A Framework for Defining a 3D Model in Support of Risk Management

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Abstract

A conceptual framework is proposed that defines the most appropriate 3D visualisations for different types of natural disasters in urban environments. Based on the disaster type, the needed level of detail for a 3D model is derived, which is then linked to the time needed to process the data and obtain this level of detail. The levels of detail are compliant with the 3D international standard CityGML. The framework is designed to serve risk managers and to help them make a better selection of 3D model representations to perform their tasks. After a brief introduction on the relations between types of disasters, data needed to manage the disasters and different users involved in the risk management process, the paper elaborates on the parameters according to which types of hazards are classified. The framework is demonstrated for an earthquake case in Eskisehir, Turkey. The paper concludes with a discussion of the advantages and disadvantages of the given framework, as well as an outline of future research.

1 Introduction

Natural disasters have caused many casualties and injuries, as well as economic, cultural and structural damage, over the history of civilisation. Given that more than half of the world population currently lives in cities and that many economic assets are concentrated in urban areas, naturally, the vulnerabilities increase due to the growing complexity of urban processes.

Natural disaster risk is a function of hazards, elements of risk and vulnerability. Risk is defined as the expected losses, including lives, personal injuries, property damages, and economic disruptions, due to a particular hazard for a given area and time period (WMO 2002). Risk assessment is one of the key elements of a natural disaster management strategy as it allows for better mitigation and preparation. It provides input for decision making, and it increases risk awareness among decision makers and other stakeholders (U.S. HHS 2002). Previous studies have shown that the presentation of hazards, vulnerability, coping capacity and risk in the form of digital maps has a higher impact than traditional analogue information representations (Martin and Higgs 1997). Digital maps are increasingly being used by disaster managers. Many authors believe that 3D visualisations have the potential to be an even more effective communication tool (Kolbe et al. 2005, Marincioni 2007, Raper 1989, Zlatanova et al. 2002). 3D graphical representations significantly reduce the amount of cognitive effort and improve the efficiency of the decision-making process (Kolbe et al. 2005, Zlatanova 2008). However, to achieve an appropriate 3D visualisation, two aspects must be ensured: appropriate presentation and appropriate tools for interaction.

The use of 3D spatial data for the whole disaster management process is a new, but quite attractive, topic in geoscience. There have been several studies on the use of 3D geographic information for modelling hazard phenomena and corresponding urban environments. Uitto (1998) proposed a framework using GIS for urban disaster management, considering the disaster vulnerability concept. Herold et al. (2005) outlined a framework for establishing an online spatial disaster support system for disaster management. The framework integrates GIS, spatial databases and the Internet for disaster management concepts. Zlatanova et al. (2007) discussed an emergency response framework. Technical necessities of multi-risk emergency situation response systems were evaluated from a 3D spatial information perspective, and they proposed a system architecture that covers data management and communication for problem areas. These studies, however, have not provided an adequate methodology for defining the level of 3D urban modelling for various types of natural hazards.

This paper presents a framework that establishes a link between the disaster type (e.g., flood or earthquake) and several components of 3D urban visualisation. The framework takes into consideration issues such as the resolution of the 3D model, the time/effort needed to create a model, and the availability of software and source data. This chapter is organised into five sections. The next section provides the needed background information. Section 3 introduces the framework. Section 4 demonstrates how the framework is applied. The last section elaborates upon the next steps for extending and testing the framework.

2 Background

Generally, 3D urban modelling is a holistic process of conceptualisation, data capture, sampling and data structuring and depends on the aim of visualisation (Raper 1989). In risk management, 3D modelling is very much dependent on the type of disaster being represented and the type of users involved in the risk management process. This section introduces related topics such as hazard classification, users and 3D urban objects of interest for risk analysis. Since 3D urban objects can be modelled with different resolutions, types of geometry and attributes, aspects of 3D semantic modelling are also briefly introduced.

