GeoJournal **52:** 263–269, 2001.

3D urban models: Recent developments in the digital modelling of urban environments in three-dimensions

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Received 31 March 2001; accepted 5 October 2001

Key words: 3D model, aerial photograph, spatial information technology, urban environment, visualisation

Abstract

This paper reports on recent developments in the visualisation of urban landscapes. There is a growing interest in the contstruction of 3D models of urban and built environment for which a host of digital mapping and rendering techniques are being developed. This paper extracts some of the cases that we came across during worldwide interviews carried out in March 2000. Building on this review, we identify the range of data and techniques adopted for the development of 3D contents and how they could contribute to geographical analysis and planning of urban environment. A particular focus is given on the effectiveness of GIS and its related methods for their capacity to accommodate the demands for visual representation of urban environment as well as the basis for analysis and simulation.

Introduction

Advancement of information technology has provided wide arrays of new digital tools that can support the generic activity of geographical analysis and urban modelling. In spatial decision-making and designing, in particular, these tools support different stages of the process which involve rapid and effective storage and retrieval of information, various kinds of visualisation to inform survey and analysis, and different strategies for communicating information and plans to the affected community (Delaney, 2000).

There are also a range of users – central and local governments, urban and rural planners, environmental agencies, telecommunications and utility companies, consultants' market surveyors, architects and engineers – who try to develop and utilise the increasingly sophisticated 3D models of the urban environment in order to plan and monitor services and impacts.

The combination of diverse modelling techniques and a multiplicity of uses leads us to the emergence of a very wide range of visualisation efforts, many of which are independently developed with different technologies under different initiatives. In addition to their designated applications, these models and data are potentially of great general importance to the understanding of urban structure as well as the mechanism of urban growth, spatial analysis and planning in the wider context. The use of 3D functions is particularly powerful in visualising urban and built environments, giving the option to deliver the relevant information in an intuitively comprehensive form (Day, 1994).

So far, lack of coherence amongst these efforts has prevented the formation of a standard modelling paradigm that can conceive such market. In fact, apart from those produced by their immediate competitors within their own industry, many tend to overlook the results in other related fields; thence not building a constructive competition but merely incurring variations, which in turn may hinder the development of modelling technology as a whole (Batty *et al.*, 2001).

This paper aims to categorise the typology of these independent movements under the same framework and seek a coherent structure in which each modelling project could be fitted. We begin by noting the underlying cause and demands for the recent development of GIS-based modelling methods. We then review some of the activities that digital tools can support, emphasising on the methods of visualisation and also focusing on the integration of 2D mapping and 3D block modelling. This is illustrated by some state-of-the-art cases, worldwide, suggesting that rapid changes are taking place in the ways such visualisations are being developed. We note developments in remotely sensed survey and in the development of 3D models integral to spatial databases as reflected in GIS.

The rise of demands for urban modelling

Ever since our society came to form urban agglomerations, there has been a constant manifestation of interest in the study of urban environment. Yet in geographic studies, urban geography has been regarded as less topical in comparison to the other more established fields (Carter, 1995).

This can be explained partly by the nature of urban environment that comprises a number of elements from landscape modelling to transportation networks to various socioeconomic exchanges. In addition, as each element plays its own role in the formation of urban structure, every city possesses a unique structure with its own momentum, presenting entities that are occasionally regarded as too diverse for a single topical study. Nevertheless, "*geography is not about the precise analysis of particular service areas... it is more concerned with the ways in which these relationships are reflected in the functional and physical structure of the town*" (Dickinson, 1959).

Two approaches have been pursued in order to understand the underlying forces, (1) the symbolic and analytical approach of geomorphology and spatial modelling for interpreting the urban society as quantitative phenomena, and (2) the iconic and empirical approach of data mining and landscape visualisation with a focus on context specific designing of urban environment.

The former has been rigorously pursued during the 1960s and from then on, where there has been a continuous search for the theoretical ground to address the conjectures and remarks for urban environment. The latter was also being explored alongside it but mainly from an empirical viewpoint. Constructing a model was still a time-consuming and labour-intensive task in earlier days, let alone the visualisation of 3D representation (Lowry, 1965). Apart from some noble attempts through photomontage, architectural parse drafting and the conventional wood block modelling, it has been only since the rise of information technology that we could create mass-scale urban models in 3D form (Delaney, 2000).

