reviewed paper

Three-dimensional building reconstruction: a process for the creation of 3D buildings from airborne LiDAR and 2D building footprints for use in urban planning and environmental scenario modelling

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1 ABSTRACT

The process of three-dimensional building reconstruction based on high-resolution building height models taken from airborne LiDAR and building footprints offers a high-degree of precision. In many areas of the world, this data is available for entire cities and can be leveraged by municipal survey departments as well as LiDAR data service providers.

The major disadvantage to using conventional methods of building reconstruction is that they are largely manual; suitable for individual or small groups of buildings, an almost Herculean task when creating a 3D model that includes thousands of buildings. Until recently, airborne LiDAR was either not widely available or lacking in sufficient resolution. Due to advancements in laser scanning equipment however, high-density LiDAR data capture has become more pervasive – particularly in Europe, making the use of airborne laser scanning an effective means of creating 3D models for a myriad of environmental and planning applications.

In contrast to other processes, we have developed a technology to automatically extrude building geometry as well as standard roof forms (i.e., flat, pitch, gable and hipped). The technology was conceived as an alternative to current photogrammetric or manual LiDAR extrusion methods in order to achieve greater economies of scale by creating 3D building models for entire urban regions rather than for smaller surface areas.

For the last three years, together with the University of Stuttgart, we refined the process of automatic building reconstruction whereby from airborne LiDAR whereby three-four laser points per m^2 returns building geometry with standard roof forms and even higher density LiDAR data sets enables the successful reconstruction of individual roof types.

When we speak of effectively deploying 3D building models from airborne LiDAR, we have witnessed a growing trend of using 3D building models for urban planning, noise mapping, flood water simulation and radio network optimisation. And as municipalities face ongoing challenges to creating sustainable, environmentally-friendly urban environments, more and more they are turning to geospatial information and airborne LiDAR “downstream products” such as 3D building models to answer key questions concerning urban sprawl, transportation networks, visibility, cast shadows as well as public safety and security.

2 INTRODUCTION

City planning is complex and multi-dimensional. Because we live in a three-dimensional world, shouldn’t urban spaces be planned, considered and studied in a three-dimensional environment?

And perhaps there is an even more important question: c*an virtual city models help in decision making and problem solving, enabling us to take into account not only buildings, but also human and environmental factors?*

More and more, professionals in urban planning, utilities, fire and rescue as well as security are turning to GIS data sources for 3D modelling because they offer a more holistic approach to addressing human, environmental and infrastructure issues that are part and parcel in the design of sustainable urban environments.

Three-dimensional modelling has several advantages. Beyond the modelling of topographic data it can also extend to geo-referenced data, providing not only Visual Intelligence for decision-making; it also brings together both *conceptual and design models* (civil engineering plans, subterranean utility and

power networks) and *thematic models* (building information, demography, statistics), thereby providing a holistic, *integrated* approach to urban planning.

Three-dimensional city modelling can facilitate communication between stakeholders within and outside a municipality and attract as well as consolidate interest for projects and land development that require capital spread out over a larger group of financial investors.

While we do not claim that technology or methodology is necessarily better than the other, our supposition in this paper:

1) 3D city models offer the best long-term solution for designing sustainable living environments;

2) 3D city models should be produced on a wider scale with a view to mid-term usage and future applications;

3) The use of software technology that can automatically generate large-scale 3D city models from airborne LiDAR is a more economic solution than manual processes;

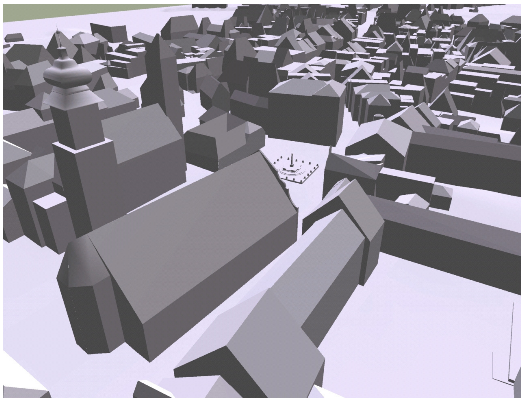
4) The leveraging of new technologies such as LiDAR provides a solid basis for a wide range of planning and analysis applications.

