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Challenges of Semantic 3D City Models: A Contribution of the COST Research Action TU0801

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ABSTRACT

This technical paper is a contribution to the identification of current challenges of semantic 3D city models. They are presented in four parts, namely 3D enriched city models and their connection with urban information models and smartcities, urban models integration, urban analyses and data. This work is an output of the COST Action TU0801 "Semantic Enrichment of 3D city models for sustainable urban development".

Keywords: *3D City Models, Enriched City Models, Semantic Approach, Urban Models*

1. INTRODUCTION

Cities are complex systems constituted of physical elements interrelated into elaborated spatial relations, with a complexity increasing as the shape and the structure are changing and evolving. To try to understand the dynamics and the processes shaping our cities, we must coherently make models according to the dynamic and complex nature of cities, but also models should remain understandable and simple enough to be operationally useful. Hence, any attempt to

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model the spatial system and the dynamics of the cities should involve this non-determination and instability of the cities and this theoretical framework as one of its basic features. In the same time it should be followed with a strong knowledge and data management providing a necessary coherence with the nature of the city. To do all that, we have to search for a new paradigm in the way of modelling urban form, thus allowing to free the process of representation from fixed types and pre-determined shapes of elements of the model and to introduce a concept that will be generative as much as it is analytical.

The future of cities based on the idea of a creation of a society of knowledge lies in the creation of semantically enriched 3D city models as powerful tools for gathering, storing, evaluating and using urban information through a comprehensive open and accessible system coherent with the nature of the cities and the way we see and understand them. Urban Information Models can emerge from the horizontal and vertical integration of different information sources with an active contribution of institutions, companies and individuals creating a complex network of urban knowledge. This in return will enable cities to act as facilitators for the exchange of urban information with a high level of details and usability. This would also help to become more effective and efficient in the way of providing policies for city management and urban planning suited to the best interests of their citizen.

3D city models must be seen as powerful tools for the integration of information coming from a wide range of levels of detail and backgrounds, from buildings and activities representations to ground and underground infrastructures. A high level of integration and interoperability between existing data and GIS related information and simulation capacities of the model can be achieved. 3D city models can become an urban analytical tool capable of harvesting information from different fields of activities. They can also become tools to generate new information and understanding through a complex urban knowledge about the conditions of the city, revealing the future in a most comprehensive way for future users. This will be considered as the true beginning of the concept of smart cities and the society of knowledge.

This paper presents some of the outputs of the COST Action TU0801 called: "Semantic Enrichment of 3D city models for sustainable urban development" which started in November 2008 and ended in November 2012 (www.semcity.net). COST- the acronym for European Cooperation in Science and Technology - is the oldest and widest European intergovernmental network for cooperation in research (www.cost.eu). This action was part of the Transport and Urban Development (TU) domain (www.cost.eu/domains_actions/tud). The main motivation of the action was to explore ways to semantically enrich 3D models with urban knowledge and models, so as to extend their functionality and usability in a perspective of sustainable development. It was an active research network of 75 permanent members gathering people from academia, industry, administration and regulation bodies from 23 participating countries. More details about the action can be found in the final report (Billen *et al.*, 2014).

The paper is structured as follows: section 2 presents the challenges we faced at the beginning and during the Research Action about 3D city models, in terms of their use, the context of their use and the related benefits/drawbacks of their use, thus leading to the elaboration of research agendas organised according to the main axes that can be built from the figure below. The paper ends with the description of some of the most important issues and perspectives as identified by the Action.

2. CHALLENGES OF SEMANTIC 3D CITY MODELS

The role of 3D city models as integrators of the urban and environmental knowledge has been strongly acknowledged all along the activities of COST TU0801 (Billen *et al.*, 2012; Leduc *et* *al.*, 2012; Billen *et al.*, 2014). This emerging vision will have major impacts on the one hand on standardisation bodies, decision makers, data producers and consequently on the industry, and, on the other hand on urban experts and scientists. Indeed, considering enriched 3D city models as urban knowledge integration platforms implies a (re-)definition of geospatial standards, new data production/integration strategies, development of new applications… Enriched 3D city models are the foundation bricks of future Smart Cities.

