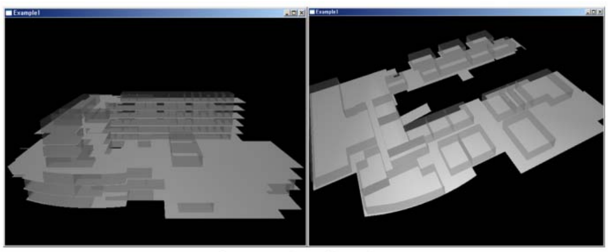


Figure 5. 3D visualization using data from a spatial DBMS

The pedestrian model that we have chosen to use in this study (described in the following section) uses grid cells as the base data format. Thus, in order to apply 3D data stored in the DB to pedestrian simulation, we should first convert the floor plan data of vector type into grid cells. Figure 6 illustrates the data processing for converting the queried polygon geometry to grid cells.

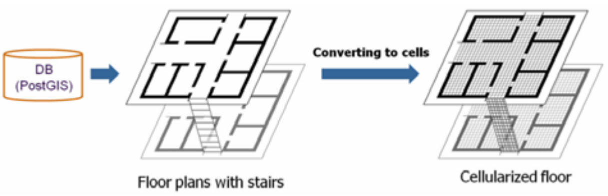


Figure 6. Converting floor plans read from DB to grid cells

4. EXTENDED PEDESTRIAN SIMULATION MODEL

Among different micro-pedestrian models, two approaches are getting attention; social force model and floor field model. A frequently cited model of former type is advanced by Helbing and collegues (Helbing *et al*. 1997, 2001) and is based on strong mathematical calculation acted on agents to determine its movement to destination (e.g. exits). Helbing's model considers the effects of each agent upon all other agents and physical environment (Figure 7) leading to the computation of $O(n^2)$ complexity, which is unfavorable for computer-based simulation with many agents (Henein *et al*. 2005, 2007).

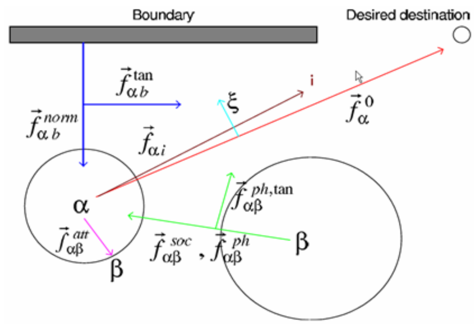


Figure 7. Helbing's social force model

On the other hand, Kirchner and colleagues (Kirchner *et al*. 2002) proposed the floor field model that uses computationally more efficient cellular automata (CA) approach. In his model, local movement rules that only consider adjacent cells are defined to translate Helbing's long-ranged interaction of agents into a local interaction. Although this model considers only local interactions, they showed that the resulting global phenomena share properties from the social force model such as lane formation, oscillations at bottlenecks, and fast-is-slower effects.

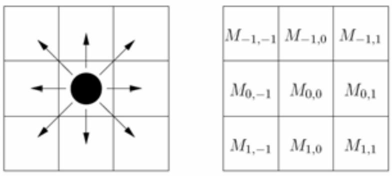


Figure 8. An agent and its possible transition (Schadschneider 2001)

The basic data structure of Kirchner model is grid cells and each cell represents the position of an agent and contains two types of numeric values which the agent consults to move. These values are stored in two layers; *static field* and *dynamic field*. A cell in the static field indicates the shortest distance to an exit. An agent is in position to know the direction to the nearest exit by these values of its nearby cells.

While the static field has fixed values computed by the physical distance, the dynamic field stores dynamically changing values indicating agents' virtual traces left as they move along their paths. As an ant uses its pheromone for mating (Bonabeau 1999), the dynamic field is similarly modeled where an agent diffuses its influence and gradually diminishes it as it moves. Without having direct knowledge of where other agents are, it can follow other nearby agents by consulting dynamic values.

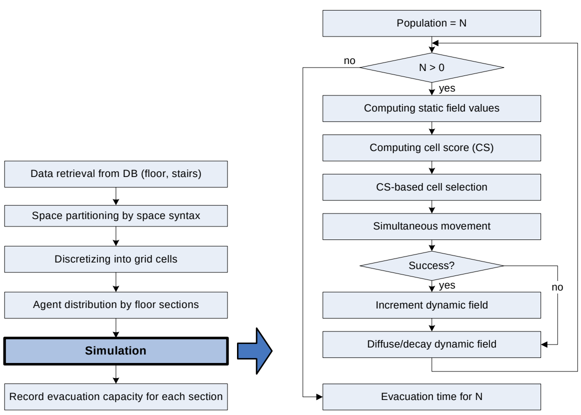
It is possible to simulate different pedestrian strategies by varying the degree to which an agent is sensitive to static or dynamic field (k_s and k_d in Eq. (1)). For example, we can model herding behaviors in panic situation by increasing sensitivity to the dynamic field. Each agent can move to adjacent nine cells including itself at each time step $t \rightarrow t+1$ according to probabilities p_{ij}, which is the normalization of the following score.

$$Score(i) = exp(k_d D_i) \times exp(k_s S_i) \times \xi_i \times \eta_i \qquad (1)$$

where,

$Score(i)$: the score at cell i
D_i : the value of the dynamic field in cell i
S_i : the value of the static field in cell i
k_d and k_s : scaling parameters governing the degree to which an agent is sensitive to dynamic or static field respectively
ξ_i : 0 for forbidden cells (e.g. walls, obstacles) and 1 otherwise
η_i : 0 if an agent is on the cell, and 1 otherwise.

Based on the formula (1), we revised the 'diffuse & decay' rule of the dynamic field value D_i. We will not discuss how we improved the rule here since the focus is not on the pedestrian model in this paper. Instead, we will briefly describe how our data model has been applied to the model followed by some test results with visualization of the developed simulator.
Floor plan data are first read in from PostGIS DB, and then go through celluarization process for the simulation. The polygon geometry data along with stair cases also in the form of polygons are discretized into cells of size 40cm×40cm considering the human shoulder widths. Not only the geometry data but also semantic information such as exits, rooms and other obstacles is retrieved from the database. For example, exits are used in computing the static field value of each cell, which is the shortest distance from the nearest exit. In the simulation, we randomly located varying number of pedestrians. In real situations, the random data may be replaced with the real pedestrians acquired by location sensors. Figure 9-(a) shows the process from data retrieval, space partitioning to simulation, and (b) shows the update rules in the simulation. Having decided which cells to move based on the score described in (1), all agents move simultaneously and increment dynamic value. Among any agents competing for a cell, only one is selected randomly for no two agents can occupy one cell. Dynamic field value, D_i is, then, diffused and decayed.



(a) (b)
Figure 9. Processes from data retrieval to simulation

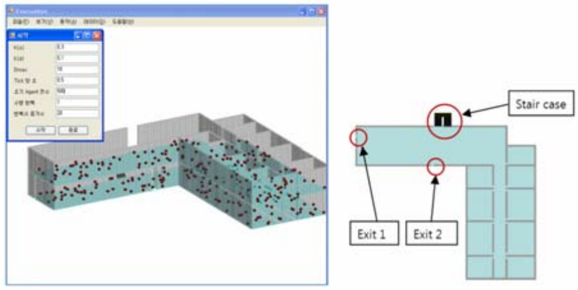
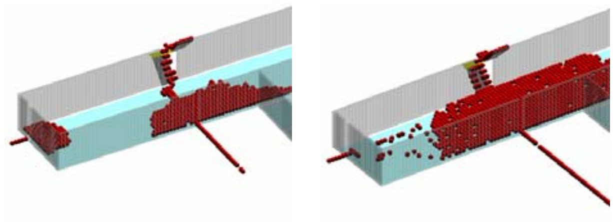


Figure 10. A snapshot of evacuation simulation with a 3D view

Figure 10 shows a 2D and a 3D view of the simulator. In order to implement 3D visualization, we used OpenGL and developed the simulator using C# language. The retrieved geometry information along with stairs was used for rendering in OpenGL and vertical walls were also displayed using the height values stored in the database.
We carried out simulations by varying the parameters k_d and k_s. $k_d = 0$ causes the agents flow directly towards exits without any herding behaviors while $k_s = 0$ makes them wander around without any clue of direction to exits. Figure 11 shows that $k_d > 0$ begins to show the herding behaviors following other agents to the second exit (Exit 1). Table 1 shows the effect of k_d on the evacuation time and the use rate of the second exit. 2000 agents were used for the test. We observed that the use rate of the side exit gets increased in proportion to k_d.



(a) $k_d = 0$ (b) $k_d/k_s = 0.5$
Figure 11. The effect of varying k_d

	k_d=0	k_d=0.05	k_d=0.1	k_d=0.25	k_d=0.5	k_d=1.0
Exit1	120	351	422	484	566	689
Exit2	1880	1649	1578	1516	1434	1311
evactime	945	723	702	688	670	632

Table 1. The effect of varying k_d on evacuation time and use of the side exit

5. CONLCUDING REMARKS

Real-time indoor LBS using localization sensors require proper indoor data model that can be implemented in DBMS. A pedestrian simulation model has been chosen as an application that can take advantage of such real-time environment. The issues that need to be solved beforehand were data model and DBMS implementation. Focusing on the fact that pedestrian models investigate movements taking place on the floor surfaces and use information obtainable from the surfaces, we suggested a less complex 3D indoor model that can be applied to pedestrian simulation. We showed the building process of this model in a DBMS.

We used the floor field model as the pedestrian model because it has shown efficiency in computation and flexibility of adjusting behavioral parameters. We showed how our model is applied to the floor field model and also improved its diffusion and decay rule so that it can be better fit in real 3D environment. Using a simple two-story campus building, we carried out some simulations by varying parameters.
Since the primary purpose of this study was not the scientific improvement of simulation model, we have not described evidence of our improvement. Considerable work remains in the development of our system. The model needs to be tested and calibrated in different real-world data. Also it needs to be tested in conjunction with localization sensors.

ACKNOWLEDGEMENTS

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TOWARDS SEMANTICALLY ENRICHED 3D CITY MODELS : AN ONTOLOGY-BASED APPROACH

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KEY WORDS: ontologies, interoperability, CityGML, urban information modelling, urban models

ABSTRACT:

Various urban models have been developed and are used in the urban domain, to perform for example air quality calculation, building energy consumption analysis or traffic simulation. The use of urban models, particularly 3D city models representing the structure of a city in three dimensions, is increasing in urban planning. The consequence of an integrated approach is the joint use of different models, most of the time in an interconnected way able to model the urban issues together with their inter-relations. 3D city models play a central role in this approach since the knowledge related to different urban issues and models can be integrated within or interconnected with 3D models. This approach leads to semantically enriched 3D city models that are well suited to decision support. Those models can also be used for a 3D visualisation of this knowledge. It is generally agreed that ontology-based approaches can provide a generic and robust way to interconnect and integrate different models. In a certain number of cases, it is necessary to take into consideration the possibility of computations involved in the correspondences between concepts. In this paper, we will focus on the description and the role of ontology-based approaches, considered as a powerful tool to improve the interoperability of the different types of urban models.

1. INTRODUCTION

Various urban models have been developed and are used in the urban domain, to perform for example air quality calculation, building energy consumption analysis or traffic simulation. 3D city models representing the structure of a city in three dimensions are special urban models derived from 3D GIS (3 Dimensional Geographic Information Systems). The use of urban models, particularly 3D city models, is increasing in urban planning. Besides, the current trend in city models is the use of "rich" models, offering more than a mere representation of usual concepts. Recent city models, such as CityGML are not purely geometric: in addition to geometric information about city objects (each object being associated with a geometry made of basic geometric objects like polygons, points, lines, etc.) those models provide a general classification of objects (building, water body, road, street, etc.) as well as non-geometric attributes like function, address, etc.
The objective of this paper is to present an ontology-based model contributing to define semantically enriched 3D city models. The first part of the paper will give an overview of urban information models and present the specificity of this kind of information. In the second part, we will present the notion of ontology and the application of ontologies to the management of the diversity and the complexity of urban information and knowledge.
As ontologies provide the basic concepts for powerful approaches facilitating the interoperability of urban models we will present in the last section some developments related to the urban field, that can be considered as the first steps towards semantically enriched 3D city models.

2. URBAN INFORMATION MODELS

According to the point of view and the purpose, the same reality can be expressed through different models: for example a physical or a numerical mock-up, an information model associated with geo-data or a mathematical model of processes represented through differential equations, as shown in Figure 1 below (from a personal discussion with Professor François Golay from EPFL, Lausanne, Switzerland).
The term *urban model* is usually related to simplifications and abstractions of real cities, in contrast to its earlier usage referring to ideal cities (Foot, 1981). Today, accurate models can be used to perform, for example, urban simulations (Waddell and Ulfarsson, 2004), building energy consumption analysis (Jones et al, 2000), water quality calculation (Kianirad et al, 2006) or air quality estimation (Moussiopoulos et al, 2006; Borrego et al, 2006).
According to Foot (1981), urban models:
- are used to evaluate the effects of changes in relation to certain land-use activities (such as residential or industrial development), transport network, etc.;
- mainly relate to spatial aspects of the urban system although they attempt to estimate the spatial consequences of changes in non-spatial variables.

Air quality models, for example, are associated with complex processes taking into account many parameters related to pollutant sources, prevailing wind, or the configuration of the streets and buildings.
Different 3D city models have been or are developed all around the world, with an intended wide range of applications such as planning and design, infrastructures and facility services, marketing or promotion (Shiode, 2001). According to the same authors, 3D city models differ by elements such as their degree of reality, i.e. the amount of geometric details that are represented, their data acquisition methods and their functionality, i.e. the degree of utility and analytical features that they allow.

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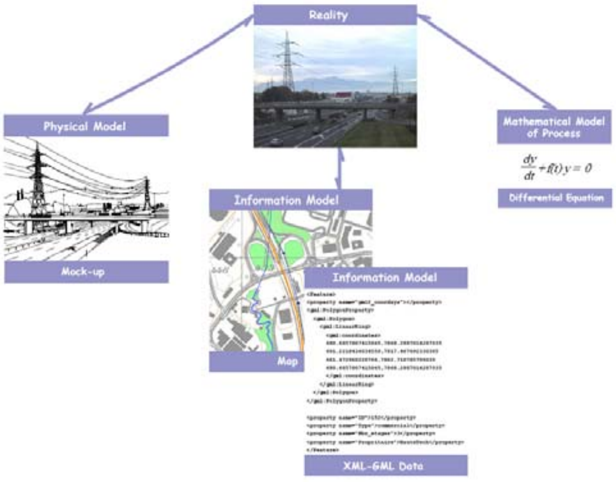

Figure 1. Different models of different types for the same reality

CityGML (OGC 08-007, 2008) is a unified model for the representation of 3D city models based on the standard GML3 of the Open Geospatial Consortium ; it is an open information model for the representation and exchange of virtual 3D city models on an international level. Urban objects (relief, buildings, vegetation, waterbodies, transportation facilities, city furniture) are represented in CityGML by features with geometric, topological and thematic properties. CityGML does not only represent the graphical appearance of city models but also contains semantic representations for thematic properties, taxonomies and aggregations of digital terrain models, sites (including buildings, bridges, tunnels), vegetation, water bodies, transportation facilities and city infrastructure. The underlying model differentiates five consecutive levels of detail (LoD), where objects become more detailed with increasing LoD for both geometry and thematic differentiation (Kolbe et al, 2005). Applied to buildings, for example, they do not exist at LoD0 as this LoD defines a coarse regional model. They exist as extruded blocks at LoD1, with their roof at LoD2, with more detailed roofs and façades at LoD3 and with their interior at LoD4. The LoD are different from what can be obtained by texturing the model in terms of visual aspect only.

Although urban models are considered as decision-making tools, they most of the time relate to one domain at the same time, such as transportation, air quality or building energy consumption, or to the physical aspects of the city as in 3D city models. Urban models could benefit from data and information coming from various domains taken into account at the same time, through a kind of "multiple inheritance", thus making this information directly available within 3D city models while providing results which could, in turn, be used and visualised through city models. As urban issues are interrelated in the real world, the interconnection of urban models can be considered as reflecting the reality more precisely. This approach would also allow urban actors to explore and to plan the city in a more global way.

In the next sections of this paper, and on the basis of case studies related to the urban domain, we will show how domain ontologies can provide a robust and reusable method to interconnect urban models and so to contribute to the semantic enrichment of urban models. Further, the use of ontology-based representations enable the development of consistency checking and reasoning features.

3. ONTOLOGIES

In the field of Artificial Intelligence several definitions of the term "ontology" have been given. According to Gruber an ontology is an "explicit specification of a conceptualization" (Gruber, 1993). A slightly different definition is "a formal, explicit specification of a shared conceptualisation" (Studer et al, 1998). A conceptualization is an abstract, simplified view of some domain that we wish to represent for some purpose, i.e. the objects, concepts and other entities that are assumed to exist in some area of interest and the relationships that hold among them. "Formal" means that some representation language have been used and so that the ontology is machine-readable. "Explicit" means that both the type of concepts used and the constraints on their use have been defined (Benjamins et al. 1998). "Shared" refers to a common understanding of some domain that can be communicated across people and computers (Studer et al, 1998).

Studies have been performed in the geographic domain which is closely related to the urban domain. Thus, following Anselin (1989) and Egenhofer (1993), the author asks a good question, about the specificity of the geographic and urban world: "What is special about spatial?". To adequately represent the geographic world, we must have computer representations capable of not only capturing descriptive attributes about its concepts, but also capable of describing the geometrical and positional components of these concepts. These representations also need to capture the spatial and temporal relationships between instances of these concepts. For example, in order to represent a public transportation system, the application ontology must contain concepts such as *street, neighborhood, bus stop,* and *timetable.* The computer representation of the transportation system has to recognize relationships such as "this bus line crosses these neighborhoods", "there is a bus stop near the corner of these streets" and "the bus stops at this location at 1:00 pm". Unlike the case of conventional information systems, most of these spatial and temporal relationships are not explicitly represented in a GIS, and can often be deduced using geographic functions.

Fikes and Farquhar (1999) consider that ontologies can be used as building block components of conceptual schemas. Fonseca (2003) agrees with Cui et al (2002) in that there is a main difference between an ontology and a conceptual schema: they are built with different purposes. While an ontology describes a specific domain, a conceptual schema is created to describe the contents of a database. Bishr and Kuhn (2000) consider that an ontology is external to information systems and is a specification of possible worlds, while a conceptual schema is internal to information systems and is chosen as the specification of one possible world.

Interconnection of urban models is made possible through an ontology-based approach. The general methodology can be summarized in the following way:

- representing as ontologies (i.e. to formally represent the underlying knowledge of) the resources to integrate or to interconnect;
- interconnecting these ontologies, what is generally not a trivial task since it is necessary to fill in the semantic gap between the source ontologies.

The following section presents the approach, on the basis of real case studies. A first part explains the way of creating the ontologies while the second part focuses on the articulation between the resulting ontologies.

4. TOWARDS SEMANTICALLY ENRICHED 3D CITY MODELS

Research and practice in the field of ontologies showed that the construction of an ontology is a complex task requiring not only a great knowledge of the field to be described but also a control of the structuring of the concepts using formal languages. During the last years several approaches and tools have been developed to do these concept extractions automatically or semi-automatically. For instance Stojanovic (2002) and Astrova (2004) propose techniques to extract ontologies from relational database schemas, while Velardi et al (2001) use text analysis technique to help in the construction of ontologies. At the same time, several languages have been developed to formalize ontologies, those being based primarily on predicate logic, on frames or on descriptive logic. The most recent works concern the language OWL which is a recommendation of the consortium W3C within the framework of the "semantic Web". New tools and new methods for analysis of ontologies are under development (Corcho et al, 2003).

4.1 Creation of the ontologies

In this section, we will briefly describe some domain ontologies related to urban models, with their main features and specificities.

Ontology of CityGML

CityGML defines the most relevant features in cities and regional models with respect to their geometrical, topological, semantical, and appearance properties. Thus we have: the terrain (named as *Relief Feature*), the coverage by land use objects (named as *Land Use*), transportation (both graph structures and 3D surface data), vegetation (solitary objects, areas and volumes, with vegetation classification), water objects (volumes and surfaces), sites (in particular buildings; bridge, tunnel, excavation or embankment in the future), *City Furniture* (for fixed object such as traffic lights, traffic signs, benches or bus stops).

CityGML has been defined as classes and relations in UML, the Unified Modeling Language (UML). Figure 2 shows a part of the UML diagram of CityGML.

A *TransportationComplex* is a particular kind of *TransportationObject* (which is itself a particular kind of *CityObject*) and is subdivided thematically into *TrafficArea* (representing the areas used for the traffic of cars, trains, public transport, airplanes, bicycles or pedestrians) and *AuxiliaryTrafficArea* (associated with grass for example). In fact, a *TransportationComplex* is composed of *TrafficAreas* and *AuxiliaryTrafficAreas*. Defining the ontology of CityGML is thus relatively easy:

- UML classes will be translated into concepts;
- associations/roles will be translated into semantic relations; association cardinalities will be expressed as restrictions relatively to relations;
- aggregation/composition will be expressed as “part of” links;
- generalisation will be expressed as “is a” links (with the meaning of subconcept);
- UML attributes will be translated either into concept attributes or into relations between concepts.

Figure 3 below shows this UML diagram (without the part corresponding to the geometry) in an ontological form.

Here are some examples to illustrate the way according which attributes have been translated:

- function as a relation between TransportationComplex and TransportationComplexFunctionType itself defined as a concept;
- *surfaceMaterial* also as a relation between the concepts T*rafficArea* and *TrafficSurfaceMaterialType* but with the following restriction: a *TrafficArea* has at most one *TrafficSurfaceMaterialType*.

Ontology of Urban Planning Process (OUPP)

The ontology of urban planning process (OUPP) is still under development at the University of Geneva. In this paper we describe the part of OUPP related to soft mobility aspects. Soft mobility refers to all ways of travelling by muscular motion. To define this ontology we have used the method proposed by Uschold and King (1995) extended by Uschold and Gruninger (1996). This method is composed of four phases: (1) identify the purpose of the ontology, (2) build it, (3) evaluate it, (4) document it.

