The backbone of a City Information Model (CIM)

Implementing a spatial data model for urban design

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Abstract. *We have been witnessing an increased interest in a more holistic approach to urban design practice and education. In this paper we present a spatial data model for urban design that proposes the combination of urban environment feature classes with design process feature classes. This data model is implemented in a spatial database that becomes the backbone of a City Information Model (CIM), integrating urban neighbourhood formulation, design, and evaluation methods into a comprehensive urban design support system. We demonstrate its application to urban design analysis and evaluation through the development of a tool for AutoCAD Map 3D that is integrated with the PostGIS spatial database.*
Keywords. *urban design; data model; GIS; design support tools; urban design evaluation.*

INTRODUCTION

In light of the challenges of sustainable urban development we have been witnessing an increased interest in a more holistic approach to urban design practice and education. This approach has multiple dimensions and challenges (Gil and Duarte, 2008):

- To integrate the activities of a wide range of stakeholders;
- To integrate analysis and evaluation in a performance based design process;
- To manage the various outputs from the various stages of the design process;
- To facilitate access to information from a variety of sources and in different data formats;
- To manage very large quantities of information, facilitating its manipulation and visualization by different users.

The field of building design has responded to similar challenges with the development of various Building Information Modeling (BIM) technologies and there have been calls for the creation of something equivalent in urban design, a City Information Model (CIM) (Khemlani, 2007; Gil et al. 2010). The CIM would extend the use of Geographic Information Systems (GIS) in urban planning as decision support tools (Webster, 1993; Batty et al., 1998) through the integration with Computer Aided Design (CAD), to become a design support tool (Dave and Schmitt, 1994; Maguire, 2003). The City Induction research project has been focusing on the development of such a system, based on an urban design method that integrates the stages of formulation, generation and evaluation of urban designs supported by a CAD/GIS software platform (Duarte et al., 2011). In this paper, we present a spatial data model for urban design practice that can serve as the backbone of a CIM. This is a general component of the City Induction project based on previous work carried out on urban design ontologies (Beirão et al. 2009;

Montenegro and Duarte, 2009) and we demonstrate its integration with the evaluation module.

Firstly, we describe the urban design data model and the structure of the spatial database, highlighting the possibilities that it offers by integrating urban environment and urban design process feature classes, and provide an example of its implementation in PostGIS using datasets for the Randstad region in the Netherlands. Secondly, we demonstrate its application to urban design analysis and evaluation through the implementation of a tool for AutoCAD Map 3D. We then discuss the benefits and the potential applications in urban planning and urban design education, and point to further work required to test its integration with the complete City Induction framework.

A SPATIAL DATABASE FOR URBAN DESIGN

A spatial database can constitute an adequate support platform to achieve the integration and interoperability requirements of an integrated urban design approach, namely:

- It can manage different user roles giving differentiated access to and production of information by the various stakeholders involved in the urban design and planning process;
- It is a platform to which different design and analysis tools can connect, but it also provides an array of analytic methods to quickly process spatially and statistically the information contained in it;
- It stores and manipulates simulataneously the geometry and attribute information (text and numbers) that is used and produced during the various stages of urban design;
- It can import information from a wide range of data, image, GIS and CAD file formats, either natively or by using plug-ins;
- The information can be accessed locally or remotely over a network for manipulation or visualisation;
- It can store very large quantities of information and provide selective access to portions of the data through queries in an efficient way;
- The information is managed in a single central repository, avoiding data duplication and ensuring that the most up-to-date version is accessed by everyone.

However, to use such an infrastructure in the urban design process, it needs to be configured with an adequate data model that supports the kinds of information, methods and user roles that make up the urban design process.

URBAN ENVIRONMENT DATA MODELS

One of the leading GIS software companies has a repository with several data models [1] but most stem from the field of geography. Although one can find various components that would be relevant to an urban environment data model, these are not integrated and do not constitute a complete set.

The most comprehensive urban environment data model for GIS is the OGC standard CityGML (Gröger et al., 2008; Kolbe, 2009). However, it follows a logic strongly oriented towards data exchange and 3D city model visualization. The model is structured around the concept of levels of detail of information that is organized according to the needs of 3D visualization and not necessarily to those of a design process. Furthermore, it reaches a high level of detail with building features, components and interiors, which are not very relevant to the urban design process.