2.1 Hazards

The development of a framework for 3D visualisation of various natural disasters first requires a classification of natural disasters depending on their characteristics. Several authors have provided classifications of the types of disasters depending on various parameters of hazard and risk characteristics (Shaluf 2007, Kaplan 1996, and Mitroff 1988). Among them, the classification given by Burton et al. (1993) is used as a starting point in the proposed framework. Burton et al. (1993) provided six parameters for assessing the potential impact of a natural disaster. *Frequency* reflects the time interval in which a natural disaster occurs. For example, earthquakes may occur with a log-normal frequency, while landslides may occur seasonally. *Duration* is the period of time over which a disaster continues. Hence, it has a wide range, from seconds to years. For example, earthquakes are very short, while some landslides (e.g., creeping slopes) are long-term processes. *Spatial Dispersion* refers to the pattern of distribution of a hazard over the geographic area in which the hazard can occur. This parameter ranges from small to large. *Speed of Onset* is an important variable since it establishes the warning time. Most extreme disasters such as earthquakes, mud flows and flash floods give virtually no warning. Other disasters, such as creeping slopes, drought and desertification, act slowly over a period of days, months or years. *Areal Extent* is the spatial density of the disaster over the whole earth (e.g., earthquake zones are limited as they are governed by the tectonic plates). *Temporal Spacing* refers to the sequencing and seasonality of the disaster events. Some disasters are random, like volcanoes, while others have seasons, such as hurricanes, tropical cyclones and floods. These parameters give sufficient background to find the proper 3D spatial object representation needed for our framework. In the proposed framework, five parameters *(frequency*, *duration*, *spatial dispersion*, *speed of onset* and *areal extent)* are taken into account as they were found to be sufficient for generating a disaster prevalence index. This forms the first component of the proposed framework. Burton's last parameter, *temporal spacing*, is not applicable for the framework since a relation of the temporal spacing to the spatial and temporal definitions in the 3D urban models could not be clearly defined. The last parameter to be used in the framework is described in Section 3.1.

2.2 Users

As different user groups or decision makers may require different types of 3D urban models and functionalities, the next parameter to be identified for the framework is the characterisation of decision makers in risk management. Correct user group determination is also important for determining the functional content of the 3D urban model. Different users are involved in different phases of disaster management. For example, fire brigades, ambulances and police might be the main responders in the emergency phase, while urban planners and risk management specialists might be the users in the preparation phase (Zlatanova et al. 2007 and Zlatanova 2008). The introduction of a fundamental classification of users is beyond the scope of this paper. The users considered in this study are general users such as financial institutions (e.g., World Bank, insurance industry), academia (e.g., universities), the private sector (e.g., industrial organisations), governmental organisations (e.g., governors, municipals), civil society organisations (e.g., Red Crescent), international financial institutions and other public bodies.

2.3 3D urban modelling

The 3D urban modelling is another important factor to be considered in the development of the framework. Although various aspects of 3D modelling can be accounted for in the proposed framework, the type of objects to be modelled, their representation and the resolution, or Levels of Detail (LoD), play the most critical roles in 3D urban modelling for natural disaster situations. Thus, the proposed framework utilises previous knowledge of semantic models to define the objects to be used and the required resolution for urban modelling applications. In practice, the LoD concept can be directly related to the resolution; therefore, it is adopted in the proposed framework.

Various initiatives exist to define objects of interest in urban areas. Among them, CityGML is one of the few 3D urban modelling concepts that considers 3D semantics, geometry and topology in a generic sense (i.e., it is not application oriented). The most important objects are *Building* objects, which provide representations of thematic and spatial aspects of buildings; *Relief*, which is simply the terrain; *Transportation*, which represents objects of all modes of transportation, for example, roads, tracks, srailway or squares; and *Land Use*, which describes areas of the earth's surface dedicated to a specific land use. Several other objects, such as *City Furniture*, *Vegetation* and *Water*, can be also useful for risk management. *City Furniture* objects are immovable objects like lanterns, traffic lights, traffic signs, advertising columns, benches, delimitation stakes or bus stops. *Vegetation* is used to represent solitary tree objects, plant covers and surface or plant canopy. *Water* objects represent the thematic aspects and 3D geometry of seas, rivers, canals, lakes and basins. The only limitation of the current version of CityGML is the lack of underground objects. However, ongoing research and developments are considering extensions in this direction (Emgard and Zlatanova 2008). These can be included later in the framework.