The initial methods of designing such models were based on computer aided architectural design where detailed measurement of the geometry was regarded as essential. Most of them failed to provide the spatial analysis aspect, and we had to wait for the outbreak of GIS technology. GIS has been intimately associated with our ability to visualise spatial data in maps and related statistical forms, especially for those with irregular and diverse contents such as the urban landscape (Okunuki, 2001).

The recent development in information technology has extended this further to the direction of 3D visualisation where our ability to render complex geometry has now become routinely embedded in standard hardware. At the same time, rendering techniques based on new methods of imaging such as remotely sensed data and photo-realistic imagery are being incorporated into such visualisations. Increase in the supply of remotely sensed data concerning the 3D environment also helps to make 3D visualisations of cities more feasible and popular (Teicholz, 2000). These are all emerging from developments in geomatic engineering and GIS to meet the demands for application of models for querying spatial data structures, and visualising the results of such queries in the 3D form (Fuchs, 1996). The next section shows the range of such data and techniques.

A typology of data and modelling methods

There are a number of factors in 3D urban models, such as clients, application, the output expected, budget, time period, and the amount of area to be covered. We also find at least three elements in the construction of the models alone: the degree of reality, types of data input, and the degree of functionality and the ability to conduct various analyses. The range of variety demonstrated within each factor shows the diversity in the current modelling arena.

The degree of reality – the amount of geometric content

The degree of reality is conceived by the amount of details captured and reproduced within the model. Naturally, the more details there are in the model, the more cost is incurred. However, the amount of geometrical details does not necessarily reflect how much reality the model can actually offer; in fact, rapid and inexpensive modelling techniques such as texture mapping and panoramic image capturing prove to be successful with the general audience (Leavitt, 1999). Figure 1 shows a summary of model typology in terms of the difference in geometrical details.

1. 2D digital maps and digital ortho-photographs: Conventional 2D GIS maps support a range of application but are incapable of giving the intuitively comprehensive 3D representation.
2. Image based rendering: Panoramic image-based modelling is an inexpensive solution for psuedo-3D visualisation, although the number of shots taken will limit its viewpoints, and it would certainly not incorporate spatial analysis functions.
3. Prismatic building block models: Block extrusion is a fusion of 2D building footprints with airborne survey data and other height resource. GIS technology allows us to overlay 2D maps on airborne data and determine the spatial characteristics of the image within each building footprint. They lack the architectural detail and convey no compelling sense of the environment but are sufficient for analysing view sheds and the shortest path.
4. Block modelling with image-based texture mapping: These are similar to the prismatic building block models but with image-based facades. The building textures are most commonly generated from either oblique aerial or terrestrial images which, in most cases, successfully compensate for the simplification of the outline of building geometry and roof morphology.
5. Models with architectural details and roof morphology: Modern digital photogrammetric systems enable an efficient recovery of 3D surface details. Automated search techniques are used for identifying the corresponding locations (points, edges and regions) in multiple, overlapping images to generate a number of possible geometries which can be tested against templates; but still require significant manual intervention for architecturally rich contents.
6. Full volumetric CAD models: As-built CAD models of individual buildings are frequently undertaken by a combination of measured building survey and terrestrial photogrammetry. The complexity of such models range from digital orthophotographs (in which images are rectified and combined to remove perspective effects) to the full architectural details, but the cost would be prohibitively expensive for full city coverage.