Beyond these considerations, some conceptual and technical issues still remain open:

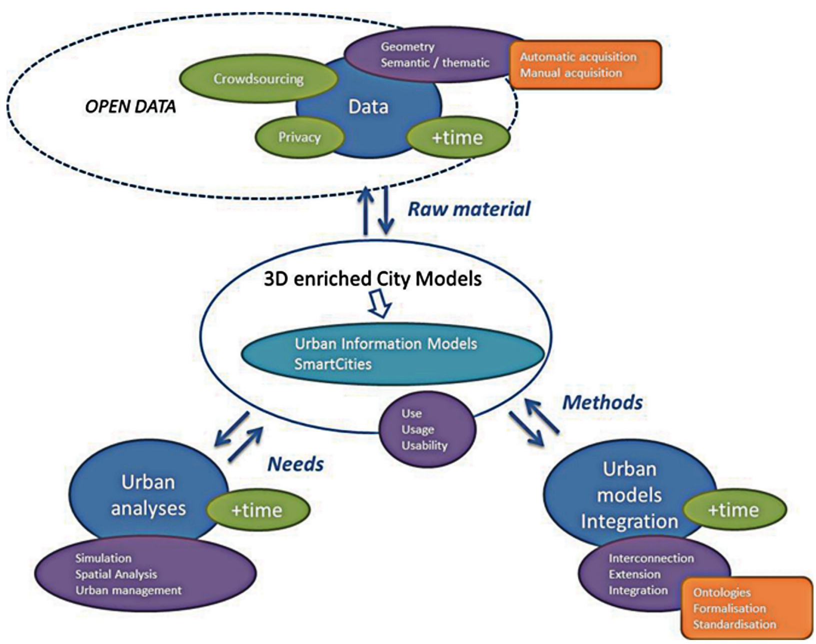
- Considerations about the types of semantic enrichment;
- Procedures for enriching 3D city models;
- Ways of visualizing enrichment information and knowledge.

Besides, even 3D city models definitions can be considered as being still debatable.

Indeed, the consideration of a modelling approach of the urban landscape based on 3D city models leads to the integration of a lot of disciplines and applications, which are diverse and not traditionally integrated as such. In other words, 3D city models can be seen as the basic ground for integrating urban knowledge, but such integration is complex and new. It is not just an extension of traditional 2D maps, or geometrical 3D city models, but the creation of a spatial model of complex urban networks of relationships between elements, attributes and configurations. This implies also to integrate time in the modelling approach; it is mandatory to capture the dynamic nature of urban knowledge.

A global view of the issues and challenges of the use of 3D city models for urban knowledge integration is presented in Figure 1 below; this schema highlights the four main components:

Figure 1. A global view on 3D enriched city models: issues and challenges



- 3D enriched city models;
- Urban models integration;
- Urban analyses;
- Urban data.

The central component gathers questions about use, usage and usability of 3D enriched city models and their possible evolution or connection with urban information models and smartcities. The whole issue of 3D enrichment and the role of 3D models as urban knowledge integrator can be addressed through urban models integration, urban analyses and data. This division in four components makes it possible to present open questions and recommendations in a flexible way.

To identify and to organise the different challenges, in order to facilitate their presentation in a clear way, we will make the analysis according to four axes built from the categories of the schema, namely: vocabulary and concepts (for 3D enriched city models), urban models integration, urban analyses and urban data.

For each of the different axes, we will first recall the context, and then we will propose challenges in terms of a research agenda.

2.1. Challenges in Terms of Vocabulary and Concepts

2.1.1. Context

Definition, usage and use of 3D enriched city models are terms far to be the subject of a common understanding amongst the actors of the planning activity in the urbanism and construction sectors; there is still work to do for outlining the nature and the scope of such models. This lack of consensus is due to the high diversity of usages that such models offer and the high diversity of disciplines involved. Indeed, this integration role goes far beyond what is known in 2D (through 2D GIS). This is a major scale issue which implies new paradigms. Up to now, we had a rather clear division between applications deeply rooted in mixing (2D) urban information at city level and applications using fragmented 3D urban information. Moving towards 3D city models brings together people that were not considering the same scale and extension of the urban phenomena. This leads to new communication issues between actors and consequently interoperability issues between systems.