These object classes compose the *object pool* in the framework. A set of objects important for any particular disaster can be obtained from this pool.

The most interesting concept in CityGML is the notion of an LoD, which defines the resolution with which 3D objects have to be modelled. The LoD is best developed for buildings. LoDs range from LoD0 to LoD4. LoD0 is the 2.5D level, over which an aerial image or a map may be draped (Kolbe et al. 2005). For buildings, LoD1 defines a box model, while LoD4 defines the inside of buildings. Naturally, the resolution increases from LoD0 to LoD4 (Gröger et al. 2006). The LoD concept is quite generic and suitable for small-to-large area applications. The LoD as developed in CityGML is adopted as a starting point in the proposed framework.

2.4 Sensor products and 3D reconstruction

Once the conceptualisation of 3D models is established (i.e., with respect to the types of objects to be modelled and their resolution), the next requirement to be satisfied for the development of the framework is the generation of the corresponding 3D models. Data used to generate 3D urban models can be obtained from passive sensors, active sensors or a combination of both (Hu et al. 2003, Kerle et al. 2008). Passive sensor methods are usually cost effective if large scale 3D urban modelling is needed and require a combination of aerial and terrestrial images. Active sensors can provide, in a short period of time, large amounts of 3D data, but the 3D reconstruction models need to mature. Most urban modelling applications require integration of different data sources and sensor products. This integration can be in the form of simple overlay or multi-data information extraction (increasing the dimensionality using DSM and 2D images, increasing spatial resolution using high spatial resolution panchromatic images with multispectral images in relatively low spatial resolution and multi-criteria analysis to assess the natural disaster risk by considering various elements at risk) (Kerle et al. 2008, Tao 2006).

Sensor products and methods for reconstruction are important factors in the proposed framework. Risk managers have to be aware of how much effort and money is needed to obtain an effective 3D model for visualisation. For example, current technology is relatively limited in terms of radar systems (less than 45), as compared to more than 130 laser scanners and thousands of optical systems. In practice, this means that a method based on products of laser scanning or optical sensors are more likely to be better matched with the resources of a specific municipality. The selection of products is also dependent on the desired LoD. For instance, 3D models textured with images always require the use of optical sensors. The efforts required for creating a detailed 3D model (e.g., buildings in LoD3) differ significantly from the efforts needed for obtaining an LoD1 model. The proposed framework aims to help risk managers in municipalities make the most appropriate decisions regarding the resolution of the 3D model.

3 The framework

The framework consists of the following four groups of parameters: 1) hazard assessment, 2) user/elements at risk, 3) data and process requirements and 4) needs for visualisation (Figure 1). *Hazard Assessment* refers to the determination of the three characteristics of the 3D urban model, which are *Hazard Characteristic Medium*, *Indoor/Outdoor Resolution* and *Data Representation*. Hazard Characteristic Medium is the vulnerability value of any model object (e.g., of a building in an earthquake case or a sea water object in a tsunami case). Indoor/Outdoor Resolution defines the abstraction levels of each modelling object. Low spatial resolution would mean a low LoD, while high spatial resolution would mean a high LoD. Data Representation involves the data and procedures needed for a specific model. Here, the alternatives to 3D data representations such as boundary (surface) or volume approaches (e.g., voxel) should be evaluated.

