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Design of a spatial database to analyze the forms and responsiveness of an urban environment using an ontological approach

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A B S T R A C T

This paper introduces a spatial database and ontology-enabled framework that models and operationalizes the relation between urban forms and their responsiveness to the needs of its user. The objective is to offer a framework that provides a practical implementation of the concept of responsive environment introduced by Bentley, Alcock, Murrain, McGlynn and Smith (1985) in order to provide enough reusability and flexibility to reflect different urban modeling viewpoints and conceptualizations. The developed system is organized in three modules: the first and second modules model the ontology of a responsive environment and the layout of an urban environment while the third module is a spatial database that supports further computational analysis of urban forms. We applied several spatial data metrics that analyze the structural properties of urban forms and the emerging opportunities as identified by the notion of responsive environments. The framework is experimented and applied to the district 12, region 4 of the city of Tehran in Iran. The modeling abstractions lead to the generation of several semantic bridge rules and map layers that reflect different levels of urban responsiveness. The emerging patterns are qualitatively evaluated and found to be correlated with inhabitants' own perception of an urban environment. The results show that the suggested framework can be applied to the analysis of the responsive environments of urban forms.

1. Introduction

The identification of the properties that emerge from urban structures and their forms has been the main challenges of many urban studies (Futcher, Kershawb, & Mills, 2013; SheikhMohammadZadeh & Rajabi, 2013; Tomko & Winter, 2013; Yimin, Li, Zheng, Guan, & Liu, 2011). Such studies analyze the efficiency of the built environment in urban designs, development plans and executed policies. Urban forms, defined as the spatial arrangements of the city components, can be considered as a spatial layout that has a subtle relation with geometry. Notably, it appears that spatial databases as useful repositories of spatial data can be applied to the representation of urban forms. The main goal of this paper is to address and identify the most appropriate modeling abstractions, spatial database representations and manipulation operations that can reflect the complex properties of urban forms.

The premise of this research considers the concept of “responsive environments” as a critical property of urban environments. The objective behind the concept of “responsive environments” is to survey the opportunities offered by a given urban environment by taking into account different qualities of the city such as permeability, variety, legibility, robustness, visual appropriation, richness and personalization (Bentley, Alcock, Murrain, McGlynn, & Smith, 1985). As defined by Bentley's group, responsive environments provide an innovative view for urban design. The focus of this paper is to analyze the state of responsiveness of a built environment as modeled by a spatial database of the layout.

The forms that appear in an urban environment can be perceived from different points of view, as well as related to several research domains because the city has been an object of many studies that range from social to economical and engineering sciences. In fact, any abstraction of an urban form is influenced by its context. This has a direct impact on the urban components identified by a modeling approach, their underlying properties, attributes and relations represented at the conceptual and logical database levels. These motivate the choice for an ontological framework that supports the representation of the urban morphology within a spatial database. Over the past few years, ontologies have been progressively established as privileged solution for formal representations of knowledge and specifications of a domain-based conceptualization (Gruber, 1993). When applied to

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an urban environment and the concept of responsiveness, many interrelated spatial concepts and properties, relations should be taken into account in order to infer logical consequences from represented facts. The implementation of such ontological representation within a spatial database approach is another issue addressed by this paper.

The research starts from the identification of the responsive environments and urban modeling abstractions in the layout of an urban environment. Those concepts are described by an ontology, and refined by additional properties and attributes. We retain the principle of a modular design procedure to favor flexibility and reusability of the developed components. The knowledge derived from the responsive environments, as along with the forms of an urban environment and the spatial database, are distributed in separated modules.

The rest of the paper is organized as follows. Section 2 briefly reviews related works and the main principles of our modeling approach. Section 3 introduces the modeling abstractions developed by our approach. Section 4 describes the implementation and application to the case study applied to the city of Tehran while finally Section 5 summarizes the paper and outlines future work.