It is becoming clear for most of the researchers and urban specialists that 3D city models should go beyond a simple geometric representation of the City (buildings, roads, vegetation) and progressively evolve towards 3D dynamic representation of above and underground, physical and abstract objects, allowing combining multiple sources of information. This evolution leads to what one could call an urban information model. Such model will be necessary for the future management of cities; from that respect it is closely related to the concept of smartcities.

Semantic enrichment is a rather broad concept which corresponds to different realities depending on domains and applications. Although we have identified several types of semantic enrichment and identified ways to enrich models, namely annotations, ontologies, model extensions… there is still work to do for providing a comprehensive and usable inventory of methods.

2.1.2. Research Agenda

In terms of challenges, we can consider that the following points still need further developments:

- Inventory of uses and usage of enriched 3D city models;
- Inventory of types of semantic enrichment of 3D city models;

- Inventory of objects to be included in enriched 3D city models;
- Study on evolution of paradigms (3D city model / urban information model / smartcities);
- Methods for the evaluation of 3D city models usability.

2.2. Challenges in Terms of Urban Models Integration

2.2.1. Context

As presented in the final report of the Action (Billen *et al.*, 2014), there are various strategies for extending models, interconnecting models and integrating models. We are talking about integrating simulation models (e.g. air quality models) with 3D city models, models coming from the BIM domain (e.g. IFC) with 3D city models… and more generally any kind of semantic models (e.g. historical model) with 3D city models. It seems also crucial to ensure the integration of 2D city models allowing combining the best of both worlds. For all these cases, there is no universal solution; model's extension, models interconnection, models integration through ontologies… all of these present pros and cons.

On the other side, there is a clear need to continue to develop modelling and meta-modelling methodologies and ontological approaches.

Enriching 3D City models is strongly related to interoperability issues. On the other hand, standardisation is a good way to improve interoperability. This means that there is a strong need to support and to influence existing standardization initiatives, through:

- Promoting communication between models (ex: CityGML and IFC);
- Identifying 3D standardisation priorities (ex: make distinction between core and application models);
- Promoting the development of standard compliant systems.

This initiative requires to keep working at a high level on 3D urban paradigms (ex: relevant relations and properties) with a focus on spatial integration of urban knowledge through 3D City models. It represents a huge impact on standardization bodies (e.g. OGC, INSPIRE). Furthermore, time concept cannot be discarded: 3D city models and their applications require most of the time to consider dynamic aspects and temporality issues. It implies also a deep conceptual thinking and standardization efforts.

2.2.2. Research Agenda

In terms of challenges, the following points still need further developments:

- Make investigations on the ways of interconnecting 3D models;
- Make investigations on the ways of extending 3D models;
- Make investigations on the ways of integrating 3D models;
- Improvement of conceptualisation and formalization of 3D urban models;
- Development / improvement of standards for 3D / 4D urban models.

2.3. Challenges in Terms of Urban Simulation and Analysis

2.3.1. Context

The fundamental reason which motivates the use of 3D city models as a platform for the integration of urban knowledge is to improve urban analyses and urban management. In other words, the already identified and prospective needs for a better management of cities and understanding of urban phenomena impose the use of enriched 3D city models and the underlying development of urban information systems which are the foundation of future smart cities.

Performing 3D simulations significantly improves the quality of the output in most of the applications studied all along the action TU0801. It implies 3D simulation models which can take benefit of existing 3D city models (instead of developing non-standard ad-hoc solutions) and associated 3D data (instead of acquiring expensive one-shot data). However, there is still need to assess the benefit of such 3D approaches in all aspects of urban management (economy, environment, social, cultural, etc.).

In the perspective of a standardized and integrated 3D urban information system, there is a need to develop an urban analysis toolkit providing analyses, simulation and management functionalities which could be combined and shared. If we can think about performing and combining various queries and processes, it represents several challenges in terms of processes standardisations technical and semantic interoperability, etc. The relevance of such combined analyses is also debatable, and at least assessment methods should be developed.