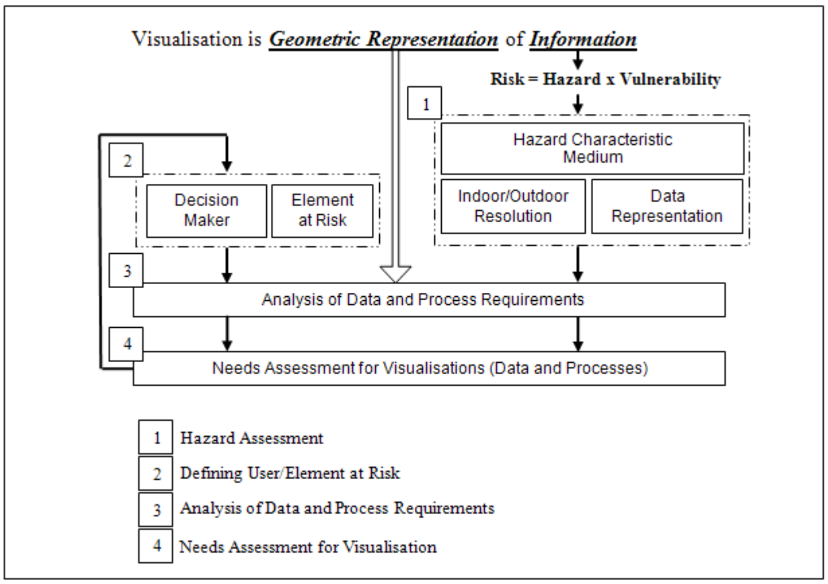

Fig. 1 Steps and workflow.

The next group of parameters is defined as the *User/Elements at Risk*. A user might be interested in different sets of risk elements, which depend on the components of the urban environment. For example, an insurance company may have interests only in buildings, while utility companies might be mostly concerned with the effect on their networks. This is to say that the objects to be considered (and included) in a particular 3D model have to be selected with respect to the user.

When urban objects and the elements at risk are defined, they are fed into the analysis of data and process requirement stages to specify efforts needed for establishing model objects with data and process efforts.

3.1 Hazard assessment

This section introduces the final parameter called *Indoor Penetration (to the Built Environment).* Some natural hazards exert their fatal effects on built environments by the intrusion of hazard-related material into the built structure. This material can be soil, mud or rock in landslides or water in floods and tsunamis. The indoor penetration parameter is used to determine the indoor LoD, together with the spatial dispersion. For instance, in many disaster cases such as tsunamis, floods and landslides, it would beneficial to have 3D indoor models with floor distributions (or even apartments) to better estimate those parts and floors of the building that will be affected.

The six hazard assessment parameters, adapted from Burton's hazard classification (see section 2.1.) and the newly introduced parameters are used to achieve two basic outputs, the first being the so-called *prevalence index* of different hazard types. The *prevalence index* of different hazard types is obtained from the parameters of *frequency*, *duration*, *spatial dispersion*, *speed of onset* and *areal extent*. Figure 2 presents a graphical representation of the prevalence index. As can be seen, a hazardous event that occurs frequently, with a long duration and slow speed of onset, over a widespread and large area causes the most pervasive effect to the urban environment. For example, specific urban earthquakes can be a more prevalent hazard than landslides.

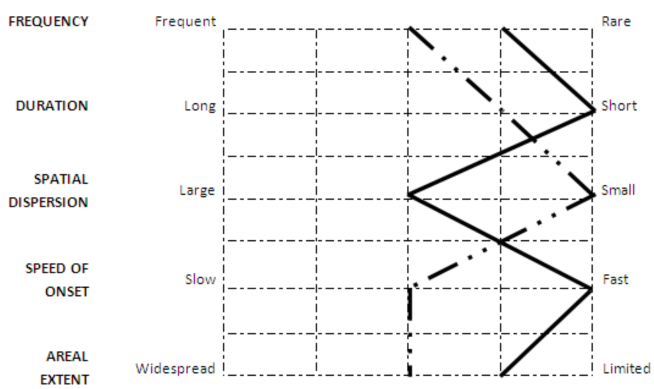

Fig. 2. Hazard prevalence level of earthquake and landslide cases (the flat line represents an earthquake, and the dotted line represents a rapidly moving landslide).