2. Modeling principles

2.1. Research background

An important objective behind the study of urban forms is to conceptually and computationally explore the relationships between the forms and characteristics of the city (Bahrainy & Khosravi, 2013; Chena, Li, Zheng, Guan, & Liu, 2011; Jiang & Claramunt, 2004a, 2004b; Khirfan, 2010; Tomko & Winter, 2013). This also reflects one of the primary incentives behind the emergence of Space Syntax (Hillier & Hanson, 1984) that, with its innovative computing perspective, made a significant and experimental contribution to the analysis of urban structures (Ariza-Villaverde, Jiménez-Hornero, & Ravé, 2013; Jiang, Claramunt, & Klarqvist, 2000; Jiang & Liu, 2009; Koohsari, Kaczynski, Giles-Corti, & Karakiewicz, 2013). Many recent researches have explored the characteristics of urban forms via an integration of spatial and semantics criteria for many application domains. Amongst several relevant examples, let us mention the analysis of urban climate (Eeftens et al., 2013; Futcher et al., 2013), disaster management (Liu, Luan, & Zhong, 2012), energy consumption (Chena et al., 2011) and transportation studies (Gainza & Livert, 2013; Rybarczyk & Wu, 2014). A comprehensive review of these researches shows that the morphological criteria range significantly from first order to more intricate derived measures such as landscape metrics (Fan & Myint, 2014; Herold, Couclelis, & Clarke, 2005), densities and spatial distributions (Edussuriya, Chan, & Yec, 2011; Filicaia, 2007), sky views and open spaces (Eeftens et al., 2013), and accessibility and connectivity measures (Contreras, Blaschke, Kienberger, & Zeil, 2013; Eeftens et al., 2013). A few works have retained ontology-based approaches to model an urban system, and apply retrieval mechanisms to geographical information as suggested by (Lutz & Klien, 2006). They used RACER (Haarslev & Moller, 2004) as a terminological reasoning engine to find out which of the application concepts are equal to or subsumed by the query concept. Retrieval strategies are based on the exploration of a spatio-temporal ontology where these dimensions are considered as a sort of main filtering condition (Mata & Claramunt, 2011). In our research, the semantic reasoning is performed based on the rules that establish the mathematical and spatial relations in the spatial database. Lüscher, Weibel, and Burghardt (2009) introduced a framework for an ontology-driven pattern recognition mechanism. In this research, the spatial structures of an urban concept is represented by an ontology, and mapped to measurable units in order to manipulate them in a spatial database. The concept that they consider in a spatial database is *terraced houses*. This concept has a simple and rigid definition in comparison to the concept *responsive environment* which is used in this research. Scheuer, Haase, and Meyer (2013) made a local knowledge accessible in form of a knowledge base and described the corresponding flood risk assessment ontology in order to put expert and local knowledge into operation. The terms and relations were gathered, and the relative importance of elicited terms was reviewed using Text-to-Onto. This is a tool for automatically extracting lexica from textual sources. Finally, the elicited concepts were matched against their semantic counterparts in the SWEET ontologies (Raskin & Pan, 2005). The ontology matching performed by Scheuer et al. (2013) is a type of terminological matching from matching classes introduced by Delgado, Mart'ınez-Gonzalez, and Finat (2013). In contrast, the ontology in our research establishes is a conceptual type (Delgado et al., 2013) in that different modeled perspectives of a domain are conceptually matched.

In another work, Bhatt, Hois, and Kutz (2011) stated that form, function and the relationship between the two serve a crucial role in design. However, a formal modelling of structural forms and resulting artefactual functions within design and design assistance systems remains elusive. They interpret “structural form” and “artefactual function” by specifying modular ontologies and their interplay for the architectural design domain. The modules are matched with the theory of ε-Connections (Kutz, Lutz, Wolter, & Zakharyaschev, 2004) and have capabilities in talking about the link relations. In comparison to their work, our research deals with similar link relations that are implemented in the spatial database and are practically used to infer the instances of database.

2.2. The architecture of the modeling approach

One of the first objectives of this research was the identification of the urban form abstractions and modeling of the notion of responsive environment. This leads us to retain an ontological approach. Ontologies, as “explicit and formalized specifications of conceptualizations” (Gruber, 1993), play an important role to extract and formalize concepts. Guarino (1998) refines Gruber's definition by making clear the difference between an ontology and a conceptualization: An ontology is a logical theory accounting for the intended meaning of a formal vocabulary. More precisely, an ontology provides a conceptualization by (i) identifying the relevant terms that form the concept for the domain considered and (ii) devising semantic relations and axioms to account for their intended meaning (Scheuer et al., 2013). Regarding the context of an urban system, the extent of available perceptions ranges from inhabitants to stakeholders and urban designers with various expertise and interests. The objective of an ontology approach is to provide a common reference, then avoiding conceptual conflicts at the modeling level (Jung, Sun, & Yuan, 2013; Kotoulas et al., 2014). Next, these ontologies should be mapped appropriately towards a spatial database. Such a spatial database models urban forms and structural properties as spatial data types and provides the city's skeleton and urban layout. The modeling approach is designed as a system distributed in three modules that comprise the ontology of the urban subject, the ontology of the urban environment and an urban spatial database (Fig. 1). Ontology modularization is a technique that favors reusability and flexibility which is one of the valuable properties of ontologies (Uschold & Gruninger, 1996). The modularization favors reusability when applying the concept of responsive environment in to a given urban layout. These modules intercommunicate with each other. The main objective of these communication components, called bridges, is to map the semantics from one module to another module. Each so called bridge is formally defined by a set of semantic rules that support the semantic mapping processes. At last a semantic reasoning that technically denotes a combination of subsumption and instantiation reasoning is performed. The subsumption reasoning infers the subclass, superclass and equal type relations between concepts and instantiation reasoning infers the instances that belong to a concept.