Other urban environment data models and databases (Koshak and Flemming, 2002; Hamilton et al., 2005) focus primarily on the retrieval, analysis and visualization of existing information, but lack components pertaining to the design process itself, i.e. building regulations, development constraints, benchmarks and multiple design proposals.

A SPATIAL DATA MODEL FOR URBAN DESIGN

We propose an urban design data model that accommodates two knowledge domains: the urban environment and the urban design process. The first domain contains data that objectively describes the existing or planned urban environment, referring to physical or administrative geo-spatial entities. The second domain contains data that is produced by the planning and design process. This information is not descriptive but rather prescriptive, analytic or interpretative of the urban environment, and is specific to an urban design project. Within each domain we define a series of groups to facilitate the understanding of the content of and the relations between the various feature classes (Figure 1). These are largely derived from previous work on urban ontologies carried out in the City Induction project (Beirão et al. 2009; Montenegro and Duarte, 2009; Duarte et al., 2011).

The urban environment domain (ue) has the following groups:

1. Landscape system (lnd)
2. Built system (blt)
3. Mobility networks system (mbn)
4. Boundaries system (bnd)
5. Information system (inf)

Groups 1-4 represent the environment and group 5 contains spatial and pseudo-spatial data. This complements the urban environment domain with essential descriptive information of the environment, its population and activities, in support of site and context analysis for creation of the program and for evaluation of the plan.

The design process domain (dp) consists of these main groups:

6. Zones (zn)
7. Axes (ax)
8. Focal points (fp)
9. Site and design regulations (sdr)
10. Site and design analysis (sda)
11. Evaluation goals (evg)
12. Evaluation outcomes (evo)

Groups 6-8 contain graphical elements of the spatial framework or master plan, produced in the formulation stages, and additional explanatory or conceptual information about a design proposal, produced in the design stages. Groups 9-12 contain design support information that is produced by the formulation and evaluation stages, providing design constraints, regulations, performance goals and assessment outcomes for the various design proposals.

The two knowledge domains (urban environment and design process) are represented in the database by two separate schemas, and each design proposal is stored in its own schema with a structure identical to that of the urban environment schema. The main urban environment schema stores information on the existing environment and is used for site context

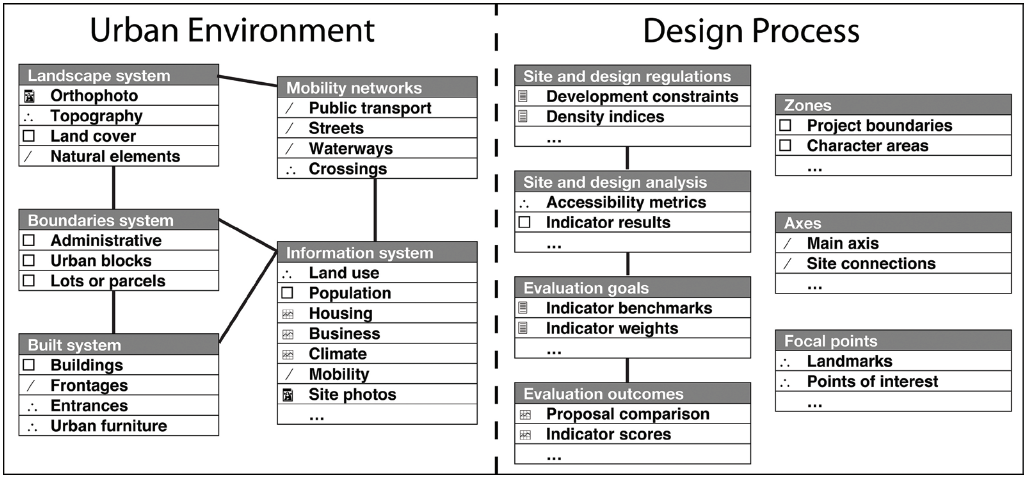

Figure 1
Schematic structure of the urban design data model, with two main schemas for the urban environment description and the design process information, and a collection of groups and feature classes belonging to each domain.

analysis and visualization. The proposal schemas store the proposed environments within the limits of the site boundary and are directly manipulated by the design generation process. The groups of each domain provide a prefix for the naming convention of data tables, thus grouping together in the database management environment the data tables that are related.