3 3D BUILDINGS AS FOUNDATION FOR URBAN PLANNING AND ENVIRONMENTAL SIMULATION

The basis for all city models and their consequent usage is of course 3D buildings, whether basic block models with flat roofs (Level-of-Detail or LOD1), building models with roof forms (LOD2) or even architectural models with façade texture and proper building geometry(LOD3).

In order to strategically deploy 3D building (or city) models, several factors must be taken into consideration, including but not limited to:

- Efficient modelling of *existing* buildings that are already present – future urban development should be planned within the context of the existing landscape in question
- Establishment of efficient workflow processes for creating 3D city models, from LOD1 up to LOD3
- LOD1 and LOD2 model generation necessitates [largely] *automatic* processes in order for them to be economically feasible on a large-scale
- The aforementioned models must be accurate with respect to building heights and geometry in order to serve as the basis for environmental simulation such as noise mapping, wind tunnel effect and flood scenario simulation and visualisation



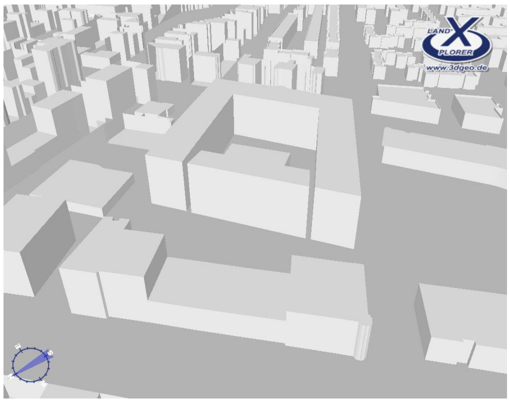


Fig. 1 LOD1: block models with flat roofs; Fig. 2 LOD2 Block models with simplified roof structures

4 3D BUILDING RECONSTRUCTION TECHNOLOGY: A PRIMER

For 3D city models to be truly effective for diverse applications used by city planners and environmental engineering companies, they must meet the following criteria:

- Ability to integrate diverse GIS and CAD data
- Industry standard data formats, Open GL and OGC standards must be observed and implemented
- Supported by technology and processes that allow for creation and maintenance of larger data sets in a cost efficient manner

Our purpose is to address the third criteria through the application of automatic processes for the creation of 3D building models from LiDAR.

4.1 Problem

The major disadvantage to using conventional methods of three-dimensional building reconstruction is that they are largely manual; these methods are suitable for individual or small groups of buildings (for example, 20-30 buildings), but present an almost Herculean task when creating a 3D city model that encompasses one hundred thousand buildings or more. Until recently, airborne LiDAR was either not widely available or lacking in sufficient quality.

Due to advancements in laser scanning equipment over the past three years however, high-density LiDAR data capture has become more pervasive, particularly in Europe, making the use of airborne laser scanning an effective means of creating 3D models for a myriad of environmental and planning applications.

The process of three-dimensional building reconstruction based on high-resolution building height models taken from airborne LiDAR and building footprints indeed offers a high-degree of precision. While in most cases not as accurate as photogrammetry, the trade-off here is a slow, manual and costly process versus a quick and cost-efficient method.

We have already mentioned that three-dimensional modelling is increasing in acceptance. *But just how does one create large-scale 3D representations of urban environment in a cost-efficient manner?*

4.2 Solution

In response to enquiries from customers and recognizing a future trend in the use of LiDAR data for creating 3D city models, we developed software technology with the University of Stuttgart to automatically extrude building geometry as well as standard roof forms (i.e., flat, pitch, gable and hipped) using building footprints, a digital surface model and a terrain model. The technology was conceived as an alternative to current photogrammetric or manual LiDAR extraction methods in order to achieve greater economies of scale by creating 3D building models for entire urban regions rather than for smaller surface areas.