Each parameter is normalised to obtain a value on a scale from one to five. Each of the five parameters that form the shape of the prevalence function is related to a hazard type. The cumulative evaluation of these parameters constitutes the hazard-related part of the prevalence approach, which aims to relate the hazard type and spatial characteristics of the desired 3D urban model.

The hazard prevalence value is used with the urban area extent and the population density parameters of the target city to evaluate the LoD level of the desired 3D urban model. If a hazard occurs in an urban area that has a high areal extent and/or low population density, the needed model detail level decreases.

To determine the resolution (or LoD), hazard characteristic medium and data representation, one or more hazard assessment parameters can be used. Indoor and outdoor resolutions (or LoD) are obtained from the spatial dispersion and intrusion parameters. The hazard characteristic medium is basically identified from the parameter type of natural hazard. The data representation is established by using a combination of the physical mode and duration parameters.

Further formalisation of the link between the hazard type (defined by the six parameters) and the derived LoD can be found in Kemes et al. 2009.

3.2 Users and elements at risk

Hazards can affect physical assets and/or humans, and therefore, the risk can be considered to be human-related or nature/infrastructure-related. In an urban area, citizens, cultural heritage (e.g., buildings and natural phenomena), assets, infrastructure (e.g., roads, utility networks and rivers), and private and public housing may be vulnerable to a specific disaster and are considered to be elements at risk. Furthermore, different risk management specialists (stakeholders) might be interested in specific elements at risk related to their professional area. For example, a water engineer may be interested only in the risk of dam breakage and will not be involved in an estimation of the vulnerability of citizens. The most likely social issues will be considered by a social expert. Therefore, it is important to know who the users (user groups) are and what elements at risk they are interested in. The identified elements at risk have a direct influence on the required 3D model and visualisation. These issues are, however, beyond the scope of this paper.

3.3 Analysis of data and process requirements

This section focuses on finding a proper representation for each model object. Each object is pointed out on a three-dimensional object representation scale composed of three axes: *Level of Detail (LoD)*, *Level of Data Processing (LoP)* and *Hazard Type (HT)* (Figure 3).

With respect to hazard type, a specific level of detail is required, which determines the level of processing. This relation may be represented as a point, line, area or volume in the three-dimensional scale. The *prevalence level* found from the hazard assessment is used to rank different hazard types. Hazards that have a low prevalence level are placed close to the origin, and those with a high prevalence are placed far from the origin. The resolution obtained from the hazard assessment is used for relating the HT and LoD. The LoD axes comply with the LoD as defined in CityGML. Further improvements and refinements of these levels will be needed, however. Currently, LoD4 is the only level for indoor, and this might be insufficient for the purpose of the framework.

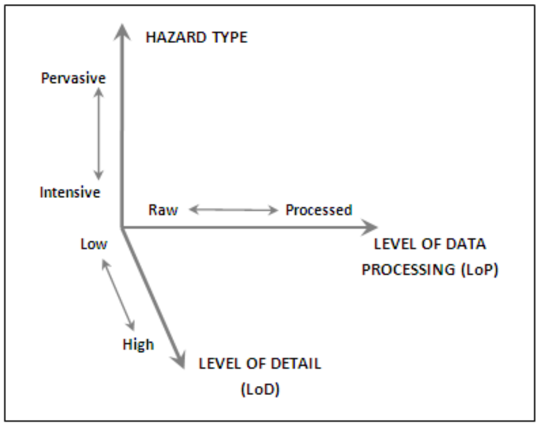

Fig. 3. The three axes used to define the 3D model: Hazard Type, Level of Detail and Level of Data Processing.