Phase 1. Identification of the purpose and the scope of the ontology

In this phase we have to answer questions such as: For which purpose is the ontology built? What are its intended uses?

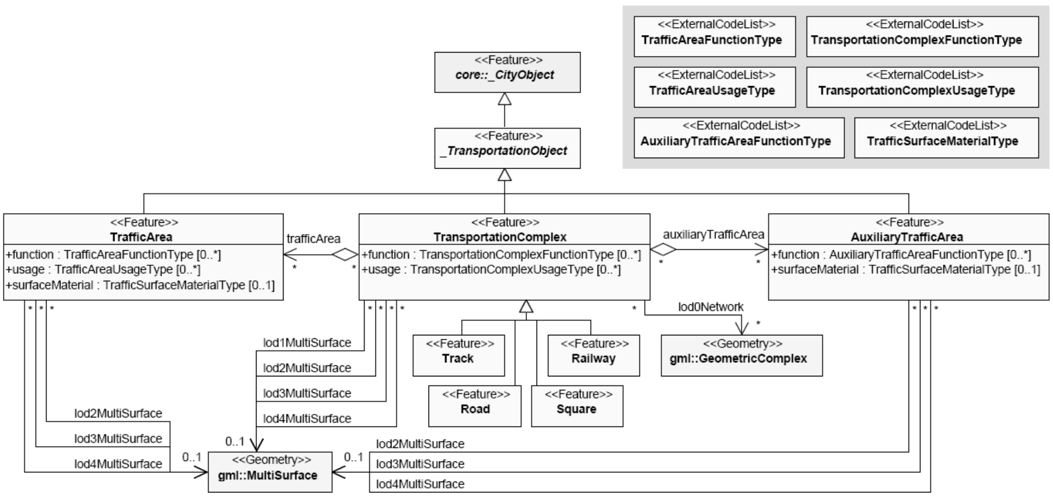

Figure 2. Part of the UML diagram of the Transportation feature of CityGML
Legend: Prefixes are used to indicate XML namespaces associated with model elements
Element names without a prefix are defined within the CityGML Transportation module

In our case the purpose is to promote soft mobility. The legal aspects (which are important to urban planners or politicians) will not be described in this paper in order to focus on some aspects such as the duration of travelling for a kind of user (as these aspects seem questioning to many potential users) or the appealing character of some paths (promenades, for example, and particularly promenades through parks). So the relevant terms to be put in the ontology include: *Duration* (of a travel), *Type_of_user* (Cyclist, Pedestrian, etc.).

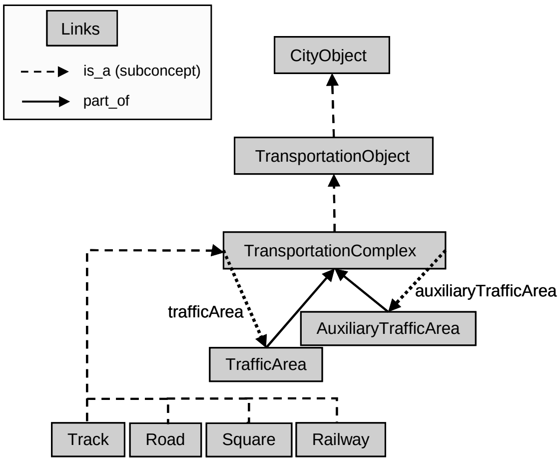

Figure 3. Part of the ontology of the Transportation feature of CityGML

Phase 2. Construction of the ontology
This phase is broken down into three parts: ontology capture, ontology coding and integration of existing ontologies (if any) into the current one.

Phase 2a. Ontology capture
This means identifying key concepts and relationships that will represent the knowledge of the domain of interest, then define them precisely and unambiguously. The knowledge can originate from experts of the domain, text mining, meta-data of databases, etc. In this case study, various documents and data related to soft mobility were mainly used. The knowledge thus extracted has to be structured. Textual definitions have to be defined by referring to other terms and including notions such as class, relation, etc. To perform this task, Uschold and Gruninger (1996) recommend the middle-out strategy, namely identifying first the core of basic terms, then specifying and generalizing them as required. In this case study, what has been identified first includes: *Type_of_user* which is a class; *Duration* which is a class and is defined by a *Value* for a particular *Type_of_user* and a particular *Section*.
Then, the top and the bottom concepts of these core concepts have been defined: the bottom concepts of *Type_of_user* are *Cyclist* and *Pedestrian*; a *Section* is ended by a *Junction* at each extremity and is part of a *Route*.
Then the different kinds of *Routes* (*Cycle_route*, *Pedestrian_route*, etc.) and the different kinds of *Junctions* (*Crossing*, *Stop*, etc.) have been defined.

Phase 2b. Ontology coding
As quoted by Gomez-Perez et al (2004) this phase means (a) committing to basic terms that will be used to specify the classes, relations, entities and (b) writing the code in a formal representation language. The Figure 4 below shows as a graph the ontology defined for representing soft mobility aspects within OUPP.

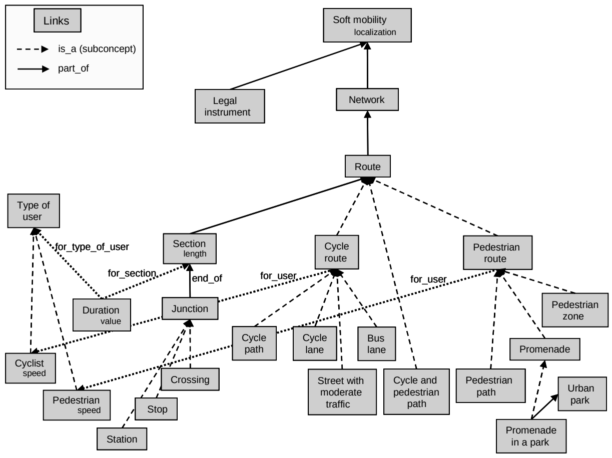

Figure 4. Part of OUPP related to soft mobility aspects

Phase 2c. Integration of existing ontologies
This optional phase deals with the identification of ontologies that already exist in the domain and their evaluation in order to be able to say to which extent they can (or cannot) be reused. This phase can be achieved in parallel with the previous phases. In our case study, an Ontology for Transportation Systems (OTN) was identified (Lorenz et al, 2005). In fact, OTN describes various transportation aspects but nothing related to soft mobility. So re-using OTN is not pertinent for creating an ontology of soft mobility but it can be useful for extending this ontology to other transportation issues such as public transport for example as this issue is represented within OTN.

Phase 3. Evaluation of the ontology
This evaluation has to be made in a pragmatic way to determine the adequacy between the ontology and the concerned application. The criteria include the following: consistency, completeness, concision (no redundancy, good degree of granularity), etc. As this case study aims at defining an ontology-based model for promoting soft mobility for the inhabitants, the evaluation phase should include usability tests with end-users.

Phase 4. Documentation of the ontology
This documentation can differ according to the type and purpose of the ontology. It means producing definitions (formal, non formal) to specify the meaning of the terms of the ontology, giving examples, etc. It can also include naming conventions such as the use of upper or lowercase letters to name the terms.
In this case study, the names of the classes begin with uppercase letters while the names of the properties begin with lowercase letters. Work on a knowledge base composed of the source documents associated with the ontology is on-going. All these ontologies have been coded into OWL using the Protégé editor.

Ontology of Air Quality Model
Air quality models are important tools to study, understand and predict air pollution levels. One of the main air quality problems at the scale of the city is related to the street canyons retaining pollutants. That is while our case study focuses on street canyon models. Many street canyon models have been defined. While most of them are two-dimensional models such as (Baik & Kim, 1999; Huang et al, 2000), there exists some three-dimensional models such as (Kim & Baik, 2004; Santiago et al, 2007).

Although different, these models show some common characteristics.
Their input parameters are:
- the pollutant source characteristics (source location, emitted product, etc.);
- the meteorological conditions, mainly the prevailing wind conditions (speed, direction related to the street canyon, etc.) but also, to some extent, the thermal conditions (solar heating);
- the street canyon geometry**,** in particular its aspect ratios such as height-to-width ratio, height-to-height ratio or its orientation with respect to the ambient wind.

Their output parameters are:
- a flow mainly characterized by its vortices (associated to an intensity, a rotation direction, a location, etc.);
- a pollutant dispersion distribution.

An ontology has been defined according to the same method as for OUPP. Figure 5 below shows it in a graph form.

4.2 Interconnection of the ontologies

In simple cases, concepts of the two ontologies can be directly connected together while more complex cases require an articulation or a link between the two ontologies (Mitra et al, 2000; Métral et al, 2008).
In this paper, we will limit the presentation to the interconnection of simple cases.

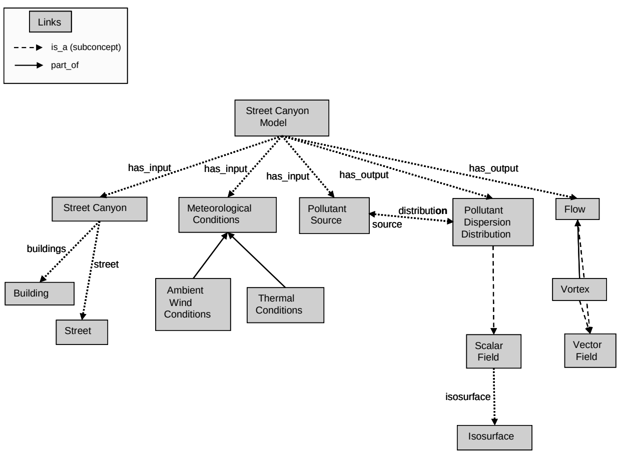

Figure 5. Part of the Ontology of a Street Canyon Model

The direct interconnection of ontologies can be done either through an equivalence link or through an inclusion link. Figure 6 below shows such an example of a direct interconnection.

The concept *Route* of OUPP is similar to the concept *Route* of OTN. The only difference relies on the context: *soft mobility* for OUPP and *public transport* for OTN. The concepts *Section* (OUPP) and *Route_Section* (OTN) are also similar: the difference here is that a *Route_Section* is oriented while a *Section* is not. A *Junction* (OUPP) is also similar to a *Stop_Point* (OTN) while being more general. Similarly, a *Section* (OUPP) is similar to a *TrafficArea* (CityGML) which is more general as it is related to all kinds of transport. As features of CityGML are related to a geometry, these interconnections make possible the representation within 3D city models of the instances associated with the concepts of OUPP or OTN.

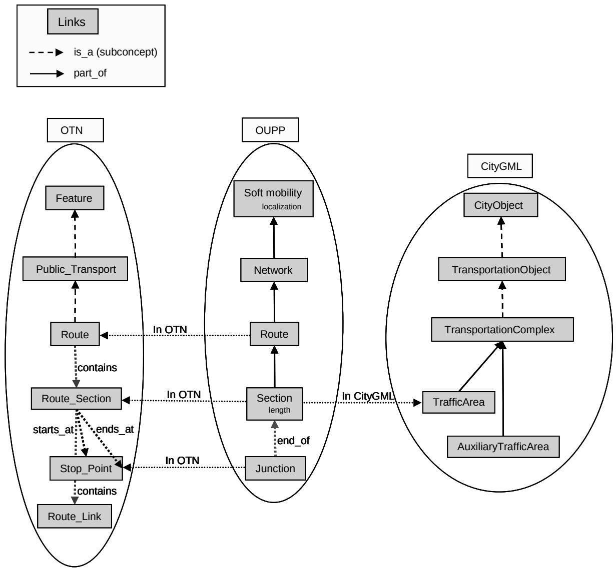

Figure 6. Direct interconnection of ontologies

5. CONCLUSION AND PERSPECTIVES

Integrating or interconnecting urban data or information is crucial, even when focusing on a single issue. A disaster management, a flood for example, requires information not only about the levels of water but also about the height of terrain and of city objects (buildings, tunnels, bridges, etc.) in order to determine which objects are affected and to which extent. These data and information can originate from different services of the same city or from different neighbouring cities but have to be interpreted, inter-related or integrated in order to manage the disaster in a global way.
After a short comparison of model-based and ontology-based approaches, an ontology-based approach has been described to interconnect urban models and information in a perspective of semantic enrichment of those models. With such interconnections it is now possible:
- to promote soft mobility by users: indeed, with the interconnection of CityGML, OUPP and OTN, it is possible to visualize in 3D soft mobility routes or routes accessible partly by foot and partly with public transportation systems;
- to compute the duration of a particular route for a type of user (Métral et al, 2009);
- to visualize, within 3D city models based on CityGML, the pollution induced by vehicle traffic in street canyons;
- to identify the best positioning of a sidewalk or a cycle path, for example;
- to visualize, within 3D city models based on CityGML, the decrease of pollution induced by the travelling of n vehicles replaced by soft mobility travelling.

The approach presented in this paper can be used for analysing multiple interconnections of urban models, for example transportation or building energy consumption models. It also enables the development of consistency checking and reasoning features that are particularly helpful when dealing with large models.
It is the first step towards what can be called semantically enriched 3D city models, with an improved semantics and thus an improved adequacy to urban planning purpose. This research work is the subject of a new COST Research Action, about semantic enrichment of 3D city models (TU0801, 2008).

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CONCEPTUAL REQUIREMENTS FOR THE AUTOMATIC RECONSTRUCTION OF BUILDING INFORMATION MODELS FROM UNINTERPRETED 3D MODELS

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ABSTRACT:

A multitude of new applications is quickly emerging in the field of Building Information Models (BIM). BIM models describe buildings with respect to their spatial and especially semantic and thematic characteristics. Since BIM models are manually created during the planning and construction phase, they are only available for newly planned or recently constructed buildings. In order to apply the new applications to already existing buildings, methods for the acquisition of BIM models for built-up sites are required. Primary data source are 3D geometry models obtained from surveying, CAD, or computer graphics. Automation of this process is highly desirable, but faces a range of specific problems setting the bar very high for a reconstruction process. This paper discusses these problems and identifies consequential requirements on reconstruction methods. Above, a two-step strategy for BIM model reconstruction is proposed which incorporates CityGML as an intermediate layer between 3D graphics models and IFC/BIM models.

1. INTRODUCTION / MOTIVATION

Building Information Models (BIM) describe buildings with respect to their geometry, topology, and semantic information about all their components. Especially the logical structure and well-defined meaning of the objects are crucial prerequisites for applications which go beyond pure visualization. These application areas include facility management, environmental and energy simulation, urban planning, architecture, civil engineering, and disaster management. The introduction of the US national BIM standard (NBIMS), which itself is based on the ISO standard IFC, lead to a major boost in the development of new applications and software systems. It can be expected that in the future many more applications, owners, and stakeholders will make use and rely on these semantically rich 3D models.

Although BIM models can (and will) be maintained during the entire existence of a building, they are generally only available for newly planned and recently constructed buildings. The reason is that they are manually created by the architects or civil engineers in the planning phase. In order to be able to employ the new BIM applications with existing buildings, BIM models have to be acquired for already built-up sites. This, however, is difficult because the BIM paradigm relies on a component based modelling consisting of walls, slabs, beams, stairs, pipes etc. These components are generally not fully visible or observable in an existing construction. Many elements even will be hidden totally. By using surveying technology like total stations and terrestrial/airborne laser scanners or techniques from photogrammetry, the 3D geometry can be reconstructed to a certain extent. However, only the visible surfaces are registered. This means that neither hidden parts nor the meaning of the surfaces or their belonging to specific object types are acquired. The same situation applies for the multitude of 3D models that are created within CAD and computer graphics systems like Google Sketchup or Autodesk's 3D Studio Max. These models generally consist of geometry and appearance information, but do not represent thematic information and the meaning of the objects. Thus, they also cannot be used for BIM applications.

As a consequence, 3D geometry or graphics models have to be interpreted, modified, and extended to become BIM models. Today, the acquisition of BIM models from observed or modelled 3D geometries is mostly done manually. The automation of this process would reduce efforts and costs substantially. However, automatic reconstruction of semantic building models is known to be a difficult problem that has been investigated by many groups over the last 25 years – with limited success so far. The main reasons result from the high demands on the reconstruction process regarding 1) the definition of a target model which restricts object configurations to sensible building structures and their components, but which is still flexible enough to cover (nearly) all existing buildings in reality; 2) the complexity of input data and reconstructed models; 3) data errors and inaccuracies, uncertainty and ambiguities in interpretation; 4) the reduction of the search space during the interpretation process. It is the purpose of this paper to present and discuss these requirements in more detail and indicate the consequences for any reconstruction process. Furthermore, we propose a two-step reconstruction strategy, which incorporates the OGC standard CityGML as an intermediate layer during the interpretation and final generation of BIM models.

2. TWO-STAGE RECONSTRUCTION PROCESS

The starting point of the proposed reconstruction process is pure 3D geometry/graphics models which can be obtained from different sources (cf. fig. 1). On the one hand, these models may be the result of manual design (CAD, computer graphics software). On the other hand, they may be derived from observations and measurements of topographic features in the field of photogrammetry and surveying (cf. fig. 1). Such models mostly result from registration methods for geometry along with methods for data segmentation and 3D geometry reconstruction. Substantial work has already been done in this area and both semi-automatic and automatic systems for 3D geometry reconstruction are available (cf. discussion in Baltsavias, 2003).

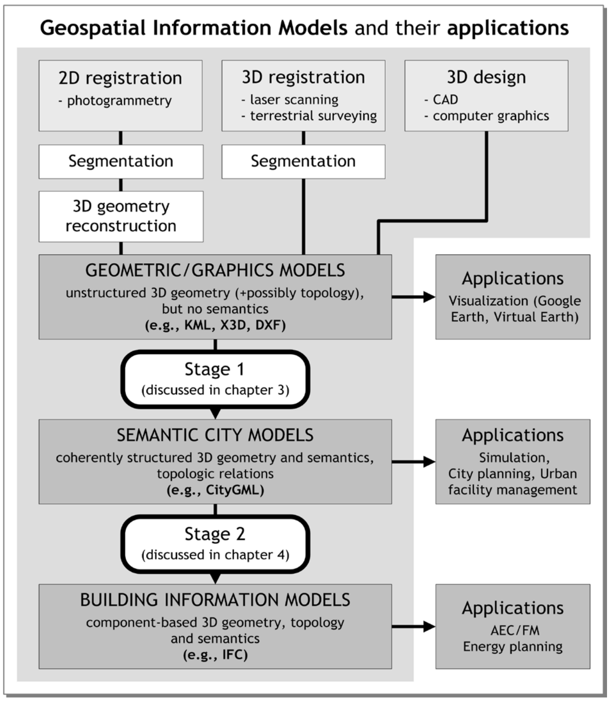

Figure 1. Two-stage reconstruction process.

The extracted geometry typically represents the observable surfaces of the topographic features which may range from simple blocks models to complex polyhedral structures depending on the level of detail. The resulting models can comprise additional geometric-topological relations and appearance information. However, they often contain no or just little semantics. The models are suited for visualization purposes in applications such as earth browsers or as input for further data interpretation. They usually base on well-known 3D graphics formats like X3D, DXF, KML, and COLLADA.

The automatic reconstruction of BIM models from 3D geometry models faces a high level of complexity. BIM models represent the built environment as designed rather than observed (Kolbe & Plümer, 2004). They geometrically describe thematic building components as volumetric primitives instead of individual surfaces. Thus, the reconstruction requires the identification and semantic classification of surfaces within the geometry model forming a building element. This is strongly impeded by the fact that geometry models mostly contain unstructured and uninterpreted geometry (“polygon soup”).

In order to reduce the complexity of the overall reconstruction process, we propose its decomposition into two individual subproblems (cf. fig. 1). In a first step, the 3D geometry models are further interpreted in order to structure the geometry and to enrich the models with semantic information which has to go beyond plain semantic tagging of surfaces (Pittarello & de Faveri, 2006). What is needed are spatio-semantically coherent models in such that all semantic components correlate to their geometric counterpart (Stadler & Kolbe, 2007). We choose CityGML as target model for this interpretation stage. CityGML is an international OGC standard for semantic 3D city models which provides a common information model for the representation of topographic features (Gröger et al., 2008). Since it is used to record observable objects it is much ‘closer’ to surveying and photogrammetric registration methods than BIM. CityGML employs a surface based representation of geometry similar to 3D graphics models which simplifies the interpretation process. Moreover, CityGML already provides an elaborate ontology of the exterior and interior built environment.

In a second step, CityGML models are used as input data for the reconstruction of IFC models (cf. fig. 1). Although CityGML and IFC are targeting different scales and the ontology of each semantic model is tailored to different scopes, both models agree to a great extent in the notion of a building and its semantic decomposition (Benner et al., 2005; Isikdag & Zlatanova, 2009). By using the explicit CityGML semantics as a priori knowledge we can narrow the search space of potential IFC building elements which have to be reconstructed.

A further advantage of the two-stage approach is the creation of a well-defined interface within the reconstruction process. Semantic 3D city models are already important products on their own. By using CityGML as standardized information model the subsequent semantic and structural refinement of 3D geometry models can be made explicit and exchanged between different systems and application areas without information loss. Moreover, semantic 3D city models form the basis for sophisticated analysis tasks in domains like simulation, city planning, and urban data mining. Thus, the reconstruction process might be aborted with the derivation of CityGML models after the first stage. Likewise, the proposed interface allows for starting the reconstruction process from existing CityGML models.

In both stages the interpretation and reconstruction of man-made structures comprises a general object recognition problem which has been topic of intense research for many years (Baltsavias, 2003, Brenner 2003). Generally, there are two opposed strategies for object recognition which can be classified as bottom-up and top-down approaches. Bottom-up approaches are data-driven, i.e., geometric primitives are directly extracted from the input data which are aggregated to form more complex structures. This is followed by the rule-based identification and combination of semantic objects. Often these rules are expressed by means of a constrained decision tree. Problems arise if objects cannot be observed in the input data due to errors or incompleteness. At this point prototypical 3D models of man-made structures have to be introduced. In contrast, top-down respectively model-driven approaches start from generating hypotheses for 3D models which are based on a predefined set of prototypes. The hypotheses can comprise arbitrary aggregations and combinations of prototypes. By verifying the hypotheses against the input data the prototypical 3D models can be subsequently refined in order to best match the input data. Thus, the verification process has to be controlled by a strong inference strategy. Finally, hybrid approaches combine both strategies. On the one hand, the instantiation of prototypes is oriented at the input data. On the other hand, model-driven hypotheses are generated taking into account identified prototypes in order to explain the input data.