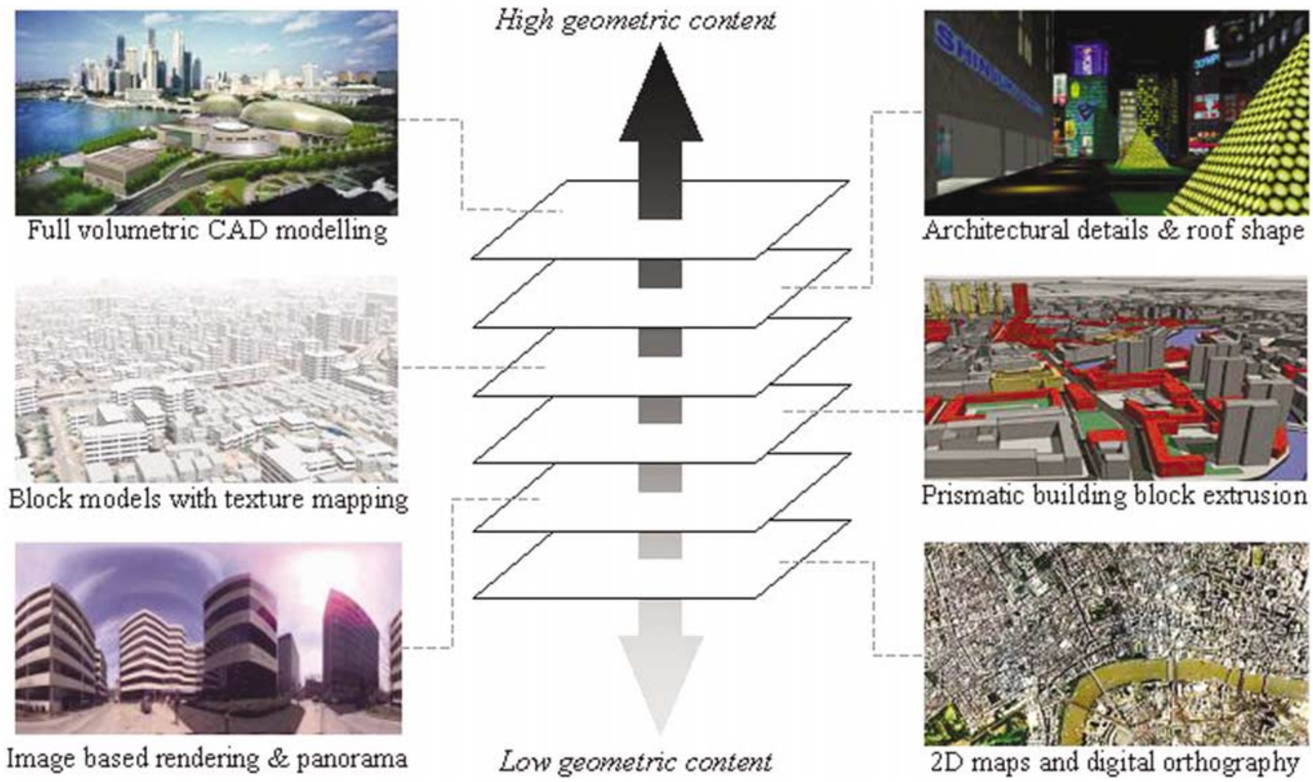

Figure 1. A typology of 3D urban models using different modelling methods.

Figure 2. Digital panoramic visualisation by Webscape (http://www.webscape.com/).

Types of data input – capturing heights and facade information

The way these data are obtained also affects the final output of the model. For instance, a limited number of panoramic shots are unlikely to produce analytically robust models whereas airborne survey data provide geometrically accurate but less photo-realistic models. Here are some of the data-acquiring methods that are commonly used in the urban modelling context.

1. Terrestrial images: Still images of building facades and video recordings of street-scapes are widely used to provide surface information. Obtaining suitable viewpoints for image acquisition in a city centre may be problematic much due to restrictions on helicopter flight paths or access to rooftops. Thus building textures are mostly generated from ground level photographs that often fail to provide optimal facade coverage.
2. Panoramic photographs: A panoramic image provides a highly realistic visualisation to all angles from static viewpoints within the survey area (Figure 2). If captured with sufficient density, they can provide a very detailed representation of an urban area complete with people, vehicle and street furniture often omitted in 3D CAD models.
3. Aerial photographs: The range of aerial survey data is becoming richer and more affordable. It provides a rapid and efficient method for the coverage of a wide city area. It should be noted however that, in order to provide a detailed building facades oblique aerial images must be acquired rather than the conventional, near-vertical aerial images.
4. Range imaging: Range images can be treated as surfaces over which high resolution intensity images can be draped, thus enabling the creation of alternative views of the object. The LIDAR (LIght Detection And Ranging) imaging techniques, in particular, are based upon camera systems that use a pulsed laser device to record the distance from the camera to each point in the image (Figure 3). Common applications use either ground based or airborne sensors, the former being suitable for architectural surveys and the latter for small-scale surveys including city models. Airborne LIDAR is invariably used in conjunction with the GPS (Global Positioning System) to deliver high-resolution digital elevation models.

