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Review

Towards integrated intentional agent simulation and semantic geodata management in complex urban systems modeling

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ABSTRACT

Mega-urbanization presents researchers with a network of densely interwoven problems that completely elude disciplinary boundaries. We report on the development of a spatial knowledge management and agent simulation framework that is designed to integrate closely with the process of trans-disciplinary research into the dynamics of complex human-environment systems. We argue that our choice of knowledge representation languages facilitates cross-domain collaboration and direct involvement of domain experts without prior experience in computer programming.

In a run-through application example, we show how standardized knowledge engineering technologies are used to turn a conventional geodatabase into a self-documenting knowledge base that can flexibly interface with modern open-data infrastructures. The resulting cross-domain world model is then coupled to a graphical actor modeling language that specializes in the formulation of behavioral theories in terms of social roles, intentions, tasks, conditions and interaction. Finally, we describe how system theories expressed in this way are automatically translated into computer simulations.

Contents

1. Introduction

Globally, the understanding of highly dynamic urbanization processes increases in importance as already 540 million people are living in cities with more than five million inhabitants – mostly located in developing and newly industrialized countries (Kraas, 2007).

In order to understand the systematics of rapidly urbanizing regions, urban development has to be analyzed by taking into account both structural contexts and action modes. Giddens (1984) for example, develops a theory of structuration, and Werlen (2000) outlined the theoretical background of a series of

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international research in the 1990s. However, in the current research context, the dimensions of topical breadth and depth of scale are mutually exclusive. No coherent research can cover the full heterogeneity of mega-urban problem complexes on the full scale from the phenomenologically observable details, up to the level of abstraction required in managerial and political decision making. Yet modern knowledge engineering enables us to build computational models not of systems and processes, but of human knowledge. In this paper, we want to advocate a knowledge engineering approach to urban systems research, since integrating scientific knowledge management with modeling and simulation tools can provide a huge benefit to this kind of research.

This paper is a progress report on the *SiKAMUS* Project,[1] where we are developing an agent-based modeling and simulation framework that combines semantic geodata management with the i^* diagram language (Yu, 1995). i^* captures actor intentionality in terms of goals, actions, interdependencies and their interaction with the environment. To run a simulation, i^* agent diagrams are translated into the GOLOG language, an agent programming language based on the situation calculus (Gans, Lakemeyer, Jarke, & Vits, 2006; Levesque, Reiter, Lespérance, Lin, & Scherl, 1997; McCarthy, 1963).

A semantic geodata model is constructed using the ProtégéOWL editor (an integrated development environment for the Web Ontology Language (OWL) (cf. Hitzler, Krötzsch, Parsia, Patel-Schneider, & Rudolph, 2012; Knublauch, Fergerson, Noy, & Musen, 2004)). This model qualitatively describes the environmental system for the agent system in i^*.

Combining OWL and the i^* agent modeling language yields a formal system that minimizes the semantic gap between domain knowledge (as expressed in the descriptive meaning of scientific theories) and the formal-symbolic representation that makes it executable in a computer simulation. The entire framework aims to become a suitable toolbox for integrating knowledge management, modeling and simulation into the process of any trans-disciplinary research that deals with the emergence of complex human-environment interaction. The knowledge-based modeling approach facilitates both cross-domain collaboration, as well as the incremental model development that is required in ongoing research.

In this paper, we will describe the current and planned development of the framework. Section 2 outlines our current application domain. In Section 3, we justify our choice of OWL and i^* from a knowledge management and engineering perspective, and describe their technical principles. Sections 4 and 5 then introduce a small application example to illustrate our idea of how OWL and i^* complement each other to form an agent simulation. Results from preliminary user tests of both the OWL and i^* components are discussed in Section 6. In Section 7, we will reflect on some shortcomings of the current approach and sketch some of the work required to remedy them.