In chapters 3 and 4 the conceptual requirements on the reconstruction will be explained for the two stages followed by a discussion on the inherent complexity and demands on a reconstruction strategy in chapter 5. Finally, in chapter 6 we draw a conclusion and give a brief outlook.

3. STAGE 1: GRAPHICS MODEL → CITYGML

In the first stage of our proposed reconstruction process a purely geometric graphics model (e.g., KML) is converted to a semantically enriched boundary model (e.g., CityGML) (see fig. 2). Work done in this field mostly concentrates on specific aspects of the reconstruction process. Thiemann & Sester (2004) propose an interpretation of geometric building models, which separates single semantic components. Schmittwilken et al. (2007) reconstruct stairs from uninterpreted laser scan point clouds. Dörschlag et al. (2007) reconstruct semantic building models according to building component hypotheses. Anyway, this approach currently adheres to specific forms of geometry and LOD handling (in the following referred to as "Replace geometry" and "Automatic LOD recognition"). In the following we defocus from specific approaches but will give a broader overview of possible interpretation variants and emerging requirements for the reconstruction process. We will start the discussion with an investigation of input and target model characteristics in terms of structure and data accuracy.

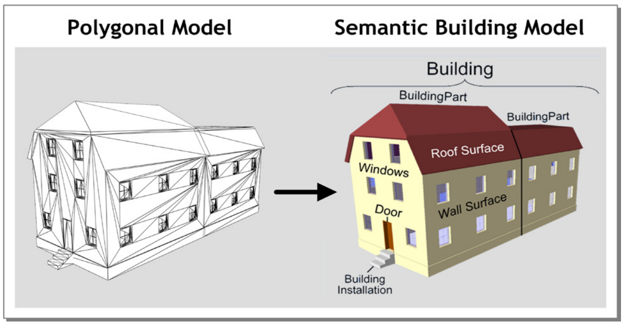

Figure 2. Deriving a semantically structured boundary model from a polygonal model.

Depending on data origin, there are various ways for the generation of graphics models. See fig. 1 for an illustration of different generation processes. In the following four categories of graphics models are examined, which are relevant in practice:

Photogrammetric models result from interpreting aerial or satellite images. Main goal is the reconstruction of roof structures, which is done either manually (photogrammetric stereo processing) or automatically (Fischer et al., 1998). Since facades are often occluded, their location is mainly approximated by extruding the eaves outline to the ground. Therefore, facades are typically displaced and all structural information is missing. Furthermore, positioning errors of images, limited image resolution and interpretation errors lead to inaccuracies in extracted roof structures. Models may even be incomplete due to occlusions, which are mainly caused by vegetation or shadows.

Airborne laser scan models are based on point clouds from laser scan flights. To reduce data volume and to smooth the resulting models, the initial point clouds are approximated by adjusting planes. These planes are the basis for the reconstruction of roof structures, which is mostly done automatically (Milde et al. 2008). Here too, facades are generally occluded by roof overhangs. Therefore, laser scan data is often combined with existing building footprints (e.g., cadastre data) resulting in facades, which are free from any structures (like balconies or window offsets). Random errors in the raw data are reduced by the use of adjusting planes. Like for photogrammetric models, incompleteness may be caused by occlusions.

CAD and planning models are based on building plans or surveys. They are highly detailed and often even include interior structures. Depending on the modelling software, resulting models are either component based or boundary representations. Here, also invisible objects may be part of the model (e.g. power supply, if contained in the underlying building plans). Typical modelling errors like overshoots, undershoots, self-intersections and permeations are significant, since they affect the topology of the model.

Visualization models are graphics models that are produced with the primary goal of (fast) 3D visualisation. The models contain few geometric details but often rely on structural information from façade images, which are projected onto the models for visualization purposes. Since models are explicitly built for visualization, only visible parts are trustworthy. Underneath the surface one has to reckon with coarse errors (e.g., overlapping objects like visualised in fig. 3). For the sake of modelling simplicity, the geometric composition of visualization models may conflict with semantic structures (e.g., representing all facades of multiple aligned buildings as one big polygon).

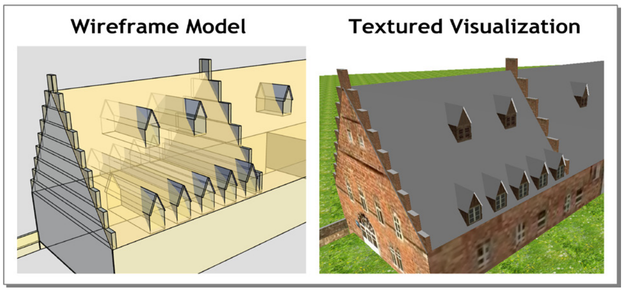

Figure 3. Dormers are extruded through the whole building (left). Visualization of the building does not reveal overlapping building and dormer bodies (right).

Regarding their structure, all presented models already comprise or may be transformed to polygons. In order to be able to deal with data inaccuracy and incompleteness, hypotheses must be also accepted even if they are not fully verified. Refer to chapter 5 for detailed discussions and strategies. Some of the models only comprise information, which is visible from the outside. This has influence on the target model's LOD.

By interpreting the input model, we want to generate a topologically sound and semantically structured boundary model. Geometry and semantics have to be structured coherently with link in between to ensure a consistent data model, which forms a convenient basis for data analysis. CityGML as target data format fulfills all these requirements (Kolbe, 2009).

Characteristics of CityGML

CityGML is a standardized information model which puts focus not only on the objects' geometry but also on their semantics, topology, and appearance. Key features of CityGML are:

- Objects may comprise coexisting geometric representations for different levels of detail (LOD concept).
- Topological relations between objects are realized by links between identical geometries (XLink concept).
- Variable complexity in the structuring of geometry and semantics – preferably coherent structures (spatio-semantic coherence, see Stadler & Kolbe, 2007).
- Aggregation hierarchies on the part of both geometry and semantics support complex object structures (hierarchical structuring).

A possible drawback when it comes to model interpretation is the versatile data model of CityGML: the same objects can be expressed in different ways allowing for ambiguity in modeling.

Fig. 4 shows the structural differences of input and target model. Whereas input models consist of unstructured geometry without further semantic information, the target models should consist of spatio-semantically coherent structures.

The structure and mechanisms of CityGML describe a generic way to define general characteristics of urban objects. E.g., a building is composed of wall, roof, and ground surfaces. In order to be able to ensure a correct interpretation of all these surfaces, profound knowledge is essential. Therefore, it is required to complement CityGML by additional constraints representing typical configurations, e.g., wall surfaces have to be upright and perpendicular to ground surfaces. Additional constraints may arise from user requirements for the target model.

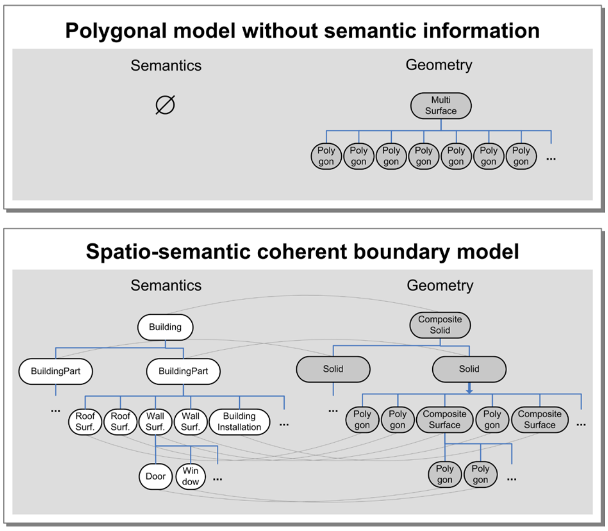

Figure 4. Semantics and geometry of input and target models.

Observing the main characteristics of input and target models, we can assess the following critical issues in the interpretation process of stage 1:

Spatio-semantic coherence

We intend to map geometry and implicitly contained semantic information of graphics models to the class hierarchy of CityGML. Therefore, it is necessary to explain implicit contents by appropriate hypotheses. The resulting target model shall be spatio-semantically coherent. Consequently, when interpreting input models, our hypothesis has to consist of both a semantic structure and the corresponding geometric representation. The respective reconstruction rules describe the interaction of semantic components as well as appropriate geometric structures. E.g., we interpret vertical surfaces, which have direct connections to two other vertical surfaces and one horizontal surface, as walls. In case of a verification of the hypothesis, they will be stored as thematic surfaces of type "WallSurface" and attached with a MultiSurface geometry (lodXMultiSurface).

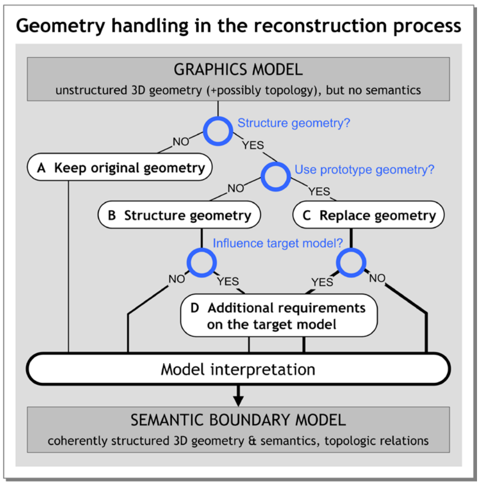

Figure 5. Alternative methods of geometry handling in the reconstruction process. Decision points are marked with circles. Increasing line weights stand for growing degrees of geometric structuring.

Geometry handling

There are several ways to deal with geometry when transforming a fine grained (but mostly error-prone) polygonal model into a sound CityGML model. Depending on the degree of geometry adaptation, we distinguish four different approaches:

A Keep original geometry – geometry remains unchanged. We merely attach semantic information to polygons. An example is given by Pitarello & de Faveri (2006).

B Structure geometry – we transform the unstructured collection of polygons into a well-formed composition of geometries (e.g., Solids, CompositeSurfaces). The structuring of geometry still has no effect on coordinate values.

C Replace geometry – depending on the target model's requirements, it might be necessary to adapt the input model's geometry. Such geometry substitutions may also result in topological changes. E.g., when deriving a LOD1 building from a detailed photogrammetric model, the roof has to be flattened and window apertures in walls will be filled (c.f. Thiemann & Sester, 2006).

D Additional requirements on the target model – Extra knowledge about buildings can be expressed as additional requirements for the interpretation process. The resulting constraints will exceed those stated by CityGML. Examples are minimal or maximal dimensions, parallelism, rectangularity, maximal amount of related objects, etc.

Approaches A and B are pure model interpretations in such that the input model's geometry is inherited. Since coordinates remain the same, these approaches are relevant for interpretation of legal data, where geometric changes may be prohibited. A possible drawback of retaining original geometry is the disability to reduce data load by joining coplanar faces, to remove data noise, and to resolve geometric and topological errors. Approaches C and D incorporate geometry in building hypothesis, i.e., replacing input geometry by geometry of prototypes. Depending on model constraints, this may cause considerable geometry modifications. Main benefit of both approaches is the big influence on the resulting model (see fig. 5).

LOD concept

The simultaneous representation of multiple LODs is a fundamental concept of CityGML. Since graphics models do not follow the same LOD definition as CityGML, the question arises how to decide on the appropriate target model LOD. Following possibilities are feasible:

- **Automatic LOD recognition** – the input model's granularity allows for drawing conclusions about sensible target LODs. E.g., if the graphics model does not contain window setoffs or molded roof structures, it will make no sense to choose a high LOD for the target model.
- **User input** – alternatively, we can ask the user to specify the target model's LOD. Problems may arise, if the input model does not fulfill the requirements of the chosen LOD.
- **Build a LOD series** – having specified one appropriate target LOD, we can think about covering also all lower LODs. The result is a LOD series with explicit linkage between multiple LOD representations.

For different LODs, the underlying geometric and semantic structure varies considerably. Therefore, the chosen target LOD has big influence on the hypotheses chosen for the model interpretation process. Consequently, it might be beneficial to use LOD adapted interpretation methods, which build on each other: prototypes of one LOD aggregate to prototypes of the next lower LOD. It has to be investigated whether an a priori generalization of the input model's geometry is sensible, if the target LOD is lower than the input model would allow for.

Topologic relations

CityGML represents topology by explicit links between geometries that are part of several objects. E.g., two buildings might share a common side wall or a specific geometry might be used in more than one LOD representation. By referring to the XLink concept of CityGML, there are two benefits for the interpretation process:

- Aggregated hypotheses for possible configurations of neighboring prototypes can share some geometries, making topological adjacency relations explicit.
- When using the same geometric entity for several LOD representations, correspondences can be recorded explicitly.

Aggregation of objects – Hierarchical structuring
CityGML employs aggregation hierarchies regarding both geometric and semantic objects allowing for different degrees of object aggregation. E.g., openings (like windows and doors) are part of thematic surfaces (walls, roof, ground), which are aggregated to building parts; building parts are again aggregated to form whole buildings. This advises a hierarchical strategy for model interpretation relying on hypotheses with increasing refinement (c.f. Dörschlag et al. 2007). An essential aspect is the direction of the interpretation process. When interpreting a building model, one can initially introduce a hypothesis for the whole building, go on with searching for building parts, afterwards distinguish between different thematic surfaces and finally end up with interpreting single polygons or vice-versa (top-down or bottom-up approach).

Ambiguities in data modeling
The generic character of CityGML allows for various modeling variants for the same city object. E.g., dormers can be modeled as building installations or as part of the building using roof and wall surfaces. They may comprise different complexities in terms of geometry and semantics. Consequently, there will be multiple valid hypotheses for the interpretation of objects. Only with the existence of an appropriate weighting function, we can determine the most likely object representation. In chapter 5 we will explicate requirements on the weighting function.

4. STAGE 2: CITYGML → IFC

The second stage of our proposed two-stage strategy aims at automatically reconstructing IFC models from CityGML input models. The CityGML models can result from the previous interpretation stage. Alternatively, already existing models can be directly fed into this second stage.

CityGML and IFC vary substantially in many aspects. A fundamental difference arises from their distinct modelling paradigms which are due to the way 3D models are acquired in the GIS domain respectively in the field of BIM and Computer Aided Architectural Design (CAAD). In GIS, 3D objects are derived from surface observations of topographic features based on sensor-specific extraction procedures. Features are hence described by their observable surfaces applying an accumulative modelling principle. In contrast, BIM models reflect how a 3D object is constructed. They follow a generative modelling approach and focus on the built environment rather than on topography. Therefore, BIM models are typically composed of volumetric and parametric primitives representing the structural components of buildings (Kolbe & Plümer, 2004). Fig. 6 exemplifies the implications of both modelling approaches.

The process of reconstructing a component-based volume model from a surface model requires the instantiation and rule-based combination of volumetric building objects such as wall, slab, and roof elements which are most likely to explain the given input model. A key aspect to the identification of the proper IFC primitives to be instantiated from the input surfaces is semantic information. This comprises the thematic classification of surfaces as well as the meaning and function of objects and their interrelationships. Both CityGML and IFC provide elaborate semantic models of the exterior and interior built environment. This a priori knowledge allows for reducing the search space of potential IFC elements. For example, a CityGML *WallSurface* object is most likely to be mapped to an *IfcWall* respectively *IfcWallStandardCase* element.

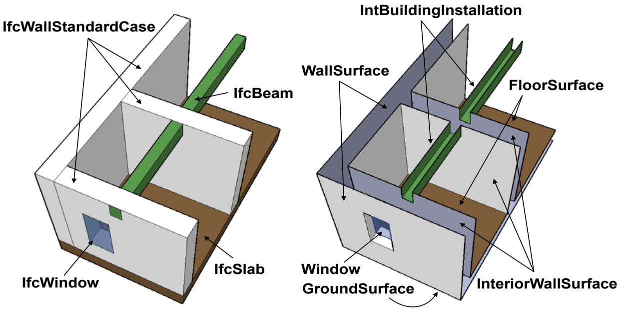

Figure 6. Snapshot of a building storey modeled in IFC (left side) and CityGML (right side).

The generation of hypotheses for IFC elements draws its complexity from the fact that building components generally can only be observed in parts and often are not observable at all. Since CityGML is used to model observed topographic features, only the visible parts are represented in the input data and can be used as a starting point for reconstructing IFC elements. Furthermore, for each visible part of a building component even two or more surfaces might be observable which are represented as individual semantic objects in CityGML. This leads to a high combinatorial complexity for the matching of IFC elements based on CityGML entities. Only in rare cases IFC elements can be directly reconstructed from a single CityGML feature. In fig. 6, a corresponding *1:1* matching relation can be found for the *IfcWindow* element and its CityGML *Window* counterpart.

More often we have to deal with *n:1* matching relations between CityGML and IFC entities in such that two or more input surfaces have to be identified to form a single IFC element. First, this is typically the case for wall components as shown in fig. 7. In this example, the interior wall surfaces I_{11} to I_{13} and I_{21} to I_{22} represent two separate wall objects W_1 and W_2 and have to be mapped to corresponding *IfcWall* elements in the target model. Furthermore, *n:1* relations occur for components which penetrate other components and hence are partly concealed and non-observable. An example for this is a single ceiling beam which continues over two or more rooms as depicted in fig. 6. Since this beam is observable from both rooms it may be represented in CityGML as two thematic *IntBuildingInstallation* objects with individual surface geometries. Thus, besides semantic information a process for identifying input surfaces to be aggregated to a single IFC element has to additionally analyze geometric-topological relations between the object geometries such as parallelism, perpendicularity, distance, and adjacency.

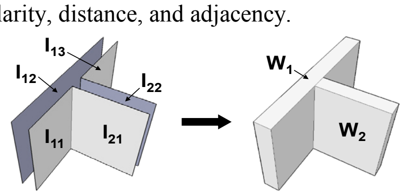

Figure 7. *n:1* match between CityGML wall surfaces and reconstructed IFC entities.

The reverse *1:m* relation results from splitting a CityGML object into two or more IFC elements. A split is performed, for example, for a CityGML *WallSurface* object spanning a complete building façade. In contrast to CityGML, IFC buildings are structured in storeys. This requires the partitioning of the façade surface into one or more *IfcWall* elements per storey. The number *m* of resulting IFC elements cannot be determined a priori due to allowed modelling ambiguities in IFC. The same is true for *n:m* matching relations. An *n:m* matching for separate input wall surfaces with more than one possible IFC element hypotheses is illustrated in fig. 8. As this example shows, the reconstruction of IFC elements will most often lead to more than one valid hypothesis for the same configuration in the input data. The reconstruction strategy therefore has to deal with competing hypotheses.

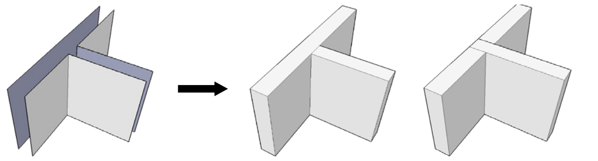

Figure 8. *n:m* match between CityGML wall surfaces and reconstructed IFC entities which are valid and hence competing hypothesis explaining the input model.

The hypothesis generation further comprises the instantiation of the potential IFC entity in such that it best fits the spatial properties of the related CityGML objects. This spatial fitting requires parameter estimation for the rotation, scale, and translation transformations as well as the element shape with respect to the identified input surfaces. According to the generative modelling paradigm, CAAD models usually employ the *Constructive Solid Geometry* (CSG) for shape representation. The primitives are defined through shape parameters which depend on the type of the IFC entity. For example, an *IfcWallStandardCase* is given by the wall height, the wall thickness, and the wall offset from axis which describe a vertically extruded solid. As a consequence of this parametric description there are strong implicit geometric constraints for the resulting CSG primitive such as parallelism and perpendicularity of wall surfaces. The estimation of shape parameters is supported by additional appearance information of observable surfaces provided by the input CityGML model. This comprises texture images or arbitrary sensor data which can be analyzed in order to deduce information about the interior build-up of components.

In contrast, CityGML employs the *Boundary Representation* (B-Rep) for the modelling of object geometry which is defined as the accumulation of all surfaces enclosing the volume of an object. Problems arise from the fact that man-made objects may have deviations from the idealized CSG shape used in building construction, e.g., opposite surfaces of a real-world wall often do not adhere to parallelism as the wall thickness changes over height. Since deviations are observable and hence incorporated into the B-Rep model, there is no set of parameters for an ideal CSG primitive which strictly explains the input data. Thus, the hypothesis generation must employ a non-strict matching of strong CSG primitives. Instead, primitives could be weakened as proposed by (Brenner, 2004). However, the concept of weak CSG primitives has not been considered for IFC so far.

The conversion of B-Rep geometries to corresponding CSG representations is ambiguous in general. Consequently, deriving CSG primitives from measured surface data is also ambiguous. In the context of reconstructing IFC from CityGML this uncertainty is even increased. The building components are only observable in parts and, thus, the CSG primitives cannot be derived from closed volumes. One has to keep in mind that the resulting ambiguity cannot be resolved without extra knowledge. The following fig. sketches a simple scene to illustrate this problem which is based on fig. 8. Even if the shown *n:m* matching problem is resolved there are still remaining geometric ambiguities for modelling the wall connection.

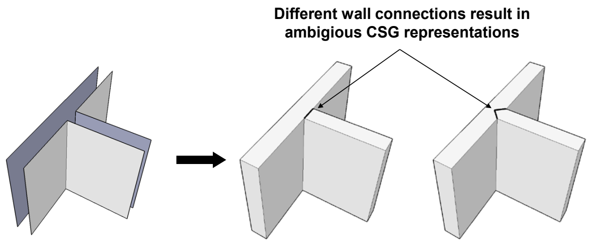

Figure 9. The conversion of B-Rep geometries to corresponding CSG representations is ambiguous and cannot be resolved without a priori knowledge or assumptions.

The parameter estimation for both transformation and shape has to obey additional contextual constraints. Unary constraints affect the interpretation process of a single IFC entity. For example, wall elements must usually meet a reasonable minimum and maximum height and length. Often the parameters defining an IFC element cannot be estimated isolated from other building components. For example, walls on the same storey usually share the same parameters for wall height and offset from ground and adjoining walls are likely to have the same wall thickness. Such many-to-many constraints do not only influence the parameter estimation of a single IFC entity but also mutually affect and dynamically change the parameters of previously generated hypotheses for other building elements.