The LoP axis represents the effort required to generate the needed geometrical representation or to obtain the available data. In our data visualisation environment, there are three main components*: urban objects (above* ground), *terrain objects (on the ground)* and *hazard medium*. The integration of these three components constitutes the resulting model. Each of these components has process steps, model components and related spatial data analysis techniques. For urban objects, the needed process steps could start with digitising (if the model generator has paper copy maps) or building footprint extraction (the generator has only aerial or high resolution images in this case). Land cover classification and building height detection from stereo pairs (in this case, we have building footprints but there is no height data) may also be beneficial for urban object determination. Terrain objects generation could be done by using contour data, stereo pairs or photogrammetric field surveys. The accuracy and compulsory process cost increases for each method, respectively. The last component, and the context of our model, is the hazard medium. The process needed for the hazard medium originates from the characteristics of specific hazards or the aim of the visualisation. The hazard medium could be dynamic or static, and thus, the process needs increase, respectively. These examples may clarify the LoP definition; some municipalities may need to have a 3D extrusion model of a given area. To create such a model and provide it to the corresponding specialists, raw data may be needed to process flood inundation areas (if data and software are available). However, if indoor model of several buildings is required, the process needs more effort to create such an output. Processing efforts (represented by the axis LoP) start with creating the needed 3D representation with data collection. Then, 2.5D terrain representations with draped aerial or satellite images can be considered but require more effort, and therefore, these come after the raw data. 3D extrusion such as façade texturing with ground images, 3D object generation and integration with the surface, automatic or semi-automatic roof construction, detailed façade modelling by using ground point clouds and detailed indoor modelling can be at the end of this axis. Processes that need personal experience and immature functionality require more effort and take place at the right side of the LoP axis. Automatic methods for creating an output are located on the left side.

3.4 Needs assessment for visualisation (data and processes)

In this section, the available data and outputs are compared with the results obtained from the data and process requirement analyses. The required new data and model can be discussed with respect to the resources of the municipality. For example, the visualisation of a given hazard may require a 3D model with LoD4 resolution. However, the municipality may only have high resolution stereo aerial images. To come up with the desired product, they will need additional data such as ground images, building data that contain detailed indoor information, software for image processing of stereo images, 3D geographic modelling software and visualisation software to combine detailed 3D geographic objects and other spatial outputs like terrain models. Moreover, this modelling process will reveal that there will be a need for a considerable amount of human resources for the operation of this advanced software. It is up to the decision makers to find the best balance between the required model and the available resources.

4 Illustration of the framework within an earthquake case study

For an illustration of the framework, an earthquake case in Eskisehir, Turkey, is used. In this case, a visualisation application must be built for the users in the Eskisehir municipality. The users are municipality staff, such as urban planners, cartographers and sociologists. They need a clear view of the distribution of vulnerable regions throughout the city. The Eskisehir municipality has an urban information system infrastructure, so they have quite some data and software (planning, cartographic and GIS software). In this case, a 3D urban model environment is used to visualise the previously calculated social, physical and accessibility vulnerability indexes of each building object (Kemec and Duzgun, 2006). Eskisehir is one of the important centres of industry in Turkey. A number of dams and two universities are located within and near the city. Due to its rapid development, Eskisehir has become a popular location for new investments. It is an industrial city in central Turkey with a population of over 500,000. The greatest part of the settlement in the city is located on alluvium. The largest earthquake (Ms: 6.4) occurred in 1956. The pilot area is a part of the city centre and has various kinds of city development textures including low-rise, historic buildings and high-rise apartments. There are nearly 400 buildings in the case study area.

Step1. Hazard Assessment: In this case, as only one hazard is considered, the result will be a horizontal cross-section. The resolution, hazard characteristic medium and data representation are defined as follows: earthquakes affect a large area, and there is no intrusion. This means that an extruded building model at LoD1 from CityGML is suitable for this case. Moreover, earthquakes occur beneath the earth's surface, and the aim of the model is a visualisation of the vulnerability index values of each building. Because it is a data-driven process model, the used data representation is B-rep.

Step2. Defining User/Elements at Risk: As mentioned above, the users are municipality staff, and they can be both technicians and non-GIS experts. In general, they need relatively realistic 3D urban models. The basic elements at risk are considered to be buildings and socio-economic structures of the people living in the buildings. To construct a realistic urban environment and express the aim of the visualisation model, the objects are defined as Buildings, Relief, City Furniture (e.g., utility poles and street lamps), Transportation and Vegetation.