Functionality – the degree of utility and analytical features

In terms of application and market demands, perhaps the most crucial feature is the functionality. Photo-realistic CAD-type models and CG parses are often less functional

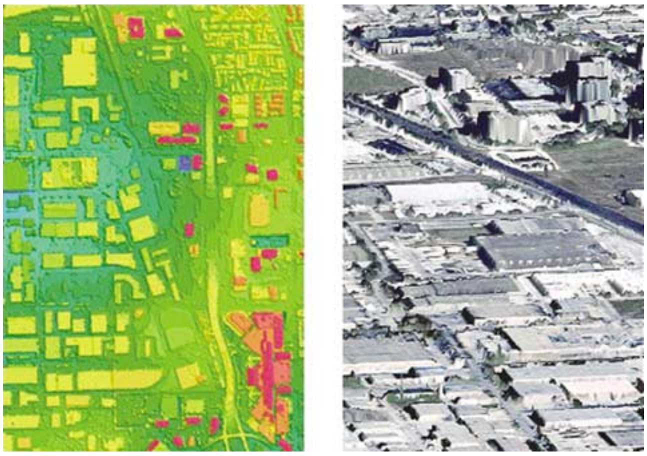

Figure 3. LIDAR-based city models (http://www.globalgeodata.com/bd-do.htm).

Figure 4. The Environmental Simulation Center model with the floorspace in downtown Manhattan (http://www.simcenter.org/).

whereas GIS-based models are generally supported by substantial attribute data and are integral to some analysis. Here are some of the model types with different degree of functionality. While the amount of analytical features does not necessarily determine the usefulness of a model in its proprietary context, the potential for extensive and alternative use will be directly reflected where GIS will prove to be powerful (Holtier *et al.*, 2000).

1. Aesthetic models: Models that are intended for aesthetic appreciation and demonstrative purposes tend to have little analytical functionality irrespective of its degree of reality. They are intended for illustrating the plans and developments to the authorities, various neighbourhood groups, or the customers in general through 3D visual presence.
2. Proprietary models with limited analytical capabilities: Typically, a model is equipped with at least one or more analytical features to serve its purpose. These include view-shed analysis, movable buildings or basic querying features which are performed through its built-in analytical tools, but these models are usually designed to be self-contained and are not suitable for extensive analysis.

Figure 5. Hybrid model of Tokyo developed by Mori-building Corporation.

Figure 6. A hybrid design review tool by Mori-building Corporation.

3. Full analytical features: Models extruded from a 2D GIS dataset often benefit from the use of the full GIS functionality by inheriting the attribute data attached to the spatial objects within the initial model (Figure 4). The range of functions that can be performed in these models include multiple spatial queries, view-shed and shadow analysis, and various scenario-based simulations; and these models are further extendable in general in terms of its analytical potentials.
4. Hybrid models and related techniques: Some models are built as a hybrid between 3D digital model as well as other media. For instance, physical wood block models are still in use where a digital model has been built alongside or on top of the traditional wooden model and the two models can be used simultaneously to complement each other (Figure 5). The notion of developing 3D models using VR displays acknowledges this role; the idea of building and displaying such a model in VR environment implies the interaction of users with the model using digital simulations of the physical movement of objects within it (Figure 6).

Applications for 3D urban models

There is a significant amount of professional interest as well as commercial incentives put into the field of 3D modelling. As of March 2000, there are over 60 of large-scale projects

Figure 7. Firespread simulation by CAD Center.

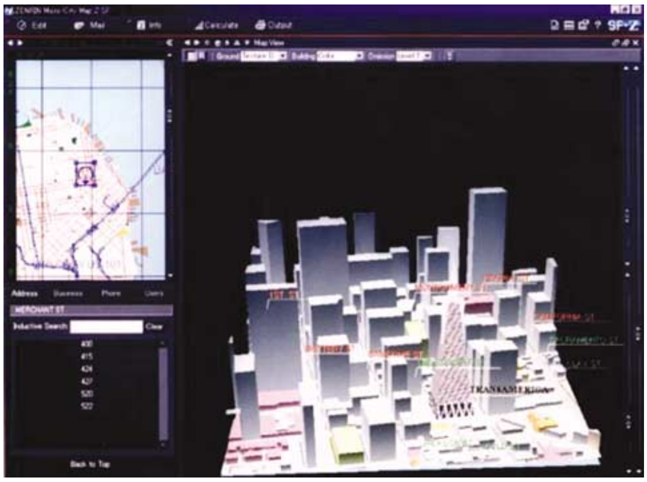

Figure 8. 3D marketing analysis tool from Zenrin Corporation.

worldwide each of which modelling a part of an existing city (Batty *et al.*, 2001). The two best developed sets of applications that we found are in New York and Tokyo, although the UCLA model of Los Angeles is probably still the most elaborate singly developed model to date (Liggett and Jepson, 1995; Jepson and Friedman, 1998). Details of this survey is described in Batty *et al.* (2001), but during the course of our survey, it became increasingly clear that most of these models were being developed for a very wide range of applications. We can define four different categories of use, (1) planning and design, (2) infrastructure and facility services, (3) commercial sector and marketing, and (4) promotion and learning of information on cities.