Whereas both the implicit geometric constraints of primitives and the unary contextual constraints usually impair the best fit to the input data, mutual constraints often aim at aligning primitives. A best fit does not necessarily imply a correct alignment of the reconstructed IFC element. If the alignment is enforced after the fitting operation, the best fit property will most likely be lost (Brenner, 2004). Thus, the parameter estimation of potential IFC primitives has to ensure a best fit and the correct alignment at the same time. This results in complex element hypotheses which have to establish interdependencies. On the other side, mutual constraints also facilitate the unification of parameters over several primitives which helps in reducing the number of overall model parameters and, thus, in simplifying the final hypothesis of the target model (Fischer et al., 1998).

Purely geometric-topological constraints on primitives cannot prevent unreasonable instantiations and combinations of IFC elements. For example, they do not express that roof elements may not be instantiated at the bottom of a building. In fact, the IFC data model itself does not formally specify rules on how to combine building components in order to form a valid building. However, the reconstruction of valid building models is to be considered the main target of the interpretation process. What is needed is a framework providing enhanced model expressiveness to describe the structure of buildings and to incorporate semantic constraints on IFC entities and their aggregations in addition to geometric-topological constraints. By this means, not only the geometric and syntactic correctness of the generated hypotheses with respect to the IFC data model can be evaluated but also their semantic and structural validity. Consequently, the creation of an enhanced model for buildings reflecting common structural, functional, and physical agreements in BIM related fields such as architecture and structural engineering is a key requirement for coming from CityGML to IFC.

By analyzing typical structures and configuration patterns of building components in existing IFC datasets, we can derive a priori likelihoods for the instantiation of single IFC elements as well as for their valid combination. These a priori likelihoods can be fed back into the enhanced model of the built environment and, thus, can be introduced as a priori knowledge into the hypothesis generation process. This knowledge can be utilized, e.g., in interpreting non-observable components. Although, generally, non-observable parts cannot be reconstructed because they are not represented in the input CityGML model, an enhanced model of the built structure helps in detecting them. For example, if a ceiling surface and the corresponding floor surface of two rooms on top of each other have a distance considerably larger than the usual thickness of a slab element, the instantiation of a single *IfcSlab* entity is syntactically correct but most likely a false interpretation. Using structural patterns we can rather assume that the ceiling is suspended. By applying stochastic information, we can even reconstruct probable configurations of IFC entities explaining the observed surfaces, for example two *IfcSlab* entities and the *IfcSpace* in between.

The verification of generated hypotheses requires the backward projection from IFC to CityGML which comprises the conversion of both geometry and semantics (Benner et al., 2005; Isikdag & Zlatanova, 2009). Although the B-Rep can be obtained automatically and unambiguously from CSG, each IFC element is transformed to a set of surfaces describing a closed volume. One has to remind that this transformation does not reflect the input data which only contains observable surfaces. It still has to be examined whether the non-observable surfaces have to be removed in order to get stable verification results.

The quality of the reconstructed IFC model depends to a great extent upon the quality of the input model. As semantic information is a premise for the identification of IFC elements, the proposed interpretation process requires the input model to provide a coherent representation of semantics and geometry (cf. section 3.3). An additional structural model of the built environment allows for detecting and possibly correcting errors within the input model such as falsely classified or even missing building components. In general, the reconstruction of the interior built environment implies an input CityGML model conformant to the quality requirements defined by LOD4. However, lower LODs may also serve as input data resulting in IFC building models which are only represented by their exterior wall and roof structure. Such building models can already be sufficient in BIM applications for which the building interior is negligible or can be used as templates for architectural interior design. Furthermore, they support current efforts to continue IFC from the building scale to the city scale and, thus, to use IFC for virtual 3D city modelling.

5. STRATEGY REQUIREMENTS

From the specifications of the graphics models, CityGML, and IFC we can define our input and target models (see chapters 3 and 4). Both CityGML and IFC specify the thematic structuring of objects in a formal way. The model semantics are defined by the international standards in the respective domains, in particular the ISO 19100 standards family and STEP. Syntactically, the models are described using formal concepts such as UML, XSD, and EXPRESS which provide a generic description of objects and their relations. However, they are not meant to qualify objects and inter-object relations in order to restrict the modeling to only sensible object configurations. In order to carry out the interpretation process, we have to increase the expressiveness of the CityGML and IFC modeling frameworks in terms of physical, functional, and semantic / logical properties. A very promising way to formulate respective constraints is by the use of formal grammars.

Formal grammars originate from linguistics. They define the symbols of a language together with the rules to compose and verify valid sentences (Chomsky 1959). The symbols of the language represent the features or components and the production rules define the valid combinations of complex configurations, i.e. hypotheses for the objects to be reconstructed. Different types of formal grammars are being used for object recognition for a long time now (Tsai & Fu, 1980). *Attributed grammars* allow to parameterize components and to define functions and constraints on the combination of parameters from different components. *Stochastic grammars* assign a priori probabilities to the occurrence of components and the applicability of rules and compute the overall probability for each reconstructed object (given by all symbols of a sentence). Starting from 1971, *shape grammars* have been used to describe valid combinations of geometric primitives (Stiny & Gips, 1971). *Split grammars* as defined by (Wonka et al., 2003) are inspired by shape grammars and describe patterns for spatial decomposition of geometric objects, here applied to building façade reconstruction.

Recently, combinations of the different types of grammars and Monte Carlo strategies for the generation of hypotheses have been proposed for façade reconstruction (Ripperda, 2008; Reznik & Mayer, 2008; Hohmann et al., 2009), the reconstruction of roofs (Milde et al., 2008), stairs and entrance areas of buildings (Schmittwillken et al. 2007). In (Dörschlag et al., 2007) it is proposed that building components are represented as prototype constraint graphs which are composed according to the rules of an attributed grammar in order to form complex building hypotheses called reconstructed constraint graphs. All these concepts allow for a high flexibility with respect to reconstructable objects. However, means for the handling of errors and unobservabilities of expected components are mostly missing yet. This will have to be solved in order to become applicable in productive environments.

When working with real-world data, one has to deal with uncertainties regarding geometry and semantics. Geometric errors are often caused by measuring or modeling inaccuracies. Both measuring and modeling imply generalization processes due to the mapping of infinitely detailed structures to models consisting of a finite number of parameters. E.g., walls in a building model may be described by a single thickness parameter, although their thickness varies in reality. Semantic errors mostly result from ontological inconsistencies. A building might be called building, house, or man-made structure and might be decomposed into building parts which are horizontal segments (floors) or vertical ones according to the underlying ontology.

Further problems for object interpretation may arise from model incompleteness. This implies both incomplete object information (missing geometry or semantics) and unavailability of object parts, e.g., due to occlusions. IFC beams might be partially observable, but for complete representation, their geometry has to be extrapolated. In order to deal with emerging uncertainties, grammars must become robust with respect to errors.

In chapters 3 and 4 we pointed out the problem of modeling ambiguities. As a consequence of their generic character, both CityGML and IFC allow for alternative modeling variants of the same real-world building which differ in terms of geometric and semantic complexity. This implies the existence of various possible interpretation results. Thus, a grammar is required that allows for multiple disjunctive production rules. Consequently, the grammar can produce alternative hypotheses and interpretations. In order to be able to choose the "best" of all competing hypotheses, a weighting function is required that takes into account following two aspects: 1) Goodness of fit, 2) Complexity of the hypothesis. The weighting function has to balance between both aspects in order to avoid overfittings.

Furthermore, it should have a defined semantics in the sense that it specifies a meaning for the "best" hypothesis. By choosing probability theory, the best matching means the most probable interpretation of the examined situation. Thus, the interpretation process amounts to a maximum a posteriori (MAP) estimation, finding the most probable model

$$\hat{M} = \arg\max_{M_i} P(M_i \mid D) \quad (1)$$

where M_i are the different hypotheses, and D the given input data. Possible frameworks are:

- Minimum description length principle (MDL), based on information/probability theory (Grünwald et al., 2005)
- Akaike Information Criterion (AIC) (Akaike, 1974)

Both MDL and AIC are grounded in the concept of entropy, which specifies the amount of information contained in a message reflecting the model complexity. Frankly speaking, the common idea is to choose the *simplest suitable* model (see also Fischer et al. 1998, Dörschlag et al. 2007).

Concerning the interpretation sequence, our target models impede the pure application of both top-down and bottom-up strategies. The model complexity leads to an infinite number of possible building hypotheses, which argues against a top-down approach. The inaccuracy and incompleteness of input models prevents a pure bottom-up approach. Therefore, we have to go for a mixed approach, which compensates weaknesses of both single approaches. Since the grammar will include disjunctive rules, a combinatorial complexity is induced, rendering the interpretation process NP-complete. Thus, strong heuristics are required, which have to cut down search space substantially.

6. CONCLUSIONS

The reconstruction of BIM models from uninterpreted 3D geometry/graphics models sets the bar very high for an automated interpretation process. In order to reduce the overall complexity and to increase the flexibility of the reconstruction process, we have proposed a subdivision into two major stages 1) from graphics models to CityGML building models, and 2) from CityGML to IFC building models. IFC and CityGML are appropriate target models for reconstruction, as these models are well-defined and their instances are usable in a broad range of applications. However, in order to be able to reconstruct either CityGML or IFC from 3D graphics models, stronger concepts than the pure data models from the specifications are required which restrict reconstructed objects to sensible building structures. Formal grammars seem to be a promising approach to express valid aggregations of components adhering to functional and logical constraints, but will have to combine geometric shapes, attributes, constraints between attributes of different objects, and stochastic aspects like uncertainty and a priori probabilities. Although formal grammars have been used for building reconstruction, there are no formalisations for CityGML or IFC available so far. Another challenge is the definition of the weighting function being key to the search for the optimal interpretation. Finally, strong heuristics are required in order to cope with the huge search space. In the future, we will investigate these issues in both reconstruction stages.

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RICH INTERACTIVE MAPPING EXPERIENCE THROUGH OPEN SOURCE FRAMEWORKS AND AJAX DATA VISUALIZATION TECHNIQUES

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ABSTRACT:
Community indicator projects across America seek to understand and analyze the inter-relationships of multiple issues over a given geographic area, typically within an urban region or city. While maps can be well-suited to portraying urban development patterns, geographic information systems (GIS) typically are limited to displaying single or bivariate spatial relationships; additional spatial statistical tools are generally needed to analyze multivariate relationships. Online interactive GIS applications using a single map frame present an even more difficult challenge when attempting to visualize multiple variables at once, especially at multiple scales. New open source web frameworks and AJAX-style data display tools, though not designed specifically for GIS purposes, offer innovative ways of overcoming this challenge. A new online mapping application covering the Long Island region in New York provides an example of how to implement these frameworks and tools. It represents a compelling example of a production-level, customized application (rather than a mashup relying on Google-Yahoo-Microsoft basemaps) that nonetheless is replicable and extensible.

1. INTRODUCTION

This paper describes an application of new AJAX-style* data visualization tools as part of an interactive mapping website in the New York metropolitan region. This example demonstrates the repurposing of tools such as dynamic transparencies to facilitate the effect of portraying spatial relationships of multiple data sets simultaneously for a given geographic area across a range of geographic scales.

The mapping website was developed for a regional community indicators project. Indicator projects in the United States compile and analyze a wide array of demographic and socioeconomic data to understand and monitor progress related to the vitality and resilience of urban regions. These projects seek to understand and analyze the inter-relationships among multiple issue domains to identify trends and map local and regional patterns (Kingsley, 1998). These domains can include housing, commercial development, population trends, transportation networks, environmental concerns, and more. Policies that facilitate housing growth, for example, can subsequently influence commercial development (and vice versa), which will help determine transportation access to and from workplaces, all of which will have environmental impacts.

While these policies can be evaluated at the regional and national scales, their impacts are felt at the local (Maantay J & Ziegler J, 2006) and even "hyperlocal" level (Kelly T, 2009). Housing might be built according to a suburban sprawl pattern, for example, or it could be concentrated in local downtown areas with commensurate commercial land use activities coupled with new public transit hubs and routes. Individuals living or working in or near these downtowns or along transit routes, as well as local planning agencies, advocacy groups, reporters and editors, and local elected officials want to understand how these impacts will affect them. Maps are effective tools for visualizing these local impacts.

The *Long Island Index* is a community indicators project focused on the two suburban counties located just east of New York City (*Long Island Index*, 2009). A central goal of the *Index* is to make information about regional indicators easily and broadly accessible. The project also tries to localize the information as much as possible to make it especially relevant to people interested in their communities, as well as the island as a whole.

The original *Index* website (www.longislandindex.org) had provided "Community Profiles" consisting of static maps and tables highlighting Census data for each village, town, and city on Long Island. The *Index* had removed those profiles when its website was redesigned two years ago, but *Index* staff and its steering committee knew they needed to provide better access to this data – the *Index* regularly receives requests from public officials, the media, and community groups for information about what the *Index*'s indicators mean for local neighborhoods. The *Index* also knew that it needed an easier way of helping people make connections among multiple issues such as housing, transportation, and jobs.

The *Index* contracted with the Center for Urban Research's Mapping Service at the Graduate Center of the City University of New York (CUNY) to apply GIS technology in an interactive, online environment to enable website visitors to mix and match data to suit their individual needs and reveal complex relationships in easily understood ways. *Index* staff wanted visualization tools that would allow users to quickly find a wealth of richly layered information without having to search multiple sites and resources.

* AJAX refers to "Asynchronous JavaScript and XML". AJAX techniques are discussed more fully in Section 2.

2. RELATED WORK & ALTERNATIVE APPROACHES

The ability to overlay and simultaneously visualize multiple data sets, in particular those that represent administrative data aggregated across statistical boundaries such as Census areas or administrative districts, using GIS is not new. But only recently have web development tools made it feasible to do so in online mapping applications (Dykes, 2005).

Desktop GIS applications have used traditional cartographic techniques to accomplish this goal (Slocum, 2009) such as:

1. Multiple symbol types such as graduated symbols located at polygon centroids overlain on a choropleth map displaying color patterns across those same polygons.
2. Multivariate dot density maps, using different colored dots for each variable displayed within common spatial units.
3. Points and/or lines symbolized categorically overlain over a choropleth map.
4. Choropleth maps that combine texture (such as cross-hatching) with hue.
5. Transparency such as a semi-transparent hillshade choropleth draped over a digital elevation model.

Some of these approaches translate well in an online environment, such as overlaying line symbols on other map layers. But most of them either have not been implemented in online mapping applications or (in the case of dot density maps or choropleth+texture maps) lose their visual power when used in conjunction with satellite orthoimagery or color-shaded spatial units that are fine-grained such as tax parcels.

Another approach is a set of maps each covering the same geographic area, with each map displaying different data. This could be either a traditional atlas or the "small multiples" approach described by Tufte (1983). But interactive online maps generally use a single map frame. We wanted to follow the single frame approach for the Long Island Index, so this ruled out a traditional atlas or small multiples.

Geo-statistical packages are very good at displaying multivariate data using graphs and scatterplots (cf. GeoVISTA's applications such as HealthVis; Edsall, 2001). But scatterplots do not display patterns in geographic space; they use Euclidian space to illustrate relationships. Also, these relationships are generally described for a large area (such as countywide or metropolitan statistics), rather than the spatial patterns in small areas such as within villages or even within Census block groups. The Long Island application needed to display these spatial relationships in very small areas as well as regionally.

Online GIS adds interactivity to traditional cartographic techniques, such as turning on/off different choropleth layers or clicking on the map to access each layer's attributes. But until recently, online mapping did not offer much more functionality than that (Plewe, 2007). In 2005, web developers started to use a set of techniques referred to as "AJAX", which was well-suited to enhanced interactivity for online mapping applications (Garrett, J.J., 2005). AJAX refers to Asynchronous JavaScript and XML. It was coined at that time to refer to a mix of different web development approaches that, when implemented together, enable web pages to behave more like desktop applications. For example, multiple components of single web pages designed using AJAX techniques can operate independently of each other and can each display data from different sources. This makes the user experience less jarring, because the entire web page does not "refresh" or reload each time a user initiates an action (such as clicking a hyperlink), only that particular section of the page or layer on the page changes.

In the article that first described the AJAX approach, Google Maps was credited as one of the main examples of implementing AJAX beyond research projects (Garrett, J.J., 2005). The use of AJAX in Google Maps has since helped changed the way people expect to experience interactive mapping. The now-common technique of dragging a map and panning without first having to click on a special icon to enable panning is a result of AJAX, and clicking on the map and retrieving information about that specific location without the entire map reloading (or more severely, the entire web page reloading) is another.

At the same time, online mapping software has become easier to use, and consumer-oriented online mapping services such as Google Maps or Microsoft "Bing" Maps provide freely accessible application programming interfaces (APIs) to facilitate the integration of different data sets onto a common basemap (Plewe, 2007; Smith, 2008). One benefit to both of these approaches is that they are relatively easy to implement in a short amount of time.

However, they are not necessarily well-suited for projects such as the Long Island Index that require highly customized cartography and functionality (Smith, 2008). With the exception of the aerial orthoimagery, for example, the map layers for this project are all hosted at the CUNY Graduate Center. There was too much data to simply mash it up with a commercially available web map service, and we needed a greater degree of control over the cartography.

So-called first- and second-generation online mapping systems such as ArcIMS are GIS-centric but not as interactive as this project called for (Plewe, 2007). We wanted to develop the application using tools that would provide the kind of user experience that is now generally expected of online maps intended for a wide audience. For example, it would have been too onerous to require our users to first click a "hand" tool in order to pan around the map, or to click an "information" tool in order to access information from the map. We evaluated several open source alternatives to ESRI's Web ADF and concluded that OpenLayers was best suited to our needs. (Going forward, ESRI's new JavaScript and/or Flex APIs may be worth considering for new applications.)

The Mapping Service did explore open source options such as MapServer and GeoServer. But using those tools would have required learning new markup syntax for map styling and online cartography (such as GeoServer's SLD files).

Other applications that are widely used such as Google Earth (http://earth.google.com/) and NASA's World Wind system (http://worldwind.arc.nasa.gov/) also employ similar techniques, but these are desktop applications rather than websites.

By 2008, other online mapping applications had begun to integrate AJAX-style tools to facilitate the simultaneous display of multiple data layers. At the time, however, we identified only a few sites with a focus on community indicators that were employing tools to overlay multiple data layers within the same map frame (such as PolicyMap at www.policymap.com and DataPlace at www.dataplace.org). Even fewer sites enabled simultaneous visualization of multiple layers. MapTube was the main example we identified, employing a dynamic transparency "slider" for each layer displayed on the map (www.maptube.org).

Since deploying the *Long Island Index* application, other applications have been developed that employ a similar combination of technologies and techniques (cf. OpenGeo, 2009). Several open source projects now use Ext JS's tools for online maps such as OpenGeo's *GeoExt* framework (www.geoext.org), MapFish (www.mapfish.org), and GeoCommons Maker! (http://maker.geocommons.com/).

3. APPLICATION OVERVIEW

The *Long Island Index* interactive mapping application is accessible at www.longislandindexmaps.org. It combines parcel-based land use data across the region, Census demographics, downtown surveys, aerial photos, and much more to create detailed neighborhood maps and give users a bird's eye view on key housing, transportation, and development issues facing the region.

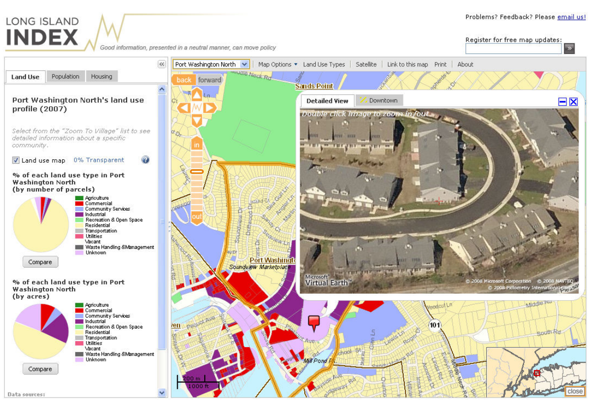

Figure 1. Screen shot of *Long Island Index* interactive map, zoomed in on the location of a new housing development, highlighting land use patterns and Microsoft's "bird's eye view" imagery integrated into the map frame

The mapping application features:

- Detailed property-level patterns of residential, commercial, industrial, and other land use types within each village and across Long Island. This data – provided under license by the Nassau and Suffolk planning departments – is not available in mapped format online anywhere else. It provides a rich picture of each of Long Island's neighborhoods.
- Key population and housing characteristics from the 2000 decennial census plus statistics listed dynamically as users zoom in to each community. Census data is mapped by block group rather than the more common Census tracts because in many cases tracts were as big if not larger than villages. This meant that we could not display variation or patterns *within* many villages if we used tracts for the maps.
- Transportation and reference features such as aerial orthoimagery (provided by the New York State GIS Clearinghouse), bus and Long Island Rail Road routes, boundaries of incorporated and unincorporated villages, special districts (such as fire, police, and sewer), and legislative districts.
- Dynamic bar charts comparing Census statistics from 1990 through 2007.
- Microsoft's "bird's eye view" oblique aerial imagery of any location on the map, embedded dynamically within the map frame. (The bird's eye view photos are accessed via Microsoft's "Bing" Maps API at www.microsoft.com/maps/isdk/ajax/.)

The map application supplements the *Long Island Index*'s annual reports and ongoing surveys. In conjunction with the January 2009 release of the *Long Island Index* 2009 indicators report, new data was added to the map including:

- Education statistics such as district size and statistics on affluence, finances and obstacles.
- Brownfield site information, showing the locations of 278 brownfield sites plus information for each on clean-up expenditures.
- Early childhood education program locations, plus child care capacity by school district.