Since the beginning of the Action, the question of the enrichment of 3D city models by simulations and spatial analyses was raised. Indeed, up-to-now, the interaction between 3D data models and simulation models (such as an AQM for example) is one directional; the simulation is performed using 3D data and simulation output is not permanently linked with the 3D data. We discussed the opportunity to keep simulation results in a 3D city model either by a change of 3D city model object attributes, or by the creation of new objects within the 3D city models. It has been identified as a possible kind of enrichment. It raises once again standardisation and integration issues and also a question about the assessment of the quality of the information that has been produced.

The Action also focused on visualization. Indeed, the growing variety of 3D information (new types of data, simulation outputs, etc.) implies the adoption of the most efficient visualisation techniques. This is a core issue knowing that visualisation is the most important communication media according to the users; it depends on application, data and processes. Work is needed to categorize and to provide formalized visualisation techniques, anticipating mobile devices and technological evolution.

2.3.2. Research Agenda

The following points can be considered as important elements of a research program for the future:

- Inventory of 3D simulation / analysis models;
- Study of existing and prospective needs of 3D simulation / analysis in the urban context;
- Development of new 3D simulation / analysis models possible within an enriched 3D city model context;
- Development of a 3D tool kit for urban management;
- Categorization and formalization of visualization techniques;
- Study of the enrichment of 3D city models with simulation / analyses outputs.

2.4. Challenges in Terms of Data

2.4.1. Context

Over the past 20 years, data management was considered as the main limitation of the development of 3D city models or more generally for 3D GIS. It is changing. First, photogrammetry and land surveying techniques have evolved and thanks to automation and sensors evolution, 3D acquisition becomes easier. Furthermore, a lot of other technologies have emerged such as global navigation satellite systems (GNSS), satellite photogrammetry, laser scanning and combined solutions such as mobile mapping, drones, etc. The amount of 3D geometric data is exploding. Data related to underground utilities or soil structures have to be taken into account as well. The data production context has changed too; we came from a world led by local or national mapping agencies (NMAs) and some big companies to a world with multiple specialised data producers, emerging collaborative communities and some powerful web solutions developers which tend to impose their business model. This evolution impacts the way data should be produced; as analysed throughout this Action, there is a trend to adopt collaborative solutions and data co-production. It is no longer possible to ignore the open data and big data streams which hold on 3D data like on any other kinds of data.

3D data face the same issue than other types of data: privacy and quality. 3D makes more critical the privacy issues as the 3D data is closer to real world and therefore usually well understood by common users. Data quality and production of standardized metadata is also an important matter. There is a need to clarify and to formalize ways to describe data geometry such as the concept of level-of-details, resolution, precision and accuracy. There is also an increasing pressure for providing up-to-date data to users; as mentioned above, they are more sensitive to data obsolescence since they can associate them more easily to real world features. There is a huge challenge about temporality and dynamic information management.

However 3D data are not only limited to 3D geometry but they also imply to consider semantic data and environmental data. 3D analyses, 3D models and consequently 3D urban management systems require performing crossed analyses on various types of data, and not only geometric features. There is a need to organize the production and collection of semantic data which can be integrated into a 3D environment (census data, cadastral data, etc.). They could also come from simulation or analyses. Environmental sensors provide also huge amounts of data about air quality, noise, etc. It is essential to consider these data to feed 3D integration platforms and to move towards smart cities.

2.4.2. Research Agenda

The following points can be considered as important elements of a research program for the future:

- Inventory and assessment of 3D acquisition techniques;
- Development of coproduction strategies including data updating;
- Identification and formalization of semantic and environmental data collection techniques;
- Further studies on 3D data privacy issues, and creation/development of ethical rules.

2.5. Prioritising Challenges

The identified elements in the previous sections are summarised in Table 1 and are organised following their research priority levels. A high priority level means that the item is currently underestimated or needs to reach a higher level of maturity. A medium priority level means that the item is clearly identified by the community and studies or solutions exist or are in development.