The quality and accuracy of the resulting 3D buildings is dependent on the density of the LiDAR flown: in essence, the more laser points per square meter the better the automated reconstruction results. Using our technology, we have been able to achieve the following:

3-4 points per sq. meter = standard rooftops like saddle, hipped, pitched etc.

7-10 points per sq. meter = individual rooftops with dormers

4.3 Process

A digital terrain model, building footprints and a digital elevation model are used as the basic data components for the automatic extrusion of 3D building models. These three data elements produce as result block models with simplified roof geometry which can be used for environmental simulation such as noise mapping, flood scenarios as well as line-of-sight studies and 3D city modelling.

Because roofs are normally in their nature complex, a catalog of the most common simple rooftypes is necessary. Thus the software is able to reconstruct basic forms such as flat, pitched or hipped roofs. Here both distance and roof slope are estimated. The roof forms of single cells created during the reconstruction process are afterwards adapted for the total roof form of the building. A parametric estimation provides a description of the outer edges of the reconstructed building, which can be then be attributed as a 3D shape file.

Thus it is possible to reconstruct a very large number of buildings in a very short time. The procedure differs thus substantially from other semi-automatic procedures where a manual intervention is necessary in each case. For errors found during the reconstruction – anywhere between 15-25 percent depending on the data inputs – an interactive Editor enables the correction of building geometry and basic roof forms within the data set.

Input Data:

- Ground Cadastral Map (Building footprints as 2D Shape files)
- DHM (LIDAR data as ESRI ASCII Grid)

Output Data:

- Buildings with Roof forms (3D-Shape), including ridgelines and eaves
- Data formats: Multipatch or PolygonZ

These data formats can be imported into other GIS software such as ESRI or converted to other industry standard formats for creating building Information Models (BIMs) or 3D city models (CityGML).

5 ILLUSTRATION OF WORKFLOW

Step 1: Creation of building structure through heuristic right-angle segmentation of the building footprints:

Fig. 3

Step 2: Creation of roof forms through segmentation of the DHM:

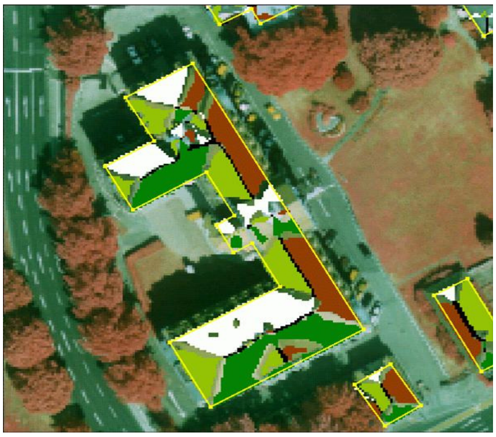


Fig. 4

Step 3: Estimation of roof parameters taken from the DHM.

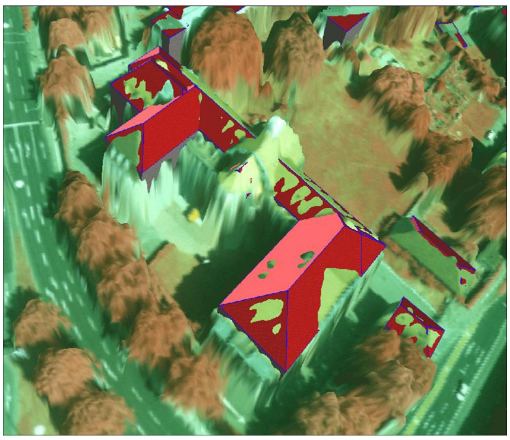


Fig. 5

Step 4: Interactive refinement and correction of the reconstructed buildings.