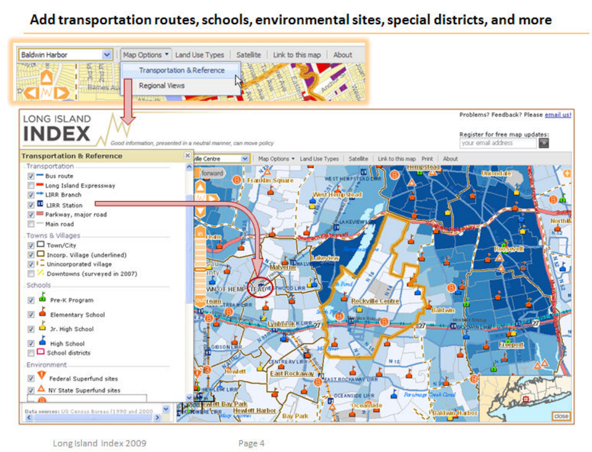

Figure 2. Local data sets such as pre-K, school, and brownfield locations and regional transit routes are featured

4. A HYBRID "GEO STACK": OPEN SOURCE AND AJAX TOOLS ATOP PROPRIETARY BACKEND SYSTEMS

The development of open source software as well as standards-based application development have made it easier to integrate disparate technologies to create online mapping services. It is now feasible to use software for database management, cartographic rendering, map navigation tools, and a user interface framework all from different – including a mix of proprietary and open – sources. The Long Island application was developed using proprietary mapping and database technology on the back end, the open source map viewing library OpenLayers (www.openlayers.org), and the JavaScript web framework Ext JS (http://extjs.com/products/extjs/). This combination of tools and frameworks enables the integration of sophisticated cartography, robust map services, and new visualization techniques.

The technology platforms include:

- ArcGIS Desktop from Environmental Systems Research Institute, Inc. (ESRI) to create map document ("MXD") files for transportation and reference layers, land use maps, demographics and regional views and ArcSDE/SQL Server to manage the data sources (see www.esri.com/products/index.html for details about ESRI software).
- ESRI's ArcGIS Server to generate web map service ("WMS") resources from the MXD files. The application also uses ArcGIS Server to generate cached tiles for the parcel-level land use map layer.
- OpenLayers consumes the WMS resources, manages and displays the map layers, and provides map navigation tools. The WMS resources consumed by OpenLayers include local resources created by the CUNY Mapping Service as well as remote resources such as the orthoimagery available from New York State's GIS Clearinghouse; see www.nysgis.state.ny.us/gateway/mg/webserv/).
- Dynamic data feeds are also provided via REST web services (such as village-specific statistics and comparison statistics).
- Ext JS provides the overall framework for the website itself and enables us to relatively easily integrate visualization and navigation tools such as dynamic transparencies, collapsible panels, and floating windows populated with dynamic data and charts.

The maps use ESRI's platform on the back end because the CUNY Mapping Service has extensive experience using ESRI products to generate maps (online and offline). Though we have historically used ArcIMS (another ESRI product) to manage and serve online applications, the learning curve was minimal to install and use ArcGIS Server's tools.

The Ext JS dynamic transparency tool is central to enabling the visual analysis of multiple layers at once (see http://extjs.com/deploy/dev/examples/slider/slider.html for a generic online demonstration of this tool). Although the Ext JS toolkit was not intended for GIS layers, we quickly realized it would meet this need.

The dynamic transparency operates on one map layer at a time, but it can be used to create the impression of visualizing a multivariate analysis. For example, a choropleth layer showing population density by Census block group is overlain on the land use layer that displays property-by-property land use patterns using a categorical color scheme, and the transparency of the choropleth is controlled by the map user from fully opaque (0% transparent) to fully invisible (100% transparent) by dragging a slider tool that automatically changes the transparency in 10% increments – see figure below.

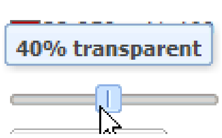

Figure 3. Screen shot of transparency slider tool

The AJAX approach controlled through Ext JS enables the choropleth Census map layer to change transparency without the rest of the page (or the other map layers) refreshing, so the transparency fades from one level to the next, becoming more or less transparent in relation to the map layer beneath it dynamically.

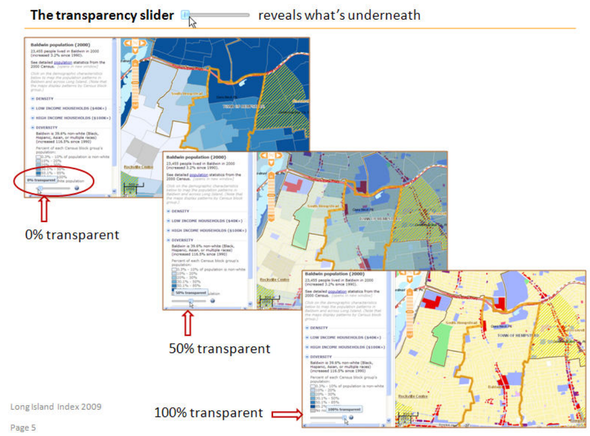

Figure 4. Excerpt from *Long Island Index* interactive map tutorial, explaining the use of the dynamic transparency tool

However, the transparency tool coupled with OpenLayers' ability to instantly (and – through AJAX – without refreshing the rest of the web page or even the map itself) swap in and out different map layers creates the effect of viewing multiple map layers at once. One can set the transparency level of the land use layer at 20% with satellite imagery displayed beneath it, display a choropleth Census block group map of low income housing concentration at 40% transparent above the land use layer, and switch to a choropleth Census block group map showing patterns of multi-family housing at 100% opacity. Switching back and forth between the Census layers enables you to visualize the overlap between Census variables along with the land use patterns (three variables).

If you are zoomed in close enough on the map to discern building-level differences based on the satellite imagery (showing through the semi-transparent land use layer), you can use the same approach to also reveal how the actual land use patterns (a 4th variable) are related to the aggregated administrative data sets.

The Census Bureau cross-tabulates some variables such as poverty by income or race/ethnicity by sex and/or age. But Census variables such as the ones included in the Long Island Index application have not been cross-tabulated already, and none of them are cross-tabulated with variables such as land use (administered by a completely separate set of local government agencies) nor with transit routes or education data. Therefore, the Long Island application provides a unique way of visually analyzing the spatial relationships among these different socioeconomic characteristics.

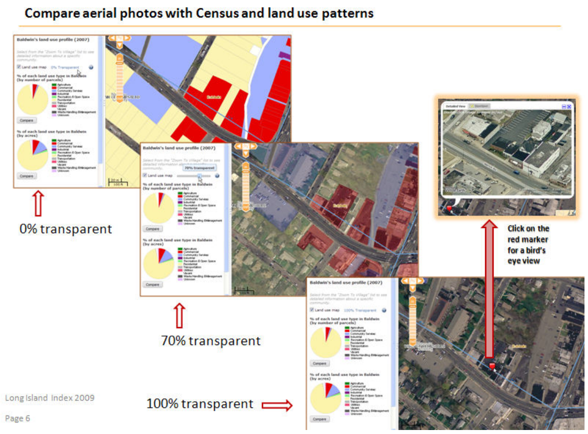

Figure 5. Excerpt from *Long Island Index* interactive map tutorial, highlighting how the dynamic transparency tool reveals aerial orthoimagery layered underneath a layer of tax parcel boundaries shaded categorically by land use

It is also important to consider the power of the transparency tool in the context of the transition from one transparency level to the next. Setting the transparency of a layer at a particular percentage using the transparency slider reveals the map patterns of the underlying layer. But watching the transition from 0% to 50% transparent, for example, makes the transparency "come alive". As a recent web design handbook notes,

> Things move smoothly in the real world. They do not "pop up". Transitions smooth out the jarring world of the Web, making changes appear more natural. (Scott, 2009)

This also overcomes a potential concern with map transparencies. Once a map layer becomes partly transparent, the semi-transparent map colors no longer match the legend; they are influenced by the underlying map layer(s). We understood this concern when we developed the Long Island Index application, but hoped that application users would realize this limitation once they used the tool and modify their expectations accordingly (for example, another map developer using transparency controls notes that "The transparency control lets mapmakers decide what works and what doesn't" – Axismaps.com, 2008). We have also created video tutorials and "frequently asked questions" (FAQ) web pages that address this issue.

Other AJAX tools included in the Ext JS framework that we applied to the Long Island Index application include:

- Interactive legend items that control the display of map elements without having to check a legend box and then separately click a "redraw map" button (cf. "smart legends" in Cron, 2008); and
- Data panels that operate independently of the map, but also control the map display. In particular, the Long Island Index includes an option to display "regional views" of pre-selected data elements. The Regional Views tool opens a panel that floats on the map (it can be moved or collapsed by the user). This panel includes a pull-down list that will change the map display by highlighting communities that meet certain criteria, such as all the villages across Long Island with more than 10% population growth from 1990 to 2000. Clicking a community shown in the resulting data list will display that community's detailed profile and highlight it on the map. Double-clicking on the community will cause the map to zoom to the community's boundaries. Clicking the "zoom out" option in the panel will cause the map to zoom to the full extent of Long Island, showing the regional patterns of the selected data item.

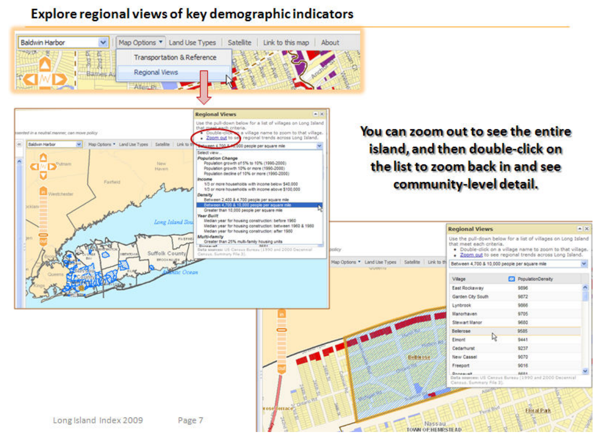

Figure 6. Excerpt from *Long Island Index* interactive map tutorial, demonstrating how AJAX-style drop down lists are linked with map navigation

5. REPLICABLE AND EXTENSIBLE

The *Long Island Index* interactive map application is replicable and extensible. With modest effort it can be modified to focus on other urban regions, and can be extended to include other visualization tools such dynamic charts and timeline controls.

Though it relies in part on proprietary software, other organizations without access to proprietary backend database and map development systems can substitute open source applications making the overall environment 100%-reliant on open source technologies.

Similarly, although the choice of variables and issue domains is pre-selected, with slight modification the platform can be designed to accommodate user-generated data, web services, and other dynamic content.

6. CONCLUSIONS

The interactive map was launched in December 2008. Since then several thousand individuals, local officials, community leaders, and industry representatives worldwide have used it. Access is free, and people can sign up for updates as the feature is expanded. Tutorials are available online for quick reference on how to navigate the maps and access the data.

The application is its own comprehensive but strategically-designed mashup, with a focused goal of illuminating regional and local planning issues across Long Island by visualizing statistics in new ways. It represents a novel implementation of multiple online mapping and web navigation technologies and techniques, customized specifically for displaying aggregated administrative data such as Census statistics at the block group level and education data at the school district level plus transportation networks and site-specific environmental activities, all overlain spatially with parcel-level land use data and contemporary aerial imagery.

Lay audiences and industry experts alike have been impressed with the integration of AJAX tools in the Long Island application. The mapping feature already has been described as "an incredible resource" and a "data gold mine" by users who have ranged from high school students to industry experts to local newspapers to government officials across both counties as well as in New York City, San Francisco, Washington State, Oregon, Maryland, and Michigan. The maps have also attracted international attention. They have been accessed by mapping consultants and government representatives from Australia, France, Germany and Japan, as well as the geographic information officer for the United Nations.

As the *Index* continues to monitor and report on indicators of interest, the interactive map will be kept up to date as well. In addition to new data, the map will incorporate updates to data as public agencies and others make this information available. Updates from the Census Bureau will be incorporated, as well as annual land use updates from Nassau and Suffolk counties.

Above all, the *Index* wants to avoid adding data to the maps just for the sake of adding data. It is important that the maps continue to help reveal relationships of interest to the *Index*. For example, the wealth of education statistics compiled by local districts as mandated by state and federal agencies can be overwhelming. Simply tossing all that data into the mix would be counter-productive, helping to obscure rather than enlighten the public's understanding of what lies at the heart of educational challenges and how to overcome them. The *Index* will strive to be strategic in how it further develops the maps, while also responding to feedback and requests from the public.

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The interactive map involved the integration of many data layers from numerous sources. Two sources require special thanks: 1) Nassau and Suffolk county governments provided access to land use information developed by each county's planning department and tax assessor's offices; and 2) the New York State GIS Clearinghouse which provided access to its web service that displays high resolution aerial photo imagery through a partnership with the US Geological Survey.

E-COLLABORATION BETWEEN THE PRIVATE AND THE CIVIL SECTOR: SUPPORT OF LONG-TERM UTILIZATION AND UPDATE OF OFFICIAL 3D CITY MODELS

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Key Words: 3D City Model, Digital City, CityGML, Urban Planning, e-Government

ABSTRACT:

Research on the creation and use of 3D city models has made rapid progress recently. An increasing number of cities and regions now own 3D city models or are planning to use them in the future. Especially planning departments see an enormous potential in the use of 3D city models to visually and algorithmically access environmental and spatial impacts of planning proposals. However, examples for the continuous use in spatial and environmental planning are not documented so far. Within our contribution it is argued that this can especially be attributed to missing concepts for the digital exchange of planning information between the civil sector and the private sector. By conceptualizing digital workflows that enable the utilization of 3D city models and the integration of planning proposals by multiple stakeholders, it will be shown how the collaborative use of official 3D city models can support their regular use as well as their continuous update. References to related research are presented to show that the technology to implement such an e-Collaboration framework is generally available. At the same time our concept also considers national and supranational aims formulated in e-Government programmes to provide governmental services via ICT.

1. INTRODUCTION

Collaboration between multiple stakeholders based on a common data model or within a shared virtual space represents an innovative and promising technology to support planning processes and project management in spatial and environmental planning via information and communication technology (ICT). Within the fields of architecture, construction and engineering (ACE) the idea of collaboration is increasingly supported by the adoption of construction software that enables users to represents a proposed construction as semantic data model rather than as purely graphical model. With respect to building construction such models are called *building information models* (BIM). The BIM approach has significant advantages compared to classical computer aided design (CAD) drawings: One BIM can be used for cost calculations, for structural analysis, for life-cycle management of buildings, and in real-estate management applications. International standards for BIM such as Industry Foundation Classes (IFC) allow the exchange of data between multiple stakeholders and software solutions. It is possible to derive multiple graphical representations from one BIM, such as ground plans, section drawings, structural models, or 3D models in varying levels of detail (LOD).

Analogue to BIM, which can be used to represent buildings through a semantic data model, City Geography Mark-up Language (City GML, Gröger et al. 2008), a standard of the Open Geospatial Consortium (OGC), can be used to represent cities through a semantic data model. *Semantic 3D city models* (Kolbe 2009) can be used to store virtual 3D city models in different levels of geometric and semantic detail and with multiple appearance models. Since CityGML-based virtual 3D city models are georeferenced and can be visualized in real-time they provide a common data model as well as a geovirtual environment (GeoVE).

Despite the progress made in 3D city modelling during the recent years and the benefits associated with semantic 3D city models for spatial and environmental planning, their utilization by authorities and planning professionals is still in the beginnings and the potentials are by far not fully tapped yet. The hypothesis of our contribution is that not the technology is missing but concepts for the long-term operational use and maintenance of semantic 3D city models. Therefore, it researches requirements for the continuous use of official 3D city models by multiple stakeholders in spatial and environmental planning via ICT. It conceptualizes an e-Collaboration framework, workflows, and processes for the exchange of digital planning information and 3D city model data between the civil and the private sector.

2. RELATED WORK

The presented research focuses on the position of e-Collaboration at the intersection of (1) 3D city models, (2) spatial and environmental planning, and (3) e-Government. Within the following chapters we will introduce the three themes, recapitulate current developments and define the terminology used.

2.1 Virtual 3D City Models

Virtual 3D city models are digital, georeferenced representations of objects, structures, and phenomena of corresponding real cities. Recently, models are extended by semantic concepts such as in the case of CityGML (Gröger et al 2008). In contrast to models that are solely created for visualization purposes, semantic models extend graphical models by storing additional information about type, usage, and role of objects as defined by an underlying ontology (Kolbe 2009). Several of the 3D city models developed recently are attributed to be *official 3D city models* which represent not only a virtual 3D city model but are linked to the land cadastre system and thereby represent the city as it is described by official and legally binding geo-information. The aim behind this approach is to ensure integrity and validity of the city model as it is needed in administrative use.

The progress achieved in 3D city modelling and the resulting increased availability of 3D city models can be attributed to recent developments in remote sensing technologies and data extraction algorithms. It is now possible to automate the reconstruction of 3D city objects (e.g., Haala and Brenner 1998, Rottensteiner et al. 2005, Becker et al. 2008) and virtual 3D city models respectively to a large degree. Thus the cost for the creation of large and city wide 3D city models have dropped rapidly during the last years. Consequently, many cities start to build up 3D city models as part of their local data infrastructure.

Parallel to the development of improved data acquisition technologies and object extraction algorithms, open data models such as KML/Collada, X3D, and City GML have been developed that are used to represent 3D city objects. Our contribution will focus on City GML-based 3D city models and neglects other solutions; however a discussion on the difference to IFC, X3D and KML can be found in the article by Kolbe (2009) and Yanbing et al. (2006) present an overview on 3D spatial data model approaches developed in recent years.

CityGML is deliberately chosen for several reasons. (1) It is an OGC standard based on Geography Mark-up Language (GML), which enables the use of web feature services for querying 3D city model data and facilitates the integration of 3D city model data with other spatial data sources made available through OGC web services (Döllner and Hagedorn 2007). (2) It defines an expandable, semantic and spatial data model, which makes it possible to adopt it to specific problems (e.g. Czerwinski 2006). (3) An open source database schema (IGG 2009, online) is free available which can be used to store, represent and manage CityGML-based 3D city model on top of Oracle 10g/11g. Along with the database schema a Java-based Import/Export tool is free available as well as a Java class library and API for facilitating work with City GML (IGG 2009, online). (4) Finally, City GML is increasingly adopted within research, by city administrations and supported by software vendors in the GIS and CAD domain.

2.2 Spatial and Environmental Planning

Contemporary challenges in spatial and environmental planning such as including social, ecologic, and economic dimensions into planning activities, designing transparent planning processes and enabling participation and collaboration between multiple stakeholders require tools and methods to facilitate communication, support collaboration, monitor land-use change, and assess environmental impacts of development scenarios and planning proposals. Geoinformation Sciences contributes many tools and methods to better solve these challenges, e.g. by making (geo-)information available to stakeholders via Web Services, by the development of land-use models for predicting future developments and analysing the impact of policies, by providing GIS analysis functionalities, or by developing planning support systems (Geertman and Stillwell 2003).

In this context, GeoVE are utilized to visually communicate and explore planning proposals and development scenarios in urban, landscape, and environmental planning (e.g. Bishop and Lange 2005, Buhmann et al. 2005, Counsell et al. 2006, Kibria et al. 2009). While early experiments in this field were often based on manual 3D modelling and Virtual Reality Markup Language (VRML) to create real-time visualizations, other approaches adopted game engines (e.g., Herwig et al. 2005, Stock et al. 2005) which provide sophisticated 3D visualization capabilities, physics engines and possibilities to interact with the GeoVEs created.

However, many of the methods and solutions developed were limited in the past – either with respect to the visual quality, the interactivity, the information intensity, the required computing power needed or simply because of the effort and costs needed to prepare the GeoVEs. Still these early experiments have shown that interactive 3D models and/or images and animations derived from them can support communication and participation processes between multiple stakeholders (e.g., Danahy 2001; Orland et al. 2001, Schroth 2007). This situation has changed, though. Software like Autodesk LandXplorer 2009 (Autodesk 2009, online), internet-based "digital globes" like Google Earth (Google 2009, online), and Java-based web-clients with support for OGC web services like the xNavigator (GDI3D 2009, online) are used to visualize large 3D city models from heterogeneous data-sources. Actually, we can observe a paradigm change from experimental models towards sophisticated, large and detailed 3d city models which are accessible over the internet (e.g. Kulawik et al. 2009). With the increasing availability of official, city-wide 3D city models as described in the previous section, planning professional now could – at least theoretically – use complex, large, and detailed 3D city models as base models into which planning proposals and development scenarios can be integrated and even published online.

Visual communication of planning proposals or scenarios is only one option for the utilization of 3D city models in spatial and environmental planning, though. Analytical functions which operate on geometric, semantic and topologic properties of 3D city models such as noise emission simulations (Stoter et al. 2008, Czerwinski 2006), simulations of air pollution dispersion (Lin et al. 2009), detection of potentially suitable roofs for solar collectors (Klärle 2008), and shadow-analysis (Lange and Hehl-Lange 2005) are further applications, which can be used to optimize planning proposals or analyse existing city structures. Such analytical functionalities add value to 3D city models as well as to spatial and environmental planning as new knowledge can be produced and spatial concepts can be algorithmically analyzed and optimized.

To make use of the theoretical advantages, it will be necessary that 3D city model data is made available to planning professionals and that they are enabled to integrate their proposals into existing 3D city models. This would support the use of 3D city models as GeoVE into which planning proposals and development scenarios can be integrated to facilitate visual communication between stakeholders and at the same time their utilization in complex spatial (3D-) analyses to assess spatial and environmental impacts of proposed developments.