Examples of the data structure

The urban design spatial data model is defined following principles from spatial data modeling (Yeung and Hall, 2007). Figure 1 represents a schematic structure of the urban design data model with the main relations between feature classes, the core data tables and some examples of custom tables that can be created to accommodate specific project or local characteristics. This expansion possibility is indicated by the ellipsis (…) punctuation in the groups that support it.

In this section we provide examples of feature classes of the two domains, namely the land cover and building feature classes of the urban environment domain, and the site analysis and evaluation scores of the design process domain (Table 1). The

Class	Land cover	Attribute	Type	Description
Schema	urbanenvironment	id	char	unique identifier
Table	ue_lnd_landcover	type	char	land cover class
Entity	polygon	permeable	char	surface permeability class
		structure	char	surface structure
Class	**Land cover**	**Attribute**	**Type**	**Description**
Schema	urbanenvironment	id	char	unique identifier
Table	ue_blt_buildings	lot_id	char	lot/parcel unique identifier
Entity	polygon	area	double	area in square meters
		height	double	height in meters
		floors	integer	total number of floors
		gf_function	char	ground floor function
		uf_function	char	upper floors main function
		units	integer	total number of units
		heritage	char	heritage class
		status	char	current status class
		year	integer	year of construction
Class	**Land cover**	**Attribute**	**Type**	**Description**
Schema	designprocess	id	char	unique identifier
Table	ue_sda_indicators_site	proposal	char	name of design proposal
Entity	polygon	ind_1	double	indicator 1 measurement
		ind_2	double	indicator 2 measurement
		...		
		ind_n	double	indicator 3 measurement

Table 1
Description of the land cover and buildings feature classes of the urban environment schema, and of the site analysis indicators feature class of the design process schema.

complete functional data structure of each table is provided, including the object classes, their geometry, basic attributes and relations.

The data structure is typical of spatial relational databases, with the important addition of a geometry field that can store the urban form's geometry in the form of points, lines and polygons.

IMPLEMENTING A TOOL FOR NEIGHBOURHOOD DESIGN AND EVALUATION

To test the feasibility and the advantages of using an urban design spatial database in the urban design process we have implemented one in the context of the City Induction project, serving as the backbone of the CIM. The database is built on the open source PostgreSQL database with its PostGIS extension, which can be linked to other spatial design and analysis platforms, namely AutoCAD Map 3D, the urban design platform chosen for the City Induction implementation (Gil et al., 2010).

Setting up the spatial database

For the pilot study, we have loaded data of the Randstad region in the Netherlands, and selected four different urban areas for analysis, namely Ijburg and de Pijp in Amsterdam, Ypenburng in de Hague and Houten near Utrecht. The amount and diversity of information and the need to make it available to different users were sufficient reasons to opt for a managed data solution in the form of a database. The data sets used were obtained via the DANS EASY service [2]:

- Bestand Bodemgebrauk 2006, for land use and land cover (CBS and Kadaster, 2006)
- Kadastrale Kaart, for property subdivision and address points (Kadaster, 2008)
- TOP10 NL, for topographic layers (Kadaster, 2009)
- Wijk- en buurtkaart 2009, for census data (CBS and Kadaster, 2009)

Initially, we started preparing the data sets using a commercial GIS platform and the files provided in 'Shape' format. However, it became clear that certain operations of merging tiles, deleting records, and editing tables either took too long or the operation failed. As a result we decided to load the data directly into the database and perform the data preparation operations using the native SQL functions and the PostGIS functions. The database proved to be far more stable and efficient in performing those

Table 2
Example of the correspondence between data attributes of the original source data sets (right) and the structure of the urban design data model (leftmost column), for the buildings feature classes.

ue_blt_buildings	Source	Table	Attribute
geometry	top10nl	gebouw_vlak	geometry
id	top10nl	gebouw_vlak	identi
lot_id	custom	ue_bnd_lots	id
area	custom	ue_blt_buildings	from geometry
height	top10nl	gebouw_vlak	hoogte / hoogteklas
floors	survey	-	-
gf_function	Bbg2006	Bbg2006	BG2006_a
uf_function	-	-	-
units	custom	ue_blt_entrances	parsed from door numbers sequence
heritage	top10nl	gebouw_vlak	typegebouw
status	top10nl	gebouw_vlak	status
year	-	-	-

operations, reducing processing times in some operations from 40 minutes to 4 minutes.