2. Application domain: mega-urbanization and water resources

In 2007, for the first time in human history, more people resided in urban areas than in rural areas. At the same time, megacities share of the urban population reached more than 40%, highlighting the preponderance of the largest agglomerations over smaller cities in the urbanization process, corresponding to Henderson's urbanization and development theory (Henderson, 2002). In India, for example, cities are expanding rapidly as increasing numbers of migrants stream into urban areas in search of economic safety (The World Bank, 2011), causing the slum population to double during the past two decades (UNDP Ministry of Housing & Urban Poverty Alleviation Government of India, 2009).

It is quite clear that Megacities, growing by about 3 Million inhabitants (as observed in the South Chinese megacity Guangzhou) are facing serious problems. Megacities are quantitatively defined as cities having a population of more than five (Kraas & Mertins, 2014), eight (Chen & Heligman, 1994; Fuchs, Brennan, Chamie, Lo, & Uitto, 1994; UN, 1987) or ten million people (Kraas & Mertins, 2014). Problems that could be recognized are structural deficits, population growth, enormous land use change, informal processes, inadequate infrastructure and environmental problems.

This high-speed urbanization describes a mostly uncontrollable interplay between processes of land use transformation and large-scale migration with far-reaching consequences for the environment and society (Wehrhahn et al., 2008). Massive land use and land cover changes initially take place within already existing build-up areas; then they expand outwards in the adjacent suburban region and the urban fringe (Wiethoff & Baier, 2009).

Typical challenges are

- lack of, or missing land use planning and growth control on the governmental level,
- considerable displacement processes in the real estate and capital market (economic level), and
- lack of access to urban infrastructures on the individual level.

Informal development in all areas of urban activity is amplified by the general loss of ability to govern and by a law enforcement that struggles with social conflicts and spatial disputes.

In mega-urban systems, water resources are often part of a daily struggle for inhabitants, since the available quantity and quality of water both influence, and is influenced by, most aspects of urban development (Anuradha & da Cunha, 2009; Baier, Schmitz, Azzam, & Strohschön, 2014; Kumar, Baier, Jha, & Azzam, 2009; Shannon, 2008; Sterr, 2009; Strohschöön, Azzam, & Baier, 2011; Strohschön et al., 2013; Uitto & Biswas, 2000; Wehrhahn et al., 2008).

When developing an understanding of human-environment interaction on this scale, the decision-making of local stakeholders is a crucial aspect, especially if one hopes to predict how altered policies or infrastructure play out in the long run. Consequentially, agent-based modeling is by now well-established as a means to bringing these complex socio-environmental systems closer to description, comprehension and ultimately, manageability (Crooks & Heppenstall, 2012). However, the (necessarily) trans-disciplinary field research dealing with mega-urban systems faces serious difficulties synthesizing discipline-specific perspectives into coherent theory systems. Obviously, segregating problem contexts along disciplinary boundaries serves the principle of *divide and conquer*: Separate the unmanageable complexity into smaller pieces that can be studied in detail (cf. e.g. Birkmann, Garshagen, Kraas, & Quang, 2010; Etzold, Keck, Bohle, & Zingel, 2009; Xu, Ge, & Hua, 2002). However the success regarding the necessary second step, re-integrating detailed insights into a holistic theoretical context, has been very limited. First and foremost this is to be attributed to the communicative difficulties inherent to trans-disciplinary research (cf. Pohl, van Kerkhoff, Hadorn, & Bammer, 2008). In integration and implementation science, model development has been identified as a means to synthesizing diverse insights into a coherent theory (Bammer, 2013, pp. 46–47). Typically, development of an agent-based model would involve manual preparation of suitable geodata sets with GIS tools for a specific modeling purpose, and development of agent programs in that particular context.

Yet in the context of mega-urban research, we can observe steady shifts in focus and approach: The science has to reflect

[1] **Si**mulating **K**nowledge-based **A**gents in **M**ega-**U**rban **S**ystems – A trans-disciplinary research project of the Chair of Engineering Geology and Hydrogeology (LiH) and the Knowledge-based Systems Group (KBSG) at the RWTH Aachen.