2.3 E-Government

E-government is defined as ICT-based services to enable information, collaboration, participation, and transactions between governmental institutions (G2G), government and business (G2B) as well as between government and citizens (G2C). According to the United Nations (UN 2005), e-Government is an important factor for economic growth and international competitiveness. It is also seen as significant contribution to the process of transformation of the government towards a leaner, more cost-effective government (UN 2008). Supranational e-Government initiatives like i2010 in Europe (COM 2005) and national e-Government activities (e.g. the German programme E-Government 2.0 and the e-GIF initiative in the United Kingdom) support the idea of e-Information, e-Participation and e-Collaboration to involve the public in planning processes and increase transparency in spatial and environmental decision-making. Research projects like the Virtual Environmental Planning project (www.veps3d.org) have shown how citizens can get involved in planning processes via e-Participation platforms based on 2D map services and 3D city models. Although further examples exist, a broad adoption of this technology can still not be observed. Amongst the reasons that hinder a broader utilization of 3D city models are organizational issues of high relevance: In general the exchange of planning information is regulated by law and plans have to be signed by planners and members of the civil administration and archived to ensure their legal validity. In the past this could not be solved through digital processes. Now, technologies and methods to enable authentication, secure data transfer, digital rights management and revision-save storage of data are available. At the same time official 3D city models are increasingly available and can be used to integrate and visualize planning proposals in a broader spatial context. If this knowledge is related to the fact that in contemporary planning practice most plans are produced in digital form (e.g. as CAD plans and models, GIS data, or BIM) the main research questions of this contribution become obvious: *Which digital workflows and processes are needed to integrate digital planning information into official 3D models to enable e-Participation and e-Collaboration under the metaphor of the virtual city on a regular basis? Which technology is needed to implement such concepts and is it available?*

3. CONCEPTUALIZING E-COLLABORATION PROCESSES BASED ON OFFICIAL 3D CITY MODELS

To conceptualize an e-Collaboration framework which supports the regular use of official 3D city models, in a first step, a stakeholder analysis is conducted to identify stakeholder groups, which will benefit from the utilization of 3D city models in planning practice. In a second step, general and stakeholder specific requirements are defined which are a prerequisite for the continuous utilization of 3D city models via ICT by multiple stakeholders. Based on a generalized illustrative example, digital processes are outlined that will have to be implemented to provide completely digital workflows and data exchange. Within this step key technology aspects of the identified processes will be discussed to assess the availability of the technology needed.

3.1 Stakeholder Analysis

Stakeholders in spatial and environmental planning are people and organizations from the civil, private, and public sector, who are involved in local planning decisions (Healey 1997).
The civil sector, i.e. public administration, is responsible for co-ordinating spatial and environmental planning activities within a city or municipality. Usually, the planning department represents the authority responsible for giving planning permission. However the planning department is by far not the only authority interested in spatial planning. It has to co-ordinate plans with environmental, transport, social and economic departments and agencies on local to national and even supranational level. Within this internal coordination processes, the integration of 3D plan representations into semantic 3D city models can be used to visually communicate and assess planning proposals, e.g. visual assessment of important lines-of-sight. Furthermore, the planning department and other authorities can use 3D city models for advanced simulations and analysis functions, e.g., noise emission simulations, shadow analysis, suitability for solar collectors, local wind-field simulations as introduced in section 2.2. In short, the integration of 3D plan representations into virtual 3D city models could support information exchange, spatial analysis, and communication processes within the administration (Government to Government - G2G).
Members of the general public are diverse stakeholders with varying interests and very heterogeneous map-reading skills and often competing interests (Selle 2000). Since 3D visualizations provide an intuitive way for communicating spatial concepts (cp. section 2.2) one of the most important arguments for the utilization of 3D city models is that they are likely to facilitate understanding and capacity building within this stakeholder group. Therefore, a continuous integration of planning proposals into 3D city models could offer an innovative solution to provide information about planning processes to the public and implement e-Participation and e-Information services (Government to Citizen - G2C) on a regular basis.
Finally, the private sector or rather the market includes as diverse stakeholders as architects, engineering companies, project developers, land owners and investors. The main advantages attributed to 3D city models from the private sector are twofold: First, 3D city models provide a "scene" into which a new design can be integrated and interactively visualized and explored, e.g. to facilitate communication between investor and architect or architect and planning department. Second, the integration of plans into 3D city models offers new ways of analyzing and assessing the impact of proposed constructions on the environment and the cityscape as discussed in section 2.2. It is obvious that these usage concepts are very similar to the concepts discussed with respect to the civil sector. Both groups have a professional interest and need access to the 3D data to work with it. Therefore, it will be necessary to enable them to exchange data (3D city model data and 3D plan representations) amongst each other (Business to Business - B2B and Business to Government - B2G).
The different stakeholders compete with each other in respect to their roles and rights regarding 3D city models and 3D plan representations. The main and most important conflict of interest arises between the cadastre and the planning department, potentially involving other departments such as city marketing, too. The cadastre department has the public mandate to maintain geodata with a very high standard and in most cases is responsible for the management of official 3D city models. However, within planning processes official 3D city models will be modified, changed and updated regularly. Therefore, an e-Collaboration framework will have to provide a solution which enables the cadastre department to maintain a valid official 3D city model and at the same time makes it usable, accessible and expandable for other stakeholders. Another conflict that arises is the question who owns 3D plan representations integrated into 3D city models during different stages of planning processes.

3.2 Key requirements for collaborative use

Within section 3.1 stakeholders who benefit from the utilization of official 3D city models in planning processes were identified and it was discussed which usage concepts and roles are associated with the three stakeholder groups. From the stakeholder analysis key requirements for the long-term operational use of official 3D city models by multiple stakeholders in planning processes can be defined:

General requirements:

– Transparent Access: 3D city models will have to be accessible by authorities, the public, and planning professionals.

- Defined Standards: To ensure integrity and comparability data standards and defined levels-of-detail of 3D plan representations are needed.
- Publishing Tools: Functions to publish 3D city model views to selected stakeholder or stakeholder groups (e.g., general public, involved engineers, authorities) are needed.
- Communication Tools: Communication tools that enable communication between stakeholders based on 3D city model views are necessary.
- Long-term Management: Plan management and versioning functions are needed to ensure the integrity of the databases for the long-term, sustainable use.
- Rights Management: Data owners and stakeholder must be enabled to administer user and access rights.

With respect to the research questions formulated, these general requirements have to be complemented by specific requirements needed to enable the integration of plan representations.

Specific requirements:

- Model Provision: Planning professionals require to get official 3D city data as base data for creating designs and conducting 3D spatial analysis.
- Model Reuse: Planning professionals must be enabled to integrate 3D plan representations into official 3D city models.
- Model Documentation: Authorities must be enabled to store revision save and digitally signed plan versions.
- 3D geo-processing functions: To increase and facilitate the analytical usage of official 3D city models, generic 3D geo-processing functions are needed.

3.4 Example E-Collaboration Use Case

In the following section a generalized illustrative use case for the utilization of 3D city models within planning processes is described. Since planning professionals (PP) are identified to play a central role as they are users of 3d city model data and provider of planning information, it will be necessary to define digital workflows that allow them to request 3D city model data and to integrate 3D plan representations into 3D city models as well as to publish their work to stakeholders involved in planning process. The workflows (Fig. 1 and Fig. 2) needed to accomplish this can be subdivided into processes, which are detailed subsequently.

Process 1: Registration and authorization of PP and announcement of the planning processes
In a first step it will be necessary that PP authorize and register themselves and announce the type of planning process they are working on. This can be realized through setting up a *P*lanning *I*nformation *M*anagement *S*ystem (PIMS), which supports authorization and registration. Such a system can be implemented based on common ICT technology comparable to a content management system, only that it stores information and data related to a plan. Within this step, basic planning information such as type of plan, responsible planner, land owner, et cetera are collected.

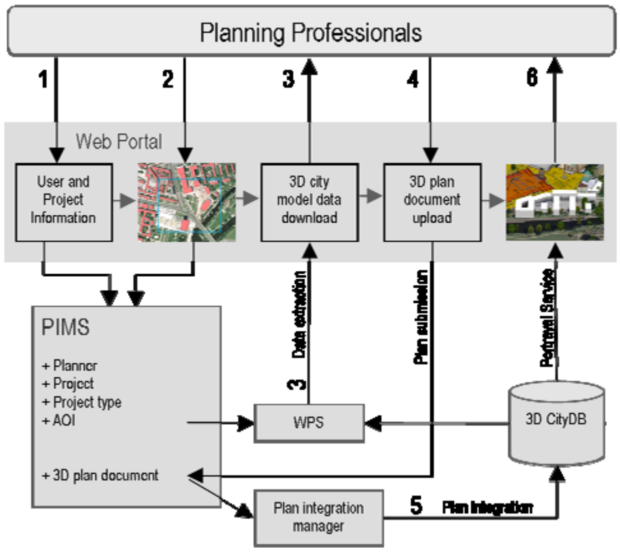

Fig. 1: Workflow diagram for the processes 1 to 6

Process 2: PP request model data for a defined area of interest (AOI).
To implement this process, we can use an input form to get the bounding coordinates of the AOI or a web-map service providing a city map and a function to define an AOI. This process should not be exclusively limited to 3D city model data but can be extended to include further data sources such as cadastre information, environmental information, cultural heritage information, and legal binding spatial and environmental planning information from (local) spatial data infrastructures. The AOI definition should are also stored in the PIMS for documentation purposes and to facilitate the integration of the 3D plan representations later on.

Process 3: Model data is automatically extracted from the 3D city model database and provided to the PP.
Based on the AOI definitions, server-side functions or web processing services (WPS) can be used to extract 3D city model data from official 3D city model databases and serve it to PP. In case of CityGML-based 3D city models it is also be possible to integrate the model data directly into 3D visualization systems using web feature services (WFS) as demonstrated by Döllner & Hagedorn (2008). Kolbe (2008) discusses the possibility to extract (City)GML data using a WFS in combination with a Web 3D Service to create KML based 3D representations. With this approach City GML data can be transformed into KML which is supported by several software solutions from the ACE domain. Kulawik et al. (2009) use a Java-based converter to process CityGML files and export them to KML and VRML/Shape for visualization purposes and to store the data in a database. Ideally, an expandable import/export manager would have to be implemented which supports the provisioning of city model data in several formats.

Process 4: PP submit planning proposal to PIMS
Based on the acquired data PP create planning proposals as 3D plan representations based on the received 3D city model cut-out. These proposal can then be submitted back to the PIMS. To ensure operability, integrity and validity only agreed exchange formats (e.g., CityGML, IFC, X3D) are accepted and level-of-detail definitions have to be obeyed. The upload can be implemented as file-upload or through transactional WFS.

Process 5: On demand integration of planning proposals into 3D city models

After planning proposals have been submitted to the PIMS, functions to integrate them into the official 3D city model are needed. In the case that planning proposals are submitted in CityGML format, this can be done by combining the official city model with the planning proposal.
However, current 3D modeling software does not support CityGML and submissions most likely might be allowed in other formats as discussed in process 4. Therefore, complex data transformations such as the transformation of IFC data to CityGML as described by Benner et al. (2004) and Isikdag & Zlatanova (2009), the transformation of triangulated multipatches to CityGML as described by Ross et al. (2009) or the transformation of one XML-based data schema into another as described by Henning (2008) can be used. In case that parameterized 2D data, e.g. building polygons with height information, is allowed as data model for representing a plan, the data must be extruded and converted to CityGML. This can be implemented through 3D geo-processing operations for OGC web processing services as discussed by Göbel & Zipf (2008) or comparable server-side geo-processing functions.
Another solution is to directly integrate planning proposals provided as 3D model in industry standard formats such as 3ds, obj, or x3d. This possibility is supported by CityGML through the option to include generic city objects. However, this approach will not include semantic object information and further information such as scale, position, and rotation might be needed to automate the on demand and integration into the official 3D city models. The on demand integration requires a plan integration manager which handles data conversation and integration.

With the introduced process steps it is possible to implement a workflow that enables PP to acquire and utilize official 3D city model data, submit planning proposals to a plan management system and integrate planning proposals into 3D city models on demand. However the data acquisition, preparation of plans, and their integration into 3D city models are just a first step. To allow participation and collaboration of further stakeholders, it will be necessary to define workflows that facilitate communication between stakeholders based on 3D city model views as illustrated in Fig. 2.

Process 6: PP explore integration results
This step is necessary to enable PP to visually assess the integration results and detect possible integration or design errors prior to publishing proposals to further stakeholders. This process requires a web-enabled 3D city model viewer which might be implemented as Web 3D Service (Kulawik et al. 2009), Web Perspective View Service or even based on clients like Google Earth. If PP are not satisfied at this point they can redesign the proposal and restart with process 4, else they can publish their planning proposals to other stakeholders.

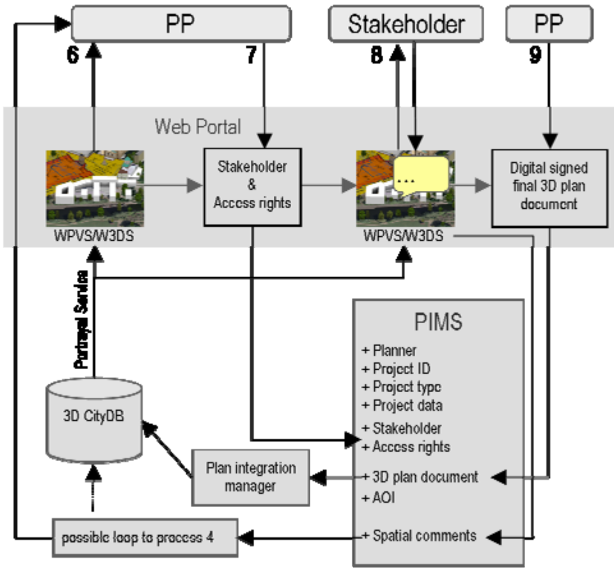

Fig. 2: Workflow diagram for the processes 6 to 9

Process 7: PP publish the planning proposal to stakeholders
Within this process PP must be enabled to define users and/or user groups that can access planning proposals. Furthermore, access rights might be necessary to differentiate between stakeholders, e.g. some stakeholders might be enabled to comment, while others are allowed to view the planning proposal and further groups might be allowed to download and use the source data for analysis or design supplements.

Process 8: Stakeholder comment on the planning proposal
By giving PP the possibility to publish planning proposals to other stakeholders the proposals can be explored and discussed or even be used for collaborative. In addition to a web-based viewer, visualization-based tools for spatial communication must be implemented, e.g., options to add spatial comments to city models or to draw on top of city model views (images). This process might result in the decision to re-work the plan or parts of it due to legal requirements or design needs identified by stakeholders. Thus process 4 to 8 are likely to be cyclic processes in practice.

Process 9: PP transfer planning proposal to administration
At a certain point plans are final and have to be submitted to planning authorities to enable them to examine if proposals fit building and planning regulations and can be approved. In contrast to the processes discussed prior this process is final. Therefore, the ownerships and the user rights connected with planning proposals have to be transferred from the PP to the responsible planning authorities, planning proposals have to be digitally signed and stored in a revision-save form. The planning authorities as responsible bodies for approving or rejecting planning proposals might restart at process 7 to include further stakeholders such as other departments or the public in the planning process.

Process 10: Registration of the approved planning proposal as temporary plan object in the official 3D city model
Upon approval of planning proposals the planning authority transfers them to the cadastre department which registers it as *temporary city object* in the official 3D city model. This ensures that approved plans are integrated at an early point of time into the data infrastructure and can be accessed by stakeholders through e-Information services. After the plan is implemented, i.e. the construction work is finished, the

temporary plan object can be used to update the official 3D city model database by changing its status from temporary to existing. However, it will be necessary to compare the digital representation with the real situation prior to the final acceptance of plan objects.

3.2.1 Excursus: The role of CityGML

In paragraph 2.1, the reasons for concentrating on CityGML as interchange format were explained. The use case shows why CityGML is very powerful as interchange format for official 3D city models: (1) Since it has become a standard in 2008 CityGML is increasingly adopted by scientists working in the field of 3D geo-information and several studies have shown that it is possible to convert CityGML into formats, which are better suited for 3D-visualization such as KML and VRML. (2) The database schema is not only compatible to Oracle 10g/11i, but it also provides a structure, which make it easier to standardize planning proposal submissions. (3) The expandable and semantic data model can store semantic information allowing new forms of analyses. Most important, the Application Domain Extensions (*ADE*) enable the various stakeholders to adopt CityGML for their specific purposes. The CityGML noise ADE, used in North Rhine-Westphalia, Germany, provides a good example (Czerwinski 2006) for the use of ADE.

However, there are of course limitations to CityGML: Although it is acknowledged by the Open Geospatial Consortium OGC, only a couple of software products support CityGML export or import yet. Furthermore, is has been argued that CityGML might be limited in its performance when storing large datasets with very high levels-of-detail. However, more precedents are necessary to test the boundaries of CityGML in official 3d city models in the context of spatial and environmental planning.

4. DISCUSSION

The presented simplified digital workflows show how the continuous utilization of 3D city models by planning professionals can be implemented based on a service-oriented architecture and existing international standards. The provision of 3D city model data as well as the continuous and automated integration of plan representations into 3D city models which becomes possible by the proposed digital transaction of planning information between planning professionals and authorities, will make it possible to establish communication and participation processes via ICT. References to related work show that the city modeling technology and methods for such an e-Collaboration framework are already available. However, the implementation of the concept will require to set-up several data provisioning, processing and integration services, which are integrated into one planning information management systems. This planning information management system makes the services available to multiple stakeholders through a central interface as described by Wang et al. (2007) and stores and manages plan documents and planning information. Thereby, one of the key challenges seems to be the sophisticated user and rights management which is necessary to ensure the integrity and validity of the system.

Moreover, business process with in municipalities will have to be adopted to the new technology and employees will have to be trained. We think that an implementation is still likely to repay the effort and investment needed as it will enable planning professionals to work with high-quality 3D city model data and at the same time offers a solution to the problem of updating and maintaining official 3D city models. Even more the quality and level-of-detail of an official 3D city model could be enhanced continuously during its lifetime. This could especially be the case if planning proposals are submitted as semantic models to the system.

The proposed digital processes are not restricted to a specific planning domain or planning scale, but might be used as well in urban planning as in open-space planning or traffic planning. In urban design competitions for example, the use of 3D city models as shared base model could facilitate the objective assessment of all contributions as described by Lange et al. (2004). They conclude that the technology is already in place, but there is still strong skepticism to overcome, particularly among architectural associations. Therefore, additional research is needed to evaluate the benefits and limitations of using 3D city models as basis for urban design competitions. In the same direction points recent research by Kibria et al. (2009), who observed that our knowledge about the appropriate degree of realism and level of detail of planning proposals from varying disciplines and on different scales is very limited, although obviously the LOD increases during planning processes.

Strongly related to this uncertainty with respect to the appropriate LOD is the question which real world objects should be modeled. The references made to 3D city modeling within this contribution refer in almost all cases to buildings. The integration of streets, railways, open space, parks, vegetation, technical infrastructure and other objects is seldom researched so far on city level, although they represent important objects. To put it even stronger: If in the future these objects are included in 3D city models and in plan documents based on a ontology as in case of CityGML, it would become possible to report on the land-use changes induced by plans. This means that a continuously updated 3D city model could be used to create regular reports on important planning and land-use indicators such as imperviousness of a plan, urban density, increase/decrease of settlement area or the percentage of urban green in a defined area. Furthermore, the integration of all these smaller objects which coin the spatial structure of a city as it is perceived from a human perspective would enable valid visual or algorithmic assessments of important lines-of-sights which is presently not possible. Finally, the integration of other objects besides buildings will be needed to foster consultation of agencies responsible for economic, transport, environmental and other relevant issues. Such inner-institutional consultations are mandatory for planning departments in most countries and the processes are not digitally implemented yet. The provisioning of an expandable and semantic official 3D city model might provide a starting point to develop innovative tools and functionalities for implementing such e-Consultation processes within the administration.

5. CONCLUSIONS

Within our contribution we conceptualized an e-Collaboration framework based on digital workflows and processes that enable multiple stakeholders to utilize 3D city models in spatial and environmental planning and to collaborate based on 3D city models via ICT. It is argued that such e-Government functions will support the long-term utilization of official 3D city models as well as their continuous update. By referencing related studies it was possible to show that the implementation of the proposed concept based on CityGML, OGC Web Services, and current ICT technology can be done. However, it was also identified that current 3D city model research is in most cases restricted to buildings and that solutions and tools that enable semantic and geometric modelling of other objects in CityGML are still missing.

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INFORMATION MANAGEMENT IN CIVIL ENGINEERING INFRASTRUCTURAL DEVELOPMENT: WITH FOCUS ON GEOLOGICAL AND GEOTECHNICAL INFORMATION

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ABSTRACT:

In civil engineering infrastructural projects, information exchange and (re-) use in and between involved parties is difficult. This is mainly caused by a lack of information harmonization. Various specialists are working together on the development of an infrastructural project and are all using their own specific software and definitions for the various information types. The variety of information types adds to the differences regarding the use and definition of thematic semantic information. Also the source of the information may vary from surveyed and interpreted to designed objects. This makes harmonization of geo-information extremely difficult. Realistic 3D models describing and integrating part of the earth already exist, but are generally neglecting the subsurface, and especially the aspects of geological and geotechnical information. This paper summarizes the first steps undertaken towards the extension of an existing integrated semantic information model to include (above and on) surface as well as subsurface objects and in particular, subsurface geological and geotechnical objects. Standards, exchange formats and existing models used as a basis for the development of a core geological model as part of an integrated 3D information model are described in this paper. Examples of definitions of subsurface geological objects and required attribute information (to be) included in the integrated 3D information model are given. Web-based visualisation tools are, too, investigated to be able to access and visualise the model also in an application-independent environment.

1. INTRODUCTION

Around the world people are busy with the planning, design, realization, or maintenance of infrastructural projects. During these various phases of infrastructural projects tasks must be accomplished, which require different skills from professionals. The execution of these tasks involves large quantities of geo-information (e.g. GIS-, CAD-, and other data sets). On the example of infrastructural development, it becomes clear that the lack of information harmonization is still a problem. It is, for example, well known, although not often expressed publicly, that the re-use and exchange of information is only seldom achieved. The limited exchange and re-use of information increases the project costs and more importantly, may lead to less optimisation in project management.

One of the main problems of professionals working in infrastructure projects is the lack of common models in which data created in the different applications can be represented together. Furthermore, due to differences in semantic or geometric properties, no guarantees are given that the set of data from one GIS or CAD system can be seamlessly converted in another (Apel 2006, Oosterom et al 2006). By defining a reference model, application-specific models can be integrated and exchanged between system platforms using service-oriented architectures (Bodum et al 2005, Döllner and Hagedorn, 2008, Lapierre and Cote 2008, Haist and Coors 2005).