The other two main tasks of data preparation were to make a correspondence between data sets, assigning to the data structure defined in the urban design data model the attributes and geometry of the existing data sources (Table 2), and to reclassify the attribute values themselves, because they were in different languages or were following a very specific classification.

In some cases the attribute data is not available in the original data sets and it has to be synthesized from other attributes, complemented by local surveys or simply ignored with consequences to the kinds of analysis that one can perform. The result is a spatial database that follows the specification of the urban design data model, ready to be manipulated by various stages of the urban design process.

Integrating the spatial database and CAD for urban form analysis and evaluation

In order to demonstrate the use of the database and the integration of CAD and GIS we measure the urban form and evaluate the performance of the different pilot study areas using a tool developed for this purpose in AutoCAD Map 3D. This tool is the proof of concept implementation of the City Induction evaluation module. The purpose of the module is to measure a series of sustainable urban form indicators and offer a variety of means to evaluate the results to support decision-making during the design process. The proof of concept tool implements a sample of indicators, listed in Table 3, identified in a review of existing sustainable urban development assessment tools (Gil and Duarte, 2010). This sample aims to test indicators of different dimensions of sustainability (environment, economy, and society) that are calculated at different levels of spatial resolution.

The tool offers at this stage a basic urban design workflow following the City Induction structure. In the 'Formulation' section it includes the functionality to set up a new urban design project and load data in the spatial database, to configure project settings, such as the acceptable 'walking distance', to define the project site and analysis boundaries, and to set-up the design requirements in terms of the weight and performance levels of each indicator (Figure 2). In the 'Generation' section the tool offers the possibility of starting a new design proposal by creating a new schema in the database and loading the design tools

Indicator	Spatial unit	Result unit
Green areas per inhabitant	site	m2
Number of light railway/tram/trolley stops	site	n
Bike paths lengths per inhabitant/dwelling	site	m
Dwelling per hectare	site	n
Connected community	site	n
Street network length	site	m
Ground space per inhabitant/dwelling	site	m2
Impermeable areas	site	m2
Average distance between building entrances	street segment	m
Distance to nearest kindergarten	entrance	m
Number of kindergarten in close neighbourhood	entrance	n
Distance to nearest light railway/tram/trolley	entrance	m
Number of access points to public transportation	entrance	n

Table 3
List of the sample urban form indicators implemented for analysis of the neighbourhood data stored in the urban design spatial database.

toolbars. Finally, it has an 'Evaluation' section with a collection of tools relating to the analysis and evaluation of these proposals. This includes tools to run the analysis on the data sets, display those results visually through thematic maps of each indicator, compare the results between several different design proposals showing a radar plot (Figure 2), compare the proposals against a reference case (not necessarily from the same project), and score the results based on the previously defined performance levels, aggregating those scores towards an overall proposal performance score. The overall score is a weighted mean at various levels of aggregation and these are summarized in a multilevel pie chart for an individual proposal.

The user interface is implemented using AutoLisp and DCL. The data visualization functionality uses AutoCAD Map3D workflows because the Map API is not accessible from AutoLisp, and finally the various indicator calculations have been implemented as plSQL functions in the PostGIS database itself. We have decided to keep the data analysis and calculations in the database because of the performance gains observed in our previous experience and to keep the data processing functionality independent from any specific user interface. The AutoLisp front-end creates PostgreSQL instructions that are sent directly to the database via the command line using DOSLib 8.6 thus performing any number of