Planning and design

Planning and detailed design reviews as well as problems of site location, community planning and public participation all require and are informed by 3D visualisation. The focus is upon aesthetic considerations of landscapes as well as daylight and line-of-sight. Visual representation of environmental impact is also widely supported by 3D models. This concerns various kinds of hazard to be visualised and planned for, and ways of visualising the impact of disasters as well as local pollutants at a fine scale (Figure 7).

Infrastructures and facility services

Urban infrastructure such as water, sewerage, and electricity provision as well as road and rail network all require detailed 2D and 3D data for their improvement and maintenance. The analysis of sight-lines for mobile and fixed communications is also crucial in environments dominated by high buildings to secure a clear reception of signals. Finally, analysis and visualisation of access route to various locations by the police, fire, ambulance and other emergency services are crucial for maintaining a safe environment.

Figure 9. City promotion site for Shibuya City, Tokyo.

Commercial sector and marketing

2D and 3D models are effective for visualising the locations of cognate uses, spatial distribution of the clients and market demands for specific economic activities as well as the availability of space for development (Figure 8). They also enable the computation of detailed data concerning floorspace and land availability as well as land values and costs of development. Finally, virtual city models in 2D and 3D provide portals to virtual commerce through semi-realistic entries to remote trading and other commercial domains.

Promotion and learning of information on Cities

3D visualisation offers entries to urban information hubs where users at different levels of education can learn about the city as well as to give access to other learning resources through the metaphor of the city (Figure 9). In particular, it provides methods for displaying the tourist attractions of cities as well as ways in which tourists and other newcomers can learn about the geography of the city.

The applications clearly vary from one another, but they share one common feature in that GIS technology plays crucial role throughout the modelling process from data capturing to automated extrusion to utilisation and maintenance of the product.

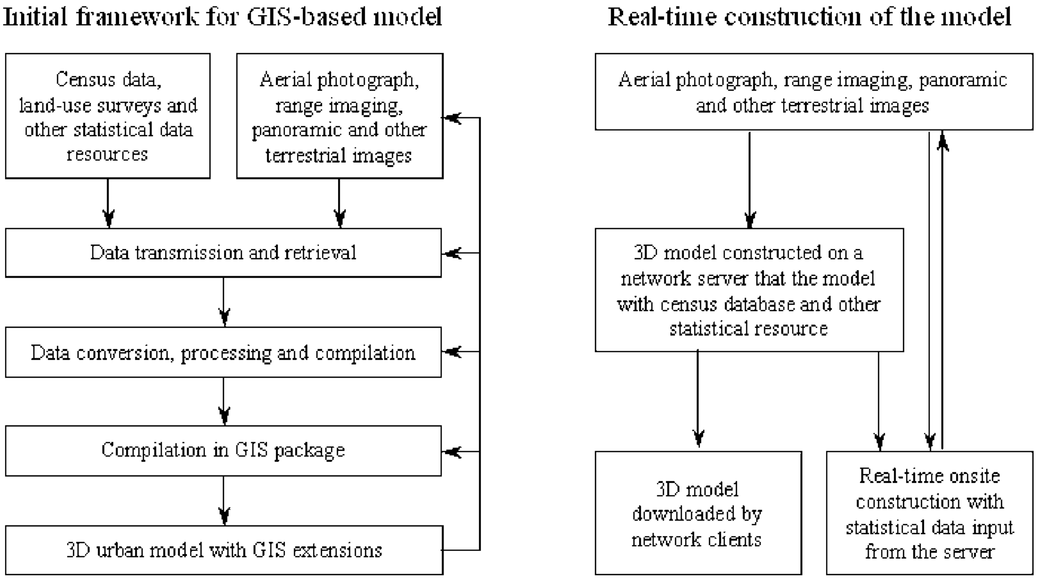

Figure 10. A framework of the current and the real-time online 3D model construction.