3D models have been extensively used in many areas but all the developments have been restricted to particular tasks (design, visualisation, etc.) and application areas. Integrated generic models discussing real-world features on the surface, above and beneath the surface are still in their infancy (Emgård & Zlatanova 2008). The integration of subsurface features, the digital terrain model and features on the terrain remains a problem to be solved (Kolbe & Gröger 2003). Although, geological data models and software provide tools to represent sophisticated geological situations in three dimensions (Apel 2006, Hack et al 2006, Lattuada, 2006, Raper and Maguire 1992, Raper 1989, Breuning and Zlatanova 2006), these models are not integrated with the surface (and above surface) models. A number of international standards and industry specific formats have been developed for geometric and semantic descriptions of existing features as well as design features both above and below the earth surface (e.g. GeoSciML, IFC, or CityGML) but they are still quite specific for a certain domain and not integrated. Challenges are in both, geometry and semantic (thematic) heterogeneities.

Looking at all information types available, especially geological and geotechnical (below) surface conditions play an important role in most construction processes. The geological situation at and around the construction site can have significant impact on how the construction process and design will be planned and undertaken as well as on the security of the construction itself. Various examples all over the world show that the geological conditions should not be neglected throughout any construction process.

This paper concentrates on the options for integrating geological and geotechnical data in an existing integrated 3D information model to be used in civil engineering projects. First current problems and user requirements for an integrated management of information are briefly presented. Then several information models, data models, exchange formats, and standards are discussed. Section 3 gives a short overview of some of the designed geological classes to be included in the integrated 3D information model. Section 4 discusses general system architecture for access and exchange of data. Finally, Section 5 concludes on the presented research and provides recommendations for further developments.

2. MANAGEMENT OF INFORMATION IN INFRASTRUCTURE PROJECTS

In the last years several studies have been performed on the need for integrated management of information during large civil engineering infrastructure projects. For example Young et al. 2007 report that 3.1% of project costs are related to software non-interoperability. Between the factors impacting data sharing, software incompatibility issues are leading (62%). A study performed in the Netherlands within the project 'Geoinformation management for civil infrastructure works' (GIMCIW, www.gimciw.nl) in the period 2006-2007 has revealed similar low efficiency in data management. Within the study several large companies were interviewed; the number of involved companies differs but in any case more than 8-10. The major conclusions of the study are:

- Large amounts of the data have a geo-component.
- The work within a project is file-based as each partner maintains a copy of all necessary data sets and is responsible for their management.
- Much of the design information is based on 2D CAD drawings (and not 3D models).
- GIS is used insufficiently, while the benefit of possibilities to perform spatial operations is well-understood.
- Geological data (boreholes, soundings, etc.) are given mostly as measurements and tests, and hardly any 3D models of geology or geotechnical data of the underground are used.
- The name of the file provides information about the content of the file, the version and the phase in the project (e.g. concept, final/approved).
- The exchange of information is via e-mail after a request by the project leader.
- The project leader is responsible for the management of data, which usually done in Excel sheets or specific software for document management (e.g. Meridian, www.meridiansystems.com).
- Often it is difficult to create a global overview on the status of the project. A company is responsible for a part of the work.
- Exchange of data and information is complicated by the use of different data formats (software).
- Data might be lost in consequent stages of the project especially when a partner has completed his/her obligations to the project.

The companies have agreed that improvements in management, access and sharing of information are urgently needed and can be achieved by: centralized storage of the most important data, web-access to all the needed data from all parties (and from the server), facilitation of data (model) conversions, standardized metadata information, extended use of 3D models, and better management of administrative data. There is strong understanding that tools should be available to present the progress within the project to both the professionals and interested citizens. In this respect an integrated 3D model is seen as one of the first steps in achieving better communication and interoperability (assuming that much of 2D interoperable challenges can be solved with recently developed national and international standards). The work on such model is ongoing. Within this work, Emgård & Zlatanova 2008 took the first step towards the development of an integrated 3D information model (3DIM) by conceptually enriching the CityGML information model with top-level abstract classes for above, on and below surface features. As discussed elsewhere (Tegtmeier et al, 2008), the concept of an integrated 3DIM is considered very appropriate for infrastructure projects Following, we have investigated available standards for the handling of geological and geotechnical subsurface objects to develop the geology abstract class as proposed in 3DIM.

This paper will now concentrate further on the developments related to organization and management of geological and geotechnical data.

3. STANDARDS FOR GEOLOGICAL OBJECTS

Currently the exchange of geological and geotechnical information in The Netherlands is largely based on the Dutch Geotechnical Exchange Format (GEF) standard (CUR 1999, GEF 2009), but for the purpose of our study we have investigated several existing and frequently applied common information models such as the Dutch NEN 3610, INSPIRE, CityGML (Gröger et al. 2007), 3DIM (Emgård & Zlatanova 2008), and the international geoscience information model GeoSciML (GeoSciML, 2007).

The Dutch harmonized base model of geo-information NEN 3610 (NEN 3610:2005) gives specifications of features on the surface, above the surface and utilities. The model defines a base class and a hierarchy of sub-classes that can be extended with sectors (domains) models. Such a sector extension is the Dutch topographic model for scale 1:10000 (TOP10NL) as described in (Quak & de Vries 2006).

At an international level, a first attempt towards an integrated information model has been undertaken within the EU initiative INSPIRE. Within Europe the INSPIRE Deliverable 2.5 of the Data Specifications Drafting Team, the 'Generic Conceptual Model' (INSPIRE 2008), has similar goals as the ones behind the Dutch NEN 3610 developments (Quak et al. 2007). In the directive 34 different spatial data themes have been identified, covering natural and man-made features as well as administrative and environmental features. For the first 9 themes ('Annex I'), the data specifications are currently being created and expected to be finished before the end of 2009. In the current draft version of the theme Coordinate Reference Systems (INSPIRE TWG CRS, 2008) it is stated that 'When using both ETRS89 and EVRS the CRS used is a compound one (ISO 19111) and shall be designated as ETRS89/EVRS. It allows unambiguous 3D geo-referencing, as requested by INSPIRE.' The other INSPIRE Annex I themes do hardly ever mention 3D explicitly and in the UML class diagrams the GM primitives of ISO 19107 Spatial Schema are used without stating if this refers to a primitive in 2D or 3D space. One exception is the theme Cadastral Parcels (INSPIRE TWG CP, 2008), which mentions the need for 3D cadastral objects.

After the Annex I data specifications have be created, it can be expected that in the Annex II (e.g. Elevation and Geology) and Annex III (e.g. Soil, Atmospheric conditions, Oceanographic geographical features, and Energy resources) themes more often explicit reference to the 3D aspects of the objects will be made.

Very promising developments are observed within the new OGC standard CityGML. CityGML is a common information model used for the representation of 3D urban objects. CityGML allows for a description of classes and relations, and geometric, topological, semantic and appearance properties for the most relevant topographic objects in cities. CityGML includes hierarchies between thematic classes, levels of details and also relations between objects and spatial properties. Presently, CityGML does not provide support of geological features. Moreover CityGML considers below surface features (utilities, tunnels, geology, etc.) a subject of the so called application domain extensions (ADE), which are subclasses directly to the *CityObject* or *Site* class. For example, a *Subsurface* ADE (focusing on tunnels) is already available (www.citygmlwiki.org).

The Dutch GEF standard is a typical example of a format for the exchange of geotechnical information. It can be compared with the 'Observations and Measurements (O&M)' schema by the OGC (OGC 2007). The GEF standard consists of three types of information about: 1) the manner and circumstances in which the measurements have been carried out, 2) how the measurement results are stored (metadata), and 3) measurements including interpretations, derived models, etc. To be able to collect all this information, a specific methodology has been suggested as well. As to the organization of the data, the actual measurement results (i.e. the raw data) are saved in the file, preceded by a header which describes in a readable form (i.e. ASCII) how the measurement is composed. In addition, information is structured using fixed keywords (e.g. 'ANALYSISCODE', 'PROJECTNAME', 'FILEOWNER', etc.).

Table 1: Comparison of the characteristics of the various standards and models

	NEN3610	INSPIRE	CityGML	GEF	GeoSciML
Covered features	On & above surface features & utilities	(Sub)sur-face natural & man-made features	Relevant topographic features in cities	Geo-technical features	Geo-scientific features
Way of modelling	Semantics	Semantics& Geometry	Geometry & Semantics	Semantics	Geometry & Semantics
Complexity	Only surface information & utilities; no geology	Surface & Subsurface information; but basic geology	Only city objects; no subsurface information, no geology	Only geotechnical measurement results	Good geology information; geology-specific
Relation above and below surface	Partly	Partly	Partly	None	None
Dimension	-	2D	3D	-	-

The last model considered is GeoSciML. GeoSciML is a geoscience data model, which has been designed for the storage and exchange of geoscience information (GeoSciML 2007). GeoSciML represents geoscience information associated with geologic maps and observations and allows an extension to other geoscience data. A common set of feature types is defined based on geological criteria (e.g. units, structures, fossils) or artefacts of geological investigations (e.g. specimens, sections, measurements). Supporting objects such as time scale and lexicons are also considered so that they can be used as classifiers for the primary objects.

These different standards and models have been investigated because of their appropriate characteristics for geological and geotechnical features. These characteristics have also been summarized in Table 1.

3DIM might become the bases for an integrated 3D information model for large civil infrastructure projects, since it allows a near complete representation of 3D urban objects. To include geological and geotechnical information in 3DIM, the information covered by GeoSciML, which provides geometric and semantic information, is evaluated with respect to the needs of the larger audience of professionals working in civil engineering projects. In contrast to CityGML and GeoSciML, NEN 3610, GEF, and INSPIRE provide only semantic information or focus on 2D representations. However, they are considered to ensure that the developed model is compliant with national and international standards.

4. GENERIC 3D INFORMATION MODEL EXTENSION FOR GEOLOGY

The thematic semantic information model (thematic semantics = the meaning of data with regard to a specific subject) of subsurface geological and geotechnical features as developed by Tegtmeier et al. 2008 is considered an extension of the 3DIM. In order to include subsurface geological and geotechnical features in 3DIM model has first been extended by including *Geology* in the subsurface class *BelowSurfaceObjects* (Emgård & Zlatanova 2008). The 3DIM has adopted many of the concepts of the base model NEN 3610 and achieved subdivisions of features into: 1) earth surface features, 2) above earth surface features, and 3) below earth surface features (Figure 1). One of the below surface classes is *Geology.* This class is the super class of all the object classes described in this section. The super class *Geology* includes, next to general geological information, mainly the geotechnical aspects of geology of importance for infrastructural construction processes.

The class Geology is further split up into different features (geological objects) to support infrastructural development. After an extensive study on the use of geological objects in infrastructure works, the following five subclasses are defined:

- *Layers* include the subsurface geological features that occur as continuous layers in the subsurface. Usually these are units of igneous, sedimentary or metamorphic origin, of comparatively homogeneous compositions with well-developed boundaries. The *Layer* can, depending on the material it consists of, further be subdivided into three sub-features, that are namely: *LayerRock, LayerStrongSoilWeakRock* and *LayerSoil.*
- *Obstacles* are objects, which do not fit the description of the geological layer, in which they are found, but which are too big to be neglected for the construction process. Obstacles are, for example, boulders, that are 'large rounded blocks of stone lying on the surface of the ground, or are sometimes embedded in the ground, different in composition from the material in the vicinity and which have been therefore transported from a distance.
- *Cavity* represents natural underground empty spaces, whose size and extension is large enough and cannot be neglected during construction processes. Natural underground spaces can be karst holes.

- *Reservoir* (water, oil and gas). Reservoirs can be described as a body of rock or soil carrying water or containing an accumulation of hydrocarbons; or as natural underground containers of liquids, such as water, oil, and gases. In general, such reservoirs are formed by local deformation of strata, by changes of porosity, and by intrusions.

The definitions used are based on the *Dictionary of Geological Terms* prepared under the direction of the American Geological Institute (AGI 1976) and the *Geological Nomenclature* by the Royal Geological and Mining Society of The Netherlands (Visser 1980).

The above mentioned classes are further specialised. Figure 2 is an example of the required subdivision for the geological feature *LayerRock* with its attributes and associations. As within a project area, different types of rock layers might occur and/ or the properties within one type of rock layer might vary, *LayerRock* will be described as an aggregation of a number of homogeneous geological units.

A GeologicalUnit can be defined as a homogeneous unit of the same material with none or only slight variations in material characteristics and properties. Each *GeologicalUnit* can be described by visual descriptions, field measurements, and field/laboratory testing. Therefore all three possibilities are included in the model (not shown here). For the management of field measurements, sampling and laboratory testing, a separate model has been developed and linked to the relevant information in another thematic semantic model with the help of IDs (e.g *sampleID*, *measurementID*, *labtestID*) (not shown here). The attributes are largely derived from the Dutch GEF.

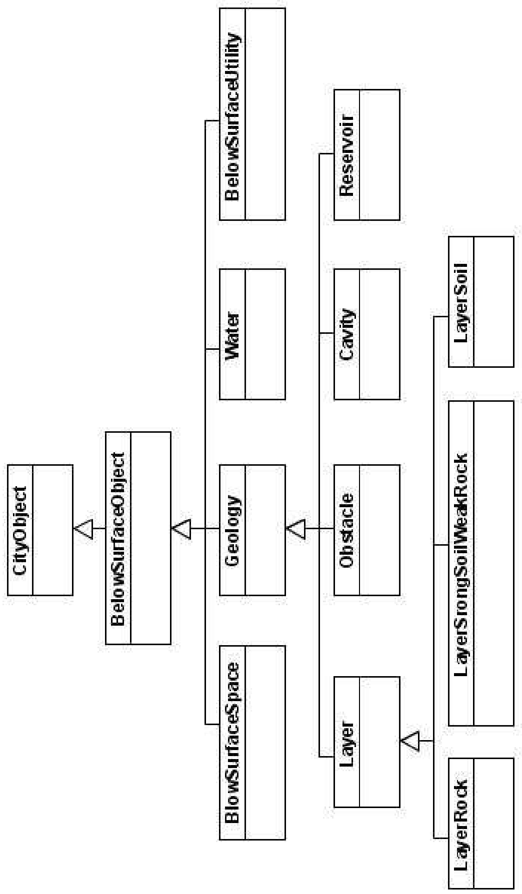

Figure 1. 3DIM top level clases of the *BelowSurfaceObject* hierarchy

The class *GeologicalUnit* can be further classified as *IntactRock* (i.e. rock that does not contain discontinuities of sedimentological, structural or other origin) and *RockMass* (i.e.rock as it occurs in situ, including discontinuities). All attributes are based on the standards discussed above and agreed with the users. For example *WeatheringDesc* refers to the possibility of the destruction of the rock material by physical, chemical and/or biological processes (Figure 2). Several attributes give further information on the weathering (not shown here).

Next to these descriptive models (including derived and processed information) for each geological feature, more detailed information collected from site investigation as well as field and laboratory measurements are needed throughout the whole lifecycle of the infrastructural project. A clear picture of the geological and geotechnical situation at the construction site as well as sufficient information about the properties and possible behaviour of the geology with respect to the construction activities is needed to ensure a safe and economic planning of the infrastructural project. For that reason, another level of the thematic semantic information model has been developed and included in the complete model (not shown here).

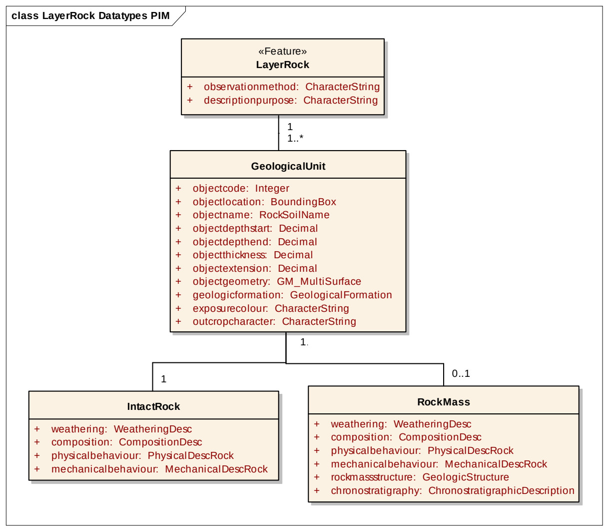

Figure 2: Subdivision of *LayerRock* into *IntactRock* and *RockMass*

At this stage the model contains all the data that might be collected and have to be available during the entire project life cycle. Practically most information included in the model should be collected throughout site investigation, field measurements and laboratory tests. The information model allows for differentiation and management of measurement data and derived results (i.e. interpretations). This is to say that the geological objects can be represented with their approximated geometries (using surfaces or/ and solids). These geometries can be used for integrated 3D visualisation with construction objects (e.g. tunnels) and above surface objects (buildings and terrain objects).

The model can be used as both exchange model and data model for centralised management of all underground measurements during infrastructure projects.

5. IMPLEMENTATION AND TESTS

As mentioned above, large infrastructural projects involve many parties, which are responsible for portions of the project and possess a variety of data sets. Although some data sets still remain for a single user only, there are large amounts of information, which has to be shared. The information could be vector (2D and 3D), raster, documents and videos (animations). Most of the information should at least be visualised (in integrated 2D/3D visual environment). Based on this analysis, we have proposed access to data via geo-portal based on web-services (Figure 3). The project web site will allow authorised access to information either to the data sets maintained by the project partners (or other data sets) or to the centralised data management system. The geo-counter provides metadata information as well.
The graphics user interface on the project site should allow for visualisation of 2D and 3D data via freeware as well as commercial viewers available within the project. Figure 3 portrays the system architecture. At the moment, only the 2D visualisation components are fully operational. Via the geo-locket the user can access files and databases needed during a specific infrastructure project and visualise the information either in 2D or in 3D viewer. The information remains accessible trough the entire period of the project.

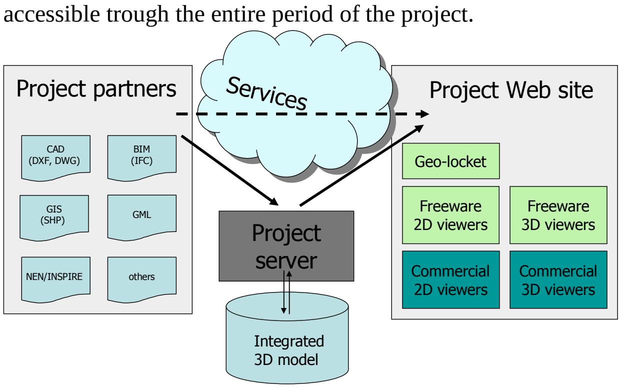

Figure 3: System architecture (GIMCIW)

The developed conceptual model (in UML) was transformed to Oracle Spatial relational model using the Enterprise Architect MDA prototype (Bennekom-Mennema, 2008). Enterprise Architect (SparxSystems, 2007) offers standard support for (relatively) straightforward MDA transformation rules from object-oriented models to relational database models. However more sophisticated transformations such as enumerations or attributes as base table check constraints required considerable custom development. The developed scripts were adapted for the geological classes and successfully executed to define a database schema. Several test sites are defined and the available data are in process of converting to the developed data model. Trial 3D visualisation was completed for only one (i.e. TUDelft campus) had features above, on and below surface (Figure 4).

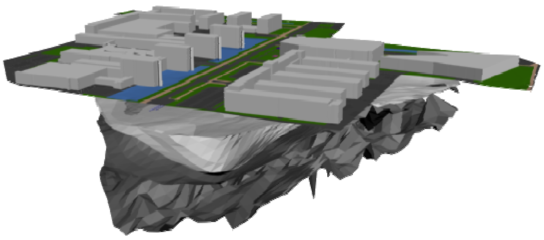

Figure 4: Visualisation of test site TUDelft campus in 3DIM (Emgard and Zlatanova 2008)

6. CONCLUSIONS AND RECOMMENDATIONS

Communication and information exchange and (re-) use is difficult in relation to civil engineering infrastructural development. In order to facilitate the information exchange and communication between different parties involved and also to achieve an economic and safe planning of infrastructural projects, harmonization of the various types of geo-information handled in infrastructural development must be realized. Ideally, a conceptual model for the thematic semantics of information frequently used in infrastructural development should be built up. As described throughout this paper, semantic models 3D models describing and integrating part of the earth already exist, but are generally neglecting geological and geotechnical information.
A solution to the integration of geological and geo-technical information has been investigated within this research. With it, a thematic semantic information model has been developed including information concerning all subsurface geological and geotechnical features considered to be of importance during the process of infrastructural development.
The development of this model has been guided by the discussions and interviews with companies and institutes involved in infrastructural projects. Therefore it can be seen as a more general model aiming at a broader group of users who work with geology and geo-technology information (in contracts to GeoSciML, which is intended for geologists). The features and the terminology in the model are also adapted with respect to this broader audience.
Another advantage of the model is that it allows not only the handling and storage of information concerning the physical description of the various geological objects, but also of information and results as derived through field and laboratory measurements aiming at a thorough description of the geology and geo-technology in the project area (i.e. information that is currently available in GEF).
Just as the CityGML information model, the thematic semantic information model provides a combination of 3D geometric as well as thematic semantic information for all objects included in the model. As an extension of 3DIM, the thematic semantic information model now makes the integrated handling and exchange of above, on and below surface information possible.
The model can also be seen as an ADE of the CityGML information model, which will allow the same browsers as developed for CityGML to be used for the visualization of the features in this model.
To prove the usefulness of the newly developed geological model, future research will concentrate on the database implementation of this extended version of the integrated 3D information model as well as testing of the set of thematic semantic information models using real world data as derived from infrastructural project case studies within The Netherlands. Emphasis will be given on 3D geometric representation and storage of the geological features, since such representations are still not a common feature. Currently the model is designed as a data model, but GML coding will be investigated as well.