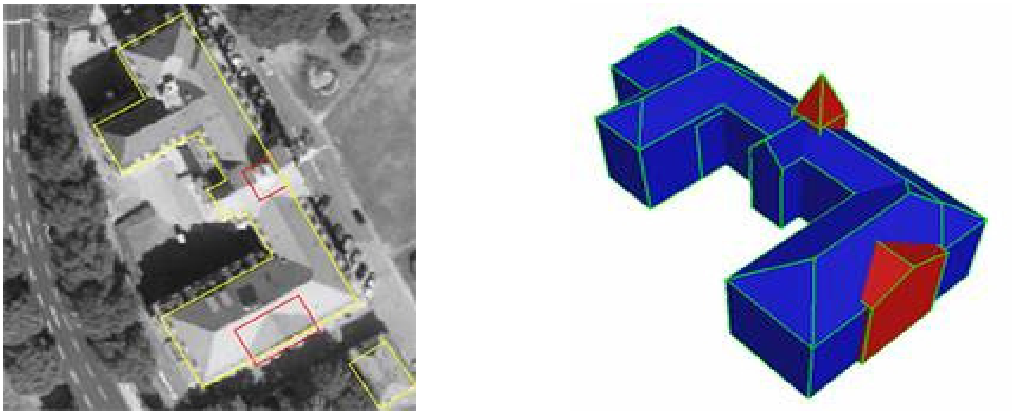


Fig. 6

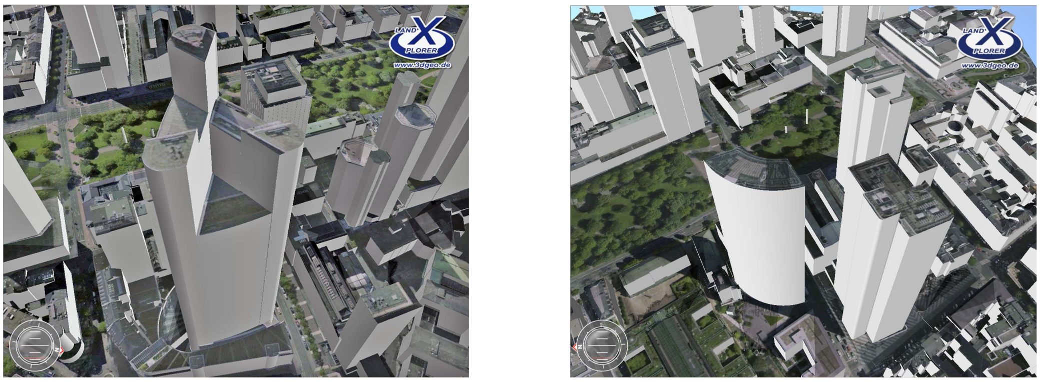


Fig. 7 Visualisation of reconstructed buildings from LiDAR data

6 FURTHER SOFTWARE DEVELOPMENT: CELL DECOMPOSITION VS. RECTANGLE SEGMENTATION

Roughly one year after the first release of our software technology, it became clear that there was also a need to provide greater accuracy for more complex building geometry and roof types. At present, software development is already well underway, this time using a process called *cell decomposition*.

Instead of creating rectangles and then intersecting them to create a single geometrical "solid", cell decomposition creates several different polygons from LiDAR data by first simplifying and then placing

neighbouring but not overlapping polygons next to each other. Depending on the density of the LiDAR data, the result is fewer errors and more faithfully reconstructed building details, including roof forms.

The goal here is to produce more accurate LOD2 3D buildings – geometric simplification is still applied, however the process remains automatic and thus an effective solution for created 3D city models quickly and in a cost-efficient manner.