3. ISSUES AND PERSPECTIVES OF THE WORK

The motivation behind the development of semantically enriched 3D city models is the belief that effective and useful urban models cannot be accomplished without a proper knowledge base

Table 1. Summary of research agenda items organised following their level of priority and their research axes

Priority Level	Concepts	Models Integration	Simulation / Analyses	Data
High	• Evolution of paradigms • Evaluation of 3D city models usability	• Interconnection methods • Integration methods • Conceptualisation and formalization methods	• 3D tool kit • Visualization techniques • Enrichment of 3D city models with simulation outputs	• Semantic and environmental data collection • Privacy issues and ethical rules
Medium	• Uses and usage • Types of semantic enrichment • Objects to be included	• Extension methods • Standards for 3D / 4D urban models	• Inventory of 3D S/A models • Existing and prospective needs of 3D S/A • Development of new 3D S/A	• 3D data acquisition techniques • Coproduction strategies

that integrates knowledge in a variety of formats and in a meaningful way. As a basis for urban models, an integrated knowledge base has been proposed as a container of a variety of traceable information needed to exhaustively describe the urban context. By organizing theoretically- and empirically-sound knowledge for a semantically enriched representation of urban spaces into a coherent framework, we have attempted to improve the methodology of the modelling process.

There is an urgent need of a converging knowledge representation that requires unity of models, strategies and perspectives, contributed by the relevant disciplines and experts. The knowledge base should provide a means for integrating and interconnecting heterogeneous data such as urban maps, photographs, cadastre data, and various unstructured data, as well as empirical studies, social surveys. This effort needs access to data, solicited and gathered by experts coming from diverse fields (e.g., architects, city planners, social science experts, geographers, computer scientists, etc.), using various solicitations and analytical methods. Semantic heterogeneity, terminology differences, inconsistency, redundant data and interoperability are some of the problems encountered. Neither the technological aspects nor the social aspects are to be given supremacy in the knowledge construction and pattern explanation. The knowledge categories should be derived from both, theoretical and empirical work in various disciplines. The knowledge space is expected to provide a starting point with enough possibilities to account for the complexity and relationships existing between urban dynamics of varying nature with the same depth as it was investigated in the past.

Context representation and use of sound inferring techniques to understand and to anticipate human activities, interactions and behaviour in the urban environment is an imperative. The new directions in information technologies directed toward pervasiveness and intelligence have increased the amount of raw data collection with a potential to increase our knowledge of the different aspects of social urban life. Individual pieces of knowledge or a collection of categories do not constitute a model. The effort to find out how those pieces of information are related to one another (e.g., causal and associative relationships) is far more challenging. Employment of a number of tools and intelligent techniques could support the process of capturing and visualizing the observable manifestation of behaviour trends and patterns i.e., the urban dynamics. Establishing the relevance of these patterns and their proper inclusion in the models of urban dynamics is as complex as any reasoning approach in an uncertain, non-deterministic, dynamic system.

Urban context knowledge is crucial in disambiguating the meaning and the relevance of the exhibited patterns in comparison to the model of urban dynamics. The main focus of our research to date has been to correlate discovered patterns with other urban-related knowledge that can help us make sense of the underlying complex systems. Extracting qualitative knowledge from large quantities of data is just the beginning in our search for the meaning and plausible explanation of urban dynamics. New platforms that combine urban informatics with the more traditional urban-related knowledge are yet to be developed and deployed.

This new enrichment and integration of information, structure and process, of course poses the biggest problem, the most important challenge and raises many technical issues that are yet to be resolved. Integrating interoperability between many different aspects of the spatial systems of the cities raises the questions of the unifying code that will provide us with a platform able to perform such an operation. This also includes the agility of city models to shift between different scales and the level of detail of the urban elements and urban systems and further on towards the exploration of integrated spatial data, allowing us to become aware of what are the mutual influences that affect spatial developments. The process of the urban development and the nature of the city itself are still at the brink of a new understanding and development in theory and practice. The new and enriched understanding of the cities and their structure, partial through the use of city models will also affect the way we comprehend and represent the process of their creation and the models of the urban reality.

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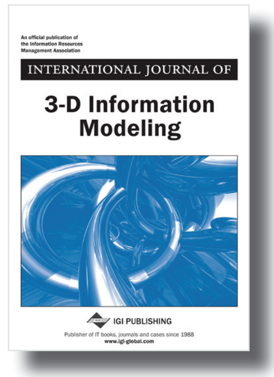

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