Framework for GIS-based urban model

We have seen that the 3D modelling scenes benefit from the extensive functionality and analytical capability of GIS as well as multiple queries feature by utilising its database structure. Development of 3D models currently depends on two factors: spatial information database and remote sensing technology. The rapid rate of information technology deployment suggests that these two features may become an integral part of 3D models in the near future. Consequently, a real-time, automated modelling technology will evolve such that we can automatically generate a model onsite wherever the remote sensing data are acquired by downloading them into standard packages that generate effective and useful models. These technological advancements of modelling features seem to be a matter of time, closely following the development of geographical information technologies, and the crucial factor will be the extent to which such automation will extend to bespoke applications, particularly those that address professional concerns. In this respect, specialist and unique adaptations of general principles are likely to remain the norm. However, software packages are likely to emerge that will be capable of generating good, standard models. This is already the case with the plug-ins and extensions to desktop GIS such as ArcView, and the Evans and Sutherland rapid 3D modelling package. More elaborate systems incorporating software such as Multigen Paradigm will also become more generally available as will software and data systems for producing remotely sensed data of good quality such as LIDAR (Snyder and Jepson, 1999).

The way these models will be delivered is also likely to change. CAD and 3D on the Internet has not moved as fast as expected due to a combination of cumbersome, non-intuitive interfaces and lack of ‘killer applications’ (Leavitt, 1999). But these will be resolved as Internet commerce begins to pick up fast elaborate interfaces and as optical fibre takes over (Gilder, 2000). Desktop will give way to the Internet as software such as the Internet Map Server and VRML/X3D-like browsers become standard. Remote access of data and software as well as the real-time generation of the contents over the network is likely to become the norm within the next decade. This will open an entirely new way in which users can interact with such models, and it will herald new ways in which the wider public will be able to participate.

The transition to ortho-photos and LIDAR type systems for recording height data is also notable. Most of the models we examined no longer use manual methods for measuring and recording height data. Various kinds of photogrammetry are now judged to be essential in the construction of such models and therein lies the route to automation of the entire process. Figure 10 illustrates the conceptual framework for real-time online construction of 3D GIS model where data input and output is no more a time-consuming and complicating process, but can be almost simultaneously attained through the network. The model is actually built onsite in real-time so that we can directly reflect the data input onto the model as they are captured, which in turn will feedback to the data input and will thus significantly reduce the time and cost of constructing the final product.

Another interesting feature of some model development is the continued use of physical iconic models, usually constructed from balsa. For example, the City of London relies extensively on their elaborate wooden model that is ported to many places by the economic development unit for marketing purposes. They have some digital imagery associated with it, but the ‘hands-on feel’ that the model gives is still important to its use. In Jerusalem, a digital model has been built alongside the traditional wooden model and there is interaction between the two in usage to evaluate development proposals. One of the main applications in Tokyo by the Mori Corporation is based around the extension of a physical model to various kinds of digital display (Figures 5 and 6), while at the time of writing, the authors have learned of an effort in Liverpool, UK to build a digital model of the city centre from detailed scanning of the traditional wooden model, thus by-passing the need for digital photogrammetry (Wooley, 2000).

Conclusion

This paper categorised a variety of urban modelling methods that have been led by the recent development of geo-spatial technology. It is clear that no standard has yet been established for the modelling arena, despite the basic commonality shared by the various modelling approaches. Nevertheless, there seems to be two different groups of approaches emerging from this diverse range of methods.

1. Ad hoc combination of in-house components: use of different package software and in-house tools of CAD, image rendering, database, and interface authoring tools. This approach is suitable for developing a proprietary model for a small area and architectural models with an emphasis on the visual effect rather than its functionality.
2. Integration of GIS software with 3D visualisation: extrusion of vertical elements on digital map data occasionally combined with image matching techniques with aerial photograph data. This is more appropriate for large area coverage as well as spatial analysis and simulations.

The distinction between the two approaches is likely to remain, as each serves different demands and clients; the former is adopted mainly in the urban and architectural designing context, whereas the latter is widely used in the market analysis, telecommunication and various simulations and a host of other uses.

Also, as these modelling methods become more sophisticated and available to a wider audience, we anticipate two conflicting movements. On the one hand, they are likely to become more contents and demand specific, tailored to accommodate specific needs for each use and thus generating even more variations; while on the other hand, the demands for data and model compatibility require a standard protocol and metadata to be adopted by the 3D models. The market will somehow discover and decide a point of compromise, but we are likely to have more than a single, unified standard as is also suggested by the distinction between the two modelling approaches above. Whatever the standards may be, GIS technologies will doubtlessly support and enhance the 3D modelling movements.

Acknowledgements

Part of this paper is extracted from a worldwide review of computer visualisation projects for cities carried out by the Centre for Advanced Spatial Analysis, University College London, in March 2000, which was funded by the Corporation of the City of London.

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