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Examples:

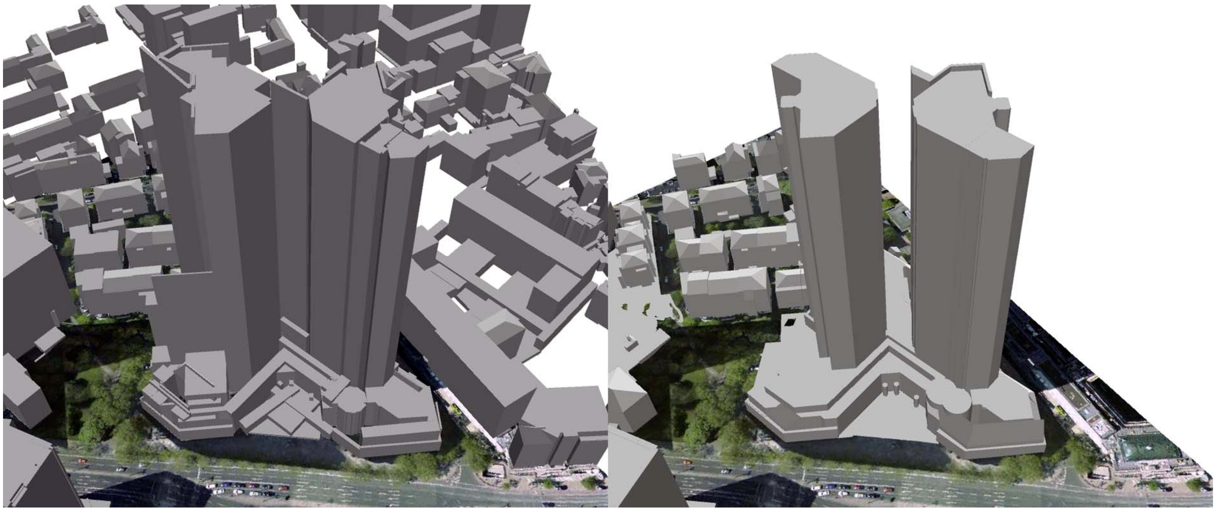

Fig. 8 Rectangle Segmentation (left) and Cell Decomposition (right)

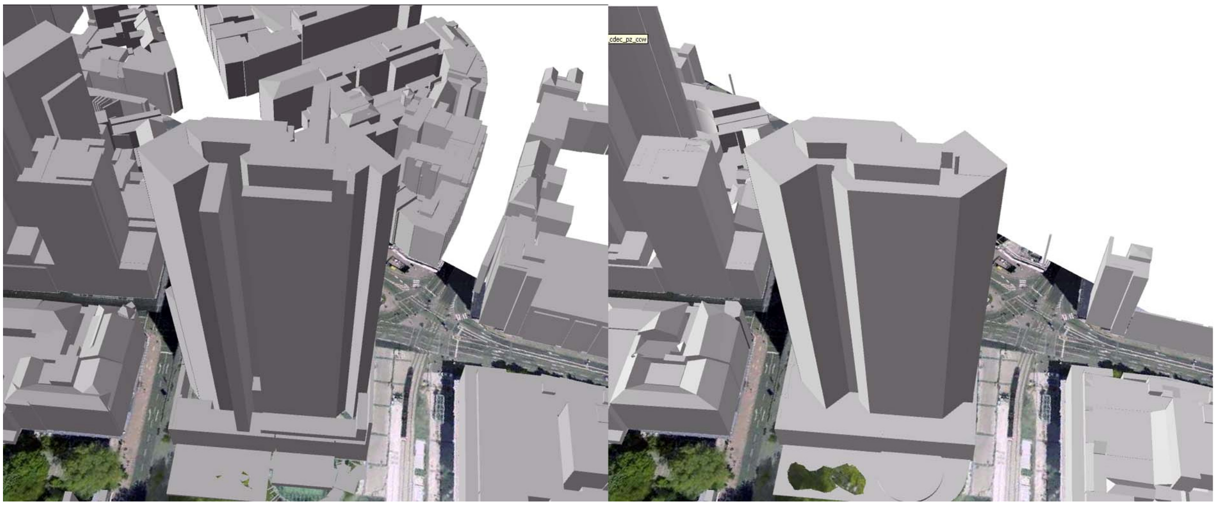

Fig. 9 Rectangle Segmentation (left) and Cell Decomposition (right)