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PERCEPTUALLY GUIDED GEOMETRICAL PRIMITIVE LOCATION METHOD FOR 3D COMPLEX BUILDING SIMPLIFICATION

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KEY WORDS: 3D complex building, Geometrical primitive location, Human vision system, Ray-casting

ABSTRACT:

Because of detailed geometrical components based description, 3D complex building contains the most elaborated perceptual and comprehensive semantic information. However, since the lack of optimal simplification method, the automatic LOD generation of such kind of model becomes a bottle neck which prohibited the high-fidelity 3D city applications. This paper proposed a perceptually guided geometrical primitive location method for the optimal simplification of 3D complex buildings. Firstly, the rendered image is snapped and a 2D discrete wavelet transform based human vision system filtering approach is adopted to extract the imperceptible details in the image, and then a kind of visual difference image is generated with sufficient perceptual information. Secondly, a ray-casting like method is proposed to precisely map the perceptual information from the image onto the geometric primitives. The statistics is carried out to determine whether a traced primitive is to be preserved or simplified. The results show that this method is able to efficiently locate the perceptible primitives and leave the imperceptible and undisplayable primitives to be further handled by simplification operations which enable a strong perceptual feature preserved simplification of 3D complex building models.

1. INTRODUCTION

Because of the limitation of rendering capability of modern display hardware, the simplification of 3D complex building model with highly detailed geometrical components is necessary in interactive applications (Li et al., 2006). However, this kind of 3D models is not only rich in coplanar, perpendicular and parallel features (Kada, 2007), but also contains components of various size which make it too difficult to be handled using existing simplification methods.

The essential problem of the automatic simplification of 3D complex building models is the optimal extraction of the geometric primitives that to be preserved (or simplified). Researchers of building generalization adopt the ground plan or the cell-decomposition to find trivial geometry from walls and roof of a building for reduction (Glander and Döllner, 2007; Kada, 2008; Sester, 2000), and methods based on scale space as well as using CSG tree aggregate the adjoined planes or small faces (Forberg, 2007; Thiemann and Sester, 2004). In these methods, geometric primitives are extracted in order to preserve the building structure and semantics. A detail review of these methods is done by (Sester, 2007). However, only the simple model is adopted in these researches rather than the 3D complex model. In computer graphics, mesh simplification is a well researched topic (Luebke et al., 2003). But the proposed polygon reduction algorithms are suitable for continuous surface rather than component based building model. The main reasons are the strong structured features of building and the aggregate detail of components (Kada, 2007; Cook et al., 2007). To overcome these defects, human perception is introduced into polygon reduction in order to allocate more geometry to more visual important details, vice versa (O'Sullivan et al., 2004). The proposed methods can be divided into two kinds: one is implemented in model space and the other in screen space. The former is usually achieved by evaluating the perception of geometry using projected errors or curvatures (Luebke and Hallen, 2001; Lee et al., 2005). However, these methods adopt a simpler implementation of human vision system (HVS) model which may not be precise. Otherwise, screen is the general intermedium for people to observe 3D models, extracting perceptual information by means of screen space is therefore preferable. Approaches based on screen space errors are able to evaluate the perceptibility of image on screen by introducing more rigorous HVS models derived from the researches on image processing (Winkler, 2000). However, existing perceptually guided simplification methods treat the perceptual information as weights to adjust the sequence of simplification operations such as edge collapse etc. (Qu and Meyer, 2008), which is obviously not suitable for aggregate details.

In conclusion, current simplification methods are proposed either for simple building models or continue surface models rather than 3D complex building models. In this case, an optimal extraction of the geometric primitives of a 3D complex building model for simplification is needed. This paper adopts a 2D discrete wavelet transform (DWT) based HVS filtering technique to extract the imperceptible details in the rendered image snapped from the model. Then, a visual difference image contains perceptual information is precisely mapped to the model using a ray-casting like method to locate all the perceptible geometry. Such idea has been firstly proposed by (Du et al., 2008) and the main contribution of this paper is a fast and precise output sensitive perceptually guided method to locate the perceptible geometric primitives.

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2. PERCEPTUALLY GUIDED GEOMETRICAL PRIMITIVE LOCATION ALGORITHM

Adopting perceptual information in screen space to guide simplification, a connection between 2D screen space and 3D model space should be created. Based on the principle of rasterization rendering, pixels are generated by rasterization of geometric primitives (Shreiner et al., 2004). Thus, there are two paths to build this connection. One is the projection of geometric primitives onto the screen. The perceptual information of the projected primitive is then decided by the projected coordinates of primitive. For example, Qu adopted a projected texture like method to find the vertex index in a vision important image (Qu and Meyer, 2008). However, this kind of method could not directly locate perceptible primitives and it can hardly deal with occlusion of primitives.

The other way to bridge 2D screen and 3D model is the ray-casting technique. The tracing back from pixels to its corresponding geometric primitives is the inverse process of rasterization rendering, as illustrated in Figure 1**.** Based on the correct rasterization rule, the emitted ray from pixel would be able to directly find the exact geometric primitive that contributes to the pixel. Perceptual information carried by the ray is then transmitted to the primitive and finally perceptible primitives are able to be located. There are several advantages of this method comparing to the former: Firstly, the perceptual information could be fully transmitted from 2D pixels to 3D primitives. Secondly, ray-casting automatically eliminates the occlusion which wipes out the inner structure naturally. Thirdly, when simplifying model for using in distance, this kind of method is able to eliminate the primitives that are smaller than the resolution of screen. So it is output sensitive.

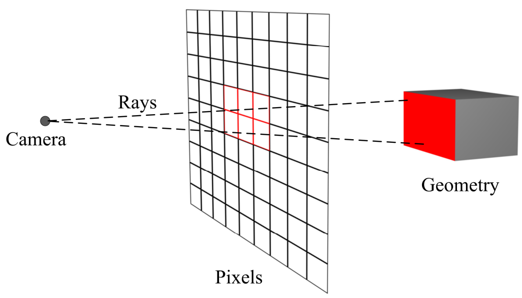

Figure 1. The tracing back from pixels to geometry

The flow chart of the algorithm is illustrated in Figure 2**.** The first step is the extraction of perceptual information in the rendered image of 3D model. Various researches on image processing had adopted HVS based perception models, such as evaluating the visual similarity of two images (Bradley, 1999; Wang et al., 2004), and image compression (Nadenau, 2000). The former requires two input images. Existing methods based on it are either too costly (Lindstrom and Turk, 2000), or not precise (simplification adopting visual discrimination metric (VDM) method (Qu and Meyer, 2008)). The latter adopts the HVS to compress the imperceptible details in an image more aggressively which is suitable for our application.

After rendering the image of 3D model at a given viewing distance, a contrast sensitivity function (CSF) based HVS model is introduced to simulate the approximate result of vision perception. Then a visual difference image indicates the imperceptible detail in the original image is generated by subtracting the vision simulated image and the original image. The vision simulation procedure includes three key steps: 2D DWT decomposition, HVS filtering and 2D DWT reconstruction. To precisely implement HVS, the image has to be transformed from the spatial domain to the frequency domain. Among many existing transform approaches, the 2D DWT better fits the HVS model because 2D DWT decomposition is similar to the multiple-channel model of the HVS, which allows the processing to be acted on each spatial frequency channel independently (Bradley, 1999). After decomposition, the CSF is implemented as finite impulse response (FIR) filters, which is more precise and adaptive (Nadenau et al., 2003).

Finally, the inverse 2D DWT transform is carried out to reconstruct the vision simulated image. The visual difference image is then generated. In this image, the imperceptible details are represented by pixels which have a value lager than 0 and the perceptible details are represented by black pixels which mean the lossless details. The perceptible primitives are then located by precisely mapping the visual difference image onto the model using a ray-casting like method which is to be detail discussed in the following section.

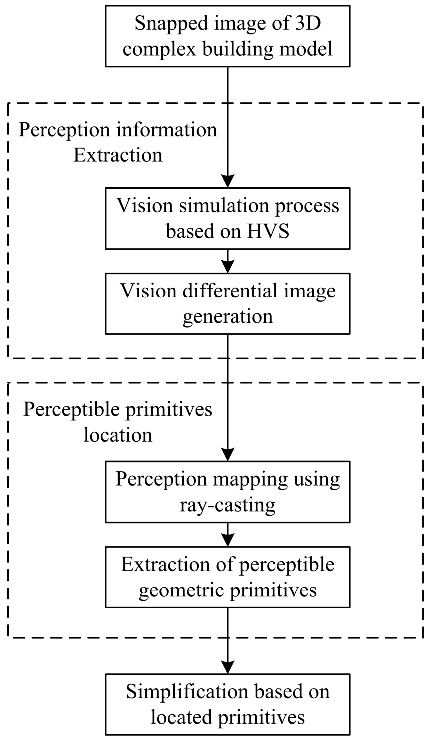

Figure 2. The flow chart of geometrical primitive location method

3. FAST LOCATION OF PERCEPTIBLE PRIMITIVES

There are two functions of the ray-casting like method. One is to extract the displayable primitives of the model. The other is to map the pixel value of the visual difference image onto the primitive that contributes to it. In order to guide the simplification, all the displayable primitives are measured based on the pixel values transmitted from the image. The perceptible ones are to be preserved and the rest that are undisplayable or imperceptible are to be simplified.

Although this method is implemented off-line, a proper index structure is needed for efficiently locating the primitives because of the huge data size and complex geometry. The most popular index structures for ray-tracing application are the BSP-tree, KD-tree and Octree (Havran, 2000). Considering the regular structure and relative simplicity of components of 3D complex building model, the Octree is chosen. The leaf node of the index contains the intersected minimum bounding boxes (MBB) of components which are not further split for quickly constructing the index structure. The ray is generated employing the position of camera and the projective coordinates of pixels in the near clipping plane.

```
//Mapping perceptual information using Ray-casting
Input Vision Differential Image (VDimage);
Get the start pixel (Pix) in VDimage;
Do{
    //Primitive locating
    Generate a Ray (R) based on Pix and Camera;
    Get the intersection point (Pt) of R and the MBB of Octree;
    While (Pt is inside the MBB of Octree){
    Find the intersection leaf node (Lnode) based on Pt;
    Record the intersected triangles (Tris) between R and the Comps
    belong to Lnode;
    Compute the other point (Pt_out) intersected between R and Lnode;
    Pt=Pt_out;
    }
    Rank the list of recorded Tris of to find the closest one (Tri_close);
    //Perceptual information mapping
    IF(the value of Pix >0){
        The traced pixel number of Tri_close++;
        The imperceptible pixel number of Tri_close++;
    }ELSE
        The traced pixel number of Tris_close++;
    Pix =the next pixel of VDimage;
}While (Pix belongs to VDimage)

//Extracting the perceptible geometic primitives (triangles)
Get the first Tri of the model;
While (Tri belongs to the model){
    The simplification mark of Tri= TRUE; // initialed to be simplified
    IF (The traced pixel number of Tri!=0)
        IF((imperceptible pixel number / traced pixel number) <0.5)
            The simplification mark of Tri= FALSE; //to be preserved
}
```

Figure 3. The pseudo code of primitive location algorithm

It should be noted that the screen coordinates of pixels for rasterization are half-integer so the ray should be adjusted by adding 0.5 to the X and Y value of screen coordinates of pixels (Segal and Akeley, 2008) .

A fast ray intersection method is adopted to efficiently locate the geometric primitive, in which the intersection test is carried out directly with the leaf nodes of the Octree along the ray. Then, pixel values which represent the perceptual information are recorded in the data structure of primitives. The result contains two types of numbers. One is the number of pixels that have a value larger than 0 indicating the quantity of the imperceptible details and the other is the number of pixels that have a value equal to 0 indicating the quantity of the perceptible details. These two numbers are accumulated during ray-casting and finally each primitive record, firstly, the number of traced pixels, which is the total number of pixels contributed by this primitive; secondly, the number of imperceptible pixels contributed by this primitive. If the number of traced pixels is equal to 0, then this primitive is marked as undisplayable and if the number of imperceptible pixels takes up half or more of the number of traced pixels, this primitive is marked as imperceptible. The rest are marked as perceptible primitives. The pseudo code of the algorithm is shown in Figure 3. After this process, all the primitives of the model are marked and the simplification is implemented based on the results.

4. EXPERIMENTAL ANALYSIS

A 3D complex building model of Chinese style built up by 98265 components and 706978 triangles was selected in the experiment, as illustrated in Figure 4. The observation equipment was a 19 inch TFT LCD monitor with the resolution of 86.27 dpi (1280x1024) and a luminance of 200 (cd/m^2). The observation distance was set at 0.5m which is a typical visual environment for desktop applications.

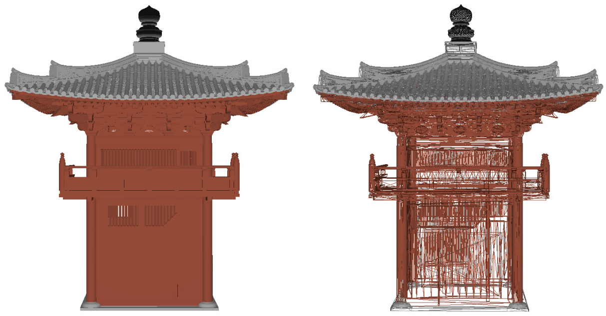

Figure 4. The 3D complex building model

The maximum spatial frequency perceived by human form the monitor was calculated to be 14.82 cycles/deg (cpd) by equation (1)(Nadenau et al., 2003):

$$f_{\max} = 0.5 f_s = 0.5 * (2v \tan(0.5^{\circ}) r / 0.0254) \quad (1)$$

where f_{max} is the maximum frequency, which is down sampled from f_s, the sampling frequency of the screen, at Nyquist rate of 0.5 cycles/pixels. The adopted CSF expression is widely used in many other works (Luebke et al., 2003):

$$A(\alpha) = 2.6(0.0192 + 0.144\alpha)\exp(-(0.144\alpha)^{1.1}) \quad (2)$$

Then, Daubechies 9/7 wavelet was selected to transform the image into frequency domain because of its fitness for the image processing (Antonini et al., 1992). The CSF was implemented as FIR filters to convolute with the wavelet coefficients and the vision simulated image was generated by the inverse DWT transform, as illustrated in Figure 5 (middle). Figure 5 (right) shows the visual difference image generated by subtracting the above two images, in which black pixels inside the model represent the perceptible detail and the grey pixels represent the imperceptible details. It can be seen that most of

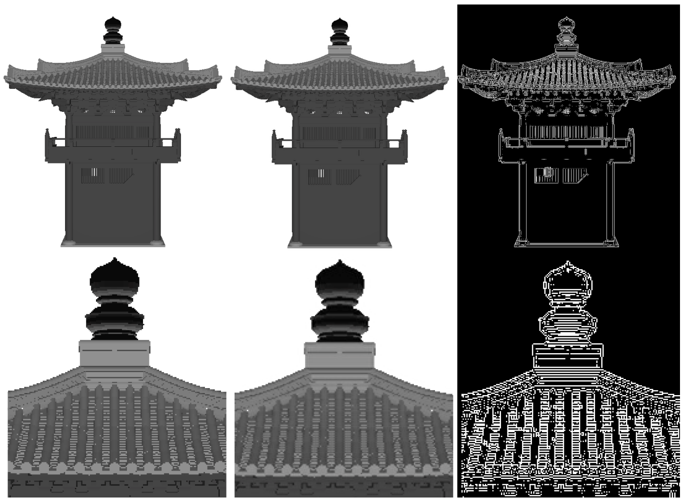

Figure 5. The first row: the rendered image (left); the vision simulated image (middle) and the visual difference image (right). The second row: the 300% zoom in images of the first row

the imperceptible details located at the regularly aligned shape edges and the trivial structures which represent high spatial frequency and low contrast sensitivity signals. The result is in conformity with results of perceptual-based image processing researches (Nadenau et al., 2003).

Figure 6 shows the index structure of the test model, the depth of Octree was 9 and the maximum number of components contained in the leaf node was 40. The visual difference image was then adopted to generate rays to intersect with the index structure and finally map the perceptual information onto the geometric primitives. The result of the location process at viewing distance of 56 m is illustrated in
Figure 7, where green triangles represent the perceptible primitives; red triangles represent the imperceptible primitives and blue triangles represent the undisplayable primitives. It can be seen that at the fixed viewing distance, almost all the triangle primitives of the model were marked as perceptible (green) as expected. But, moving the camera closer to the model, many trivial triangles that cannot be displayed at the fixed viewing distance were revealed, as well as the imperceptible ones, as shown in
Figure 7 (right). It should also be noted that some of the partly occluded triangles may also be marked as imperceptible (red) because of the perceptibility of its uncovered parts, such as the red triangle on the left side of the model in
Figure 7 (right).

The algorithm was implemented on four facades of the model respectively and all the marked triangles were then sent to simplification process using half edge collapse operator based on quadric error metric (Garland and Heckbert, 1997). All the undisplayable and imperceptible triangles were to be decimated by collapsing one of its edges. The edge that connected to the vertex of the perceptible triangle was collapsed to that vertex. So the perceptible triangles are preserved in the simplification.

The result was shown in Figure 8. The simplified model contained 6175 components and 159020 triangles which is equal to only 22.5% data size of the original model but preserved the similar appearance. Simplification examples at other viewing distances were also given, as shown in Figure 9. Notice that observing at the fixed viewing distance, the aggressively simplified model looks similar to the original model which proved the effectiveness of this approach.

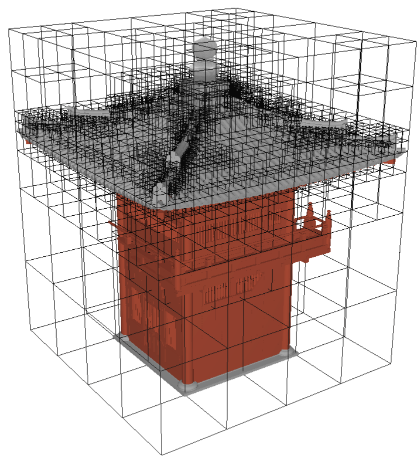

Figure 6. The generated Octree index structure

5. CONCLUDING REMARKS

Aiming the LOD model generation of 3D complex building model, this paper proposed a perceptually guided geometrical primitive location method which can precisely locate the perceptible primitives and provide useful perceptual information, which guarantees the simplification to preserve the perceptual features of final LOD models. Future research topics include the efficient perceptually guided simplification methods of 3D complex building models as well as the simplification combined with texture.

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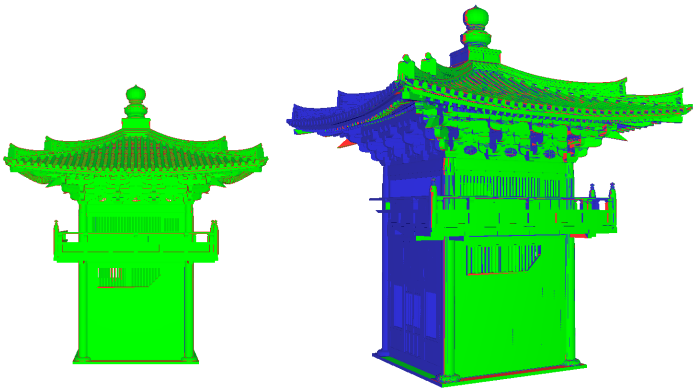

Figure 7. The result of perceptually guided primitive location at 56 m
(Left: observation at 56 m; Right: closer observation)

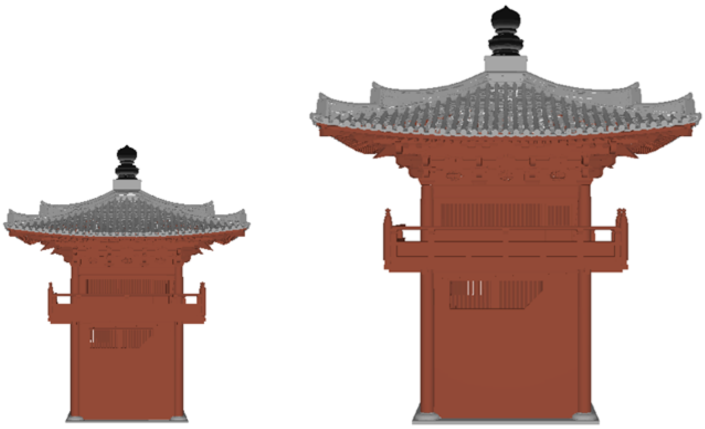

Figure 8. The result of simplification
(Left: observation at 56 m; Right: closer observation)

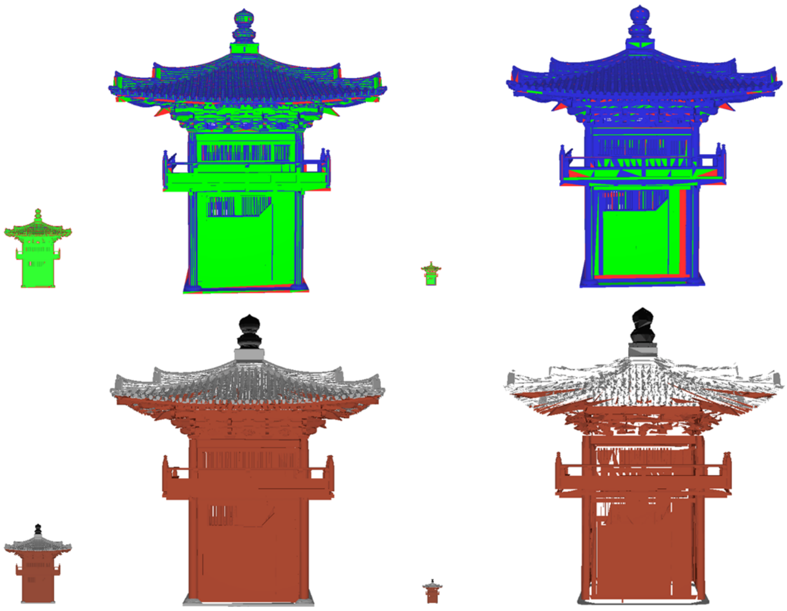

Figure 9. Results of primitive location and simplification at farther viewing distances
(Left: observation at 132 m and closer observation; Right: observation at 427 m and closer observation)

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- Semantic and thematic modeling for 3D city and landscape models
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- 3D data integration (digital elevation models and 3D objects; datasets from different providers; homogenization)

- Information integration in digital cities
- Automatic and semi-automatic methods for city model acquisition
- Interpretation of city objects in images and laser data
- Rapid mapping of 3D city models
- Multiple representations: multi-scale (levels of detail), versions, history
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- Collaboration frameworks
- Immersive visualization and virtual worlds
- (Urban) data mining in 3D city models
- City models in computer games and simulators
- New applications of virtual 3D city and landscape models (e.g., energy, environment)
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