Step3. Analysis of Data and Process Requirements: The model objects defined in the previous step are represented with LoD1 of CityGML with some modifications. LoD1 for buildings, according to CityGML, does not contain façade image mapping, but the users request realism; therefore, it will be included. The model objects and their representations in the case study are clearly defined with respect to CityGML as well. Figure 4 represents the results of the data and process requirement analysis for this case. The normal letters denote object representations, and the italic letters denote initial data types.

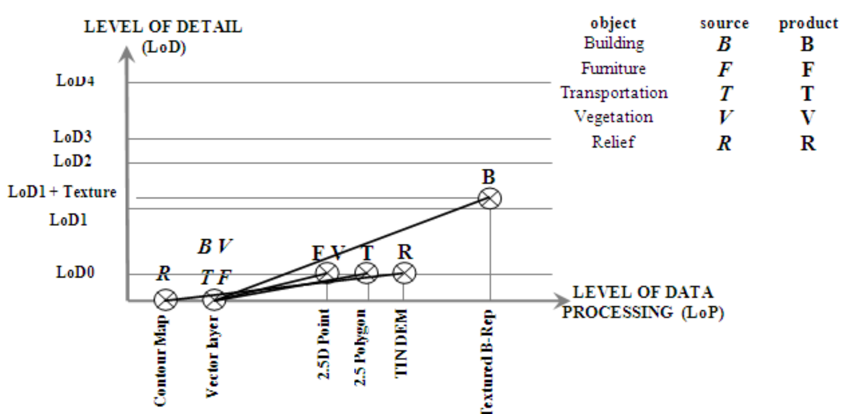

Fig. 4 . Cross-section of framework for an earthquake case.

Step4. Needs Assessment for Visualisation: The available data for urban modelling are as follows: vector layers from the Eskisehir Municipality Digital City Information System, street and building footprint layers and 1/25000 digital contour maps. To construct building objects, façade images and building height data are needed, which are collected by a field survey. Process steps to develop an urban model are: 2.5D DEM generation from digital contour maps, generation of LoD1 façade textured B-rep buildings by using building height information and ground images, draping of city furniture, tree points, road data and building models with a terrain model, relating tabular index data (hazard characteristic medium in this case) to the building objects (Figure 5).

Fig. 5. General view from the 3D city model generated for an earthquake case

5 Conclusions

The proposed framework draws a link between the disaster type and the needed 3D model for an appropriate 3D visualisation of vulnerabilities in risk assessment. To be able to establish this link, parameters are defined for hazard type (frequency, duration, spatial dispersion, speed of onset, areal extent and indoor penetration) and 3D visualisation (representation, level of detail and level of processing). The framework can be used as a tool by risk managers (and other stakeholders) to determine the necessary data types for 3D models to be used in a particular risk assessment (for simulation and/or visualisation). The main expected benefit of this proposed framework is the ability to create understandable, yet well-balanced 3D models to be used as risk communication tools.

This study shows that technological developments in CityGML, 3D data sources, data processing and 3D visualisation can be easily adapted to the framework. The initial applications of the framework are very promising and well-accepted by risk managers. However, the tests have revealed that further developments and/or refinements along all of the axes will be needed. LoDs, as currently defined by CityGML, may not be sufficient for all types of disasters. For example, in some cases, information about levels of a building is required only, without the need to create the LoD4. A combination of CityGML LoDs may be more appropriate. For example, low outdoor (LoD1) resolution with low indoor resolution (floor level) can be used for a hazard application that has a large spatial dispersion and an intrusion to the built environment (e.g., a tsunami). Future work will investigate these possibilities in detail.

The level of data processing demands further elaboration as well. Currently, the level of data processing is established by a rough estimation of the resources needed to obtain a specific model. Further investigations are needed to define the appropriate parameters that influence the data processing efforts. These parameters will most likely be specific for a municipality or data-processing unit.

More research and development are needed to formally define the relations and dependencies between users and elements at risk. A set of criteria should be made, according to which 3D objects can be selected from the object pool.

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