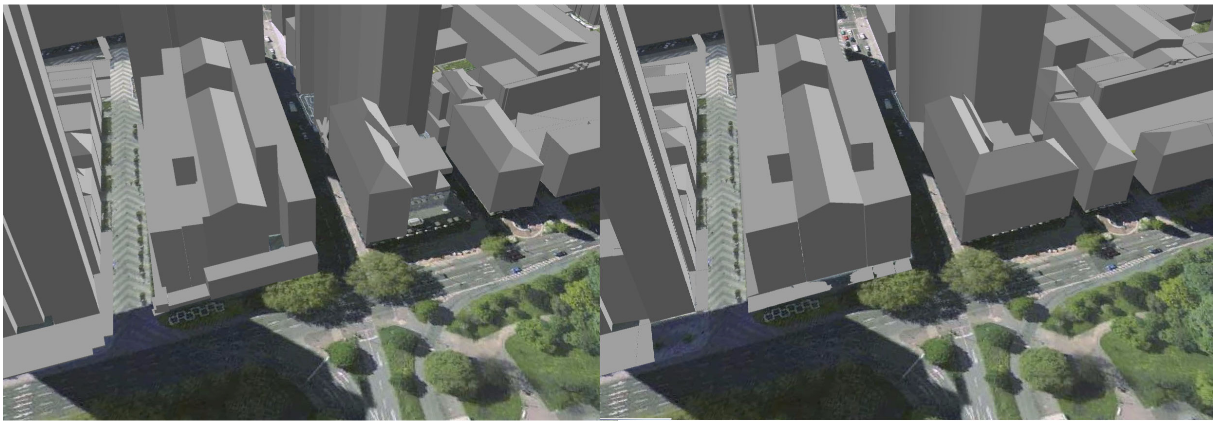

Fig. 10 Rectangle Segmentation (left) and Cell Decomposition (right)

7 FURTHER APPLICATIONS FOR 3D MODELS

Although traditional uses of airborne LiDAR are mainly concentrated in the forestry, mining, oil and gas industries, 3D virtual city models created from LiDAR is quickly gaining acceptance in North America and in Europe. Because façade texture or rather detailed building models are not required for urban planning or environmental simulation, 3D block models drawn from LiDAR lend themselves to further applications such as the planning of critical transportation networks, radio and WiFi network planning and public safety. All these applications have one common thread: to facilitate and ensure public safety and last but not least improve the quality of life as well as services for inhabitants in large urban areas.

With regards to effectively deploying 3D building models from airborne LiDAR, we have witnessed a growing trend of using 3D building models not only for urban planning but noise mapping, flood water simulation and radio network optimisation. And as municipalities face ongoing challenges to creating sustainable, environmentally-friendly urban environments, more and more they are turning to geospatial information and "downstream products" such as 3D city models to answer key questions concerning urban sprawl, transportation networks, visibility as well as public safety and security.

8 REAL WORLD EXAMPLES OF DEPLOYING 3D MODELS FROM AIRBORNE LIDAR

8.1 Visibility

Visual impact analysis and line-of-sight studies can be made using 3D block models.