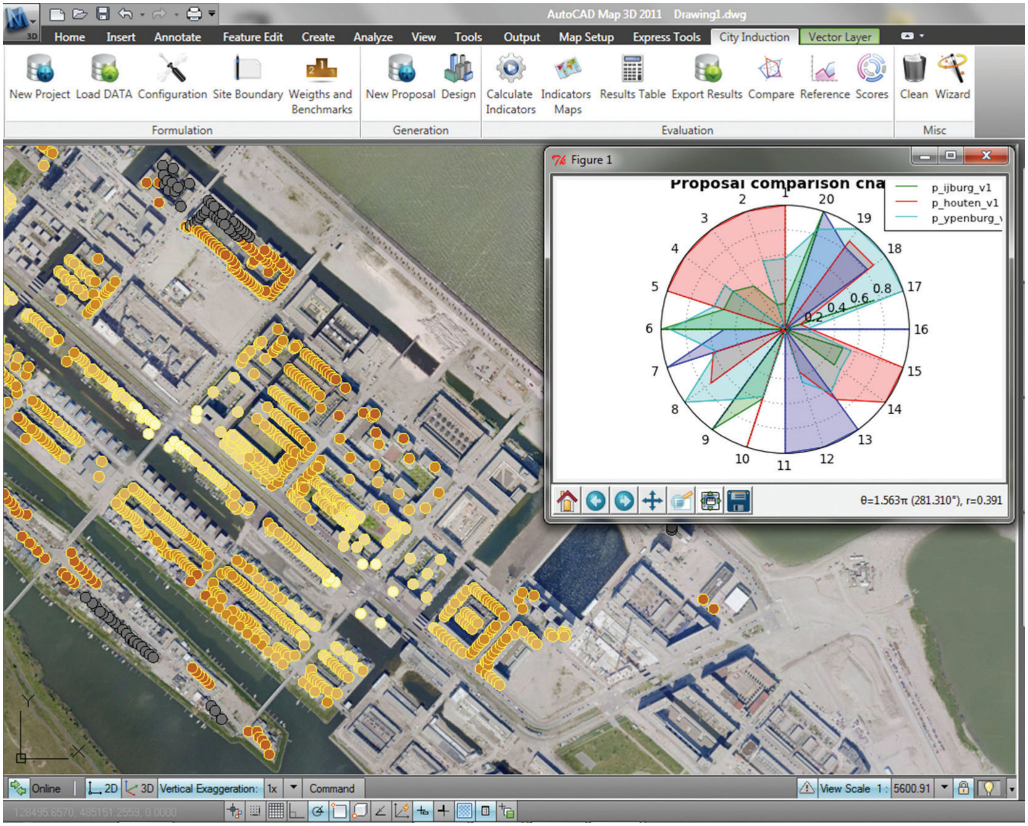

Figure 2
Screenshot of the proof of concept tool implemented in AutoCAD Map3D. It is displaying an urban neighbourhood orthophoto, overlayed with the results of the 'Number of access points to public transport' indicator in a thematic map. The proposal comparison radar chart shows this designs performance against other options. The information that is mapped in this view is being read from the PostGIS database.

operations on the data. The charting functionality to visualize the evaluation outcomes has been implemented in Python using the Matplotlib library and connecting directly to the database using the Psycopg library.

CHALLENGES AND FURTHER WORK

The use of a spatial database in the design process still requires GIS and database expertise (Pandit, 2009) and it is essential to develop user-friendly interfaces for the various design support tasks, especially to manage the data and to provide basic analysis outputs. The tests provide insight into possibilities and limitations of this integrated urban design support system.

The data collection and preparation phase common to urban design practice and education is quite challenging due to the variety of data sources and formats, and the quantity of resulting data. The proposed spatial data model offers a clearer set of requirements and a more structured knowledge framework, and with the support of ontology based tools it would facilitate the data classification and aggregation process. Furthermore, the structured nature of the database can support the development of automated data translation tools from/to standards such as CityGML (Stadler et al., 2009) and we need to identify the shared elements between the data models and ensure compatibility at those levels.

We still require an integration of the spatial database and the proof of concept tool with the formulation and generation modules of the City Induction project. This is important to fine-tune the urban design data model and confirm its compatibility with the methods developed in those modules. Furthermore, it will offer the opportunity for further testing the use of a spatial database in other phases of the design process and with different stakeholders. To explore this scenario, local authorities seem to be a good test case as they play several roles in the urban development process, from data collection to planning, evaluation and public participation.

CONCLUSIONS

In this paper we have presented an urban design data model to enable the development of spatial databases to support the urban design process. The proposed urban design data model has unique characteristics because it combines the more common urban environment description with a schema to support information relating to the design process. Testing the proposed urban design data model by building a spatial database has shown that these databases offer a suitable platform for an integrated approach to urban design, in line with the idea of a City Information Model (CIM), becoming the backbone of such a system. We demonstrate their use in the analysis and evaluation of designs integrated in a CAD environment, but we still need to test and demonstrate their use in a complete set-up that includes the formulation and the generation of urban design proposals.

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