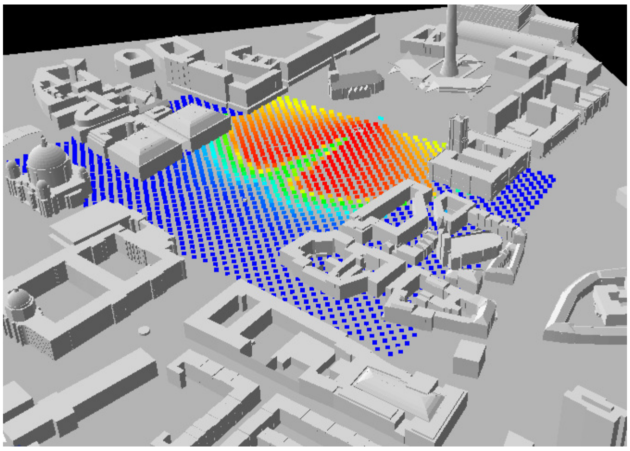

Fig. 11 Visibility & Security: Analysis of Public Spaces (Source: 3D Geo GmbH)

8.2 Flood Scenario Visualisation

3D block models from airborne LiDAR provide the backdrop and underlying structure for the visualisation of hydrology calculations in a 3D, real-time environment.

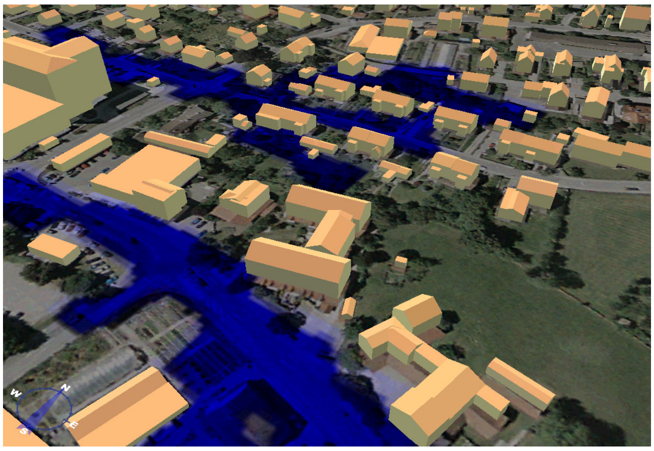

Fig. 12 Environment: Flood Scenario Modelling using LiDA

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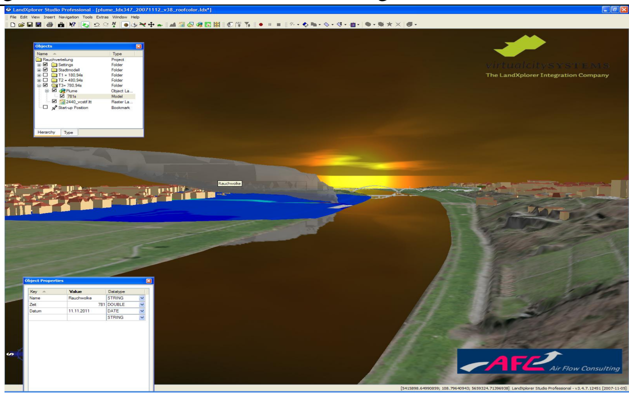

.Fig. 13 Environment: Toxic Fume Visualisation using 3D block models

9 IMPLEMENTING 3D MODELS FROM LIDAR FOR URBAN PLANNING AND ENVIRONMENTAL SIMULATION

The smart use of advanced technology such as airborne LiDAR can serve in urban planning as well as environmental simulation to create livable, sustainable urban environments. Finally, in order for 3D city models to be effectively used in a strategic way and not just simply "nice to haves", they must be created on a wide-scale and in a cost-effective manner. Once a 3D city or urban information model has been created, more value can be derived through its use in the following application areas:

Security & Visibility Decision-making Support

Visual impact analysis and line-of-sight studies can be made in real-time using a city model.

Emergency Response Management

Decision-making support for police, fire and rescue as well as Homeland Security professionals is enhanced through real-time 3D visualization of streets, buildings, neighbourhoods and topography.

Spatial Planning for Complex Urban Environments, City Models

The use of virtual city models is not restricted to city planners. Utility, water, sewage and transport companies are better able to assess and improve the efficiency of their own infrastructure and networks, and well as coordinate and share information.

Environment

3D city models as visualization tool for hydrology and noise mapping calculations for urban areas with known flood zones, high traffic areas, etc.