SELECTING 3D URBAN VISUALISATION MODELS FOR DISASTER MANAGEMENT: A RULE-BASED APPROACH

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Abstract

Urban 3D visualization hardly considers an integrated manner for the data visualization in disaster management. Generally, it should use interoperable approaches and data to reduce duplication of efforts and reduce costs. To achieve such interoperability, it is important to investigate the link between types of hazards and the required 3D model. Since a specific hazard may affect different urban features, it is believed that such a link can be described by a set of criteria. The criteria depend on the type of disaster and the urban 3D model. This paper presets a rule-based approach to derive the relation disaster/hazard type and the corresponding 3D model. The urban 3D features (and the spatial resolution) considered in our approach are compliant with level of detail (LoD) definitions as specified in CityGML.

1. Introduction

The perception of the decision makers (dealing with a specific natural hazard) is highly influenced by the visualization manner and must be considered and understood together. Digital maps are progressively used by disaster managers. 3D graphical representation significantly reduces the amount of cognition effort, and improves the efficiency of the decision making process. It is expected that 3D visualisation provided in the proper way, should help the entire disaster management process. However, visualisation has to be done correctly. Generally, 3D city models (constructed from heterogeneous data) are still quite expensive (in terms of efforts and time) and when prepared, they should be considered to be used in any natural disaster visualization application, which is applicable for a given urban

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area. There are various criteria that influence the appropriate 3D urban model for a specific natural disaster or a group of disasters. In this article, the definition of an appropriate urban model is handled as a decision-making problem applying a decision rule approach, which allows ranking of the alternatives.

In principle, the characteristics of the urban models are associated with the disaster impact area and the features of the exposed urban areas. Therefore, a relationship should be established between the urban model and the hazardous event. The urban model can have different resolutions (levels of detail). In this paper we use the level of detail (LoD) as defined by CityGML (Kolbe et al, 2005). CityGML is an OGC standard, which allows semantic and geometric information to be organized in one model. Semantic, geometrical and topological aspects of 3D city models are covered with class definitions of CityGML.

This paper is organized in five sections. The next section provides the needed background information. Section 3 introduces the rule-based approach for selecting appropriate LoD for specific disaster/risk visualization. Section 4 demonstrates how the decision rule has to be applied. The paper concludes with the discussion on advantages and disadvantages of the utilized rule-based approach and outlines future research.

2. Background

To be able to establish a link between natural hazard type and 3D models, two groups of criteria have to be considered namely *urban* and *hazard*. While the urban criteria take into account the characteristics of a specific urban area, the hazard criteria attempt to classify the hazard.

Urban systems are complex with physical and socio-economic sub-systems. On top of this, an urban texture on a narrow area with high population density makes complex structures difficult to understand and they need detailed approaches. Urban areas can be characterized by two sub-criteria (Sudhira et al. 2004):

- *Urban Area Extent*, which is related to size of the urban area. The place which has population over 5000 and don't have adjacent settlement within a 3 km buffer, is assumed to be urban area (Balk and Yetman 2004).
- *Population Density* in this paper is measured as the number of people on one hectare area.

In the literature, hazards are classified according to their occurrence reason natural or man-made/technological (Mitroff 1988, Haddow and Bullock 2003, Shaluf 2007), occurrence environment as atmospheric, hydrologic, lithosphere and biosphere related hazards (Kaplan 1996, Richardson 1994). Generally, there is no adequate scale to compare the magnitudes of different types of natural hazards. Magnitude comparison could be done with devised scales that consider basically the effect of natural disaster on the socio-economical and physical environment, specially constructed for some hazard types to compare different cases. For example Modified Mercalli earthquake intensity scale (Wood and Neumann 1931), scale of tsunami intensity (Soloviev 1978), volcanic eruption scale (Tsuya 1955, Newhall & Self 1982, Fedetov 1985) and landslide damage intensity scale (Alexander 1986b) etc. The intensity of the hazard and its spatial effect on affected areas form the basis of urban modeling studies. In the literature there is not yet a matured classification method to compare the spatial effects of different type of disasters. Kemec et al. (2009) introduce a spatial hazard approach to compare the hazardous events characteristic. According to this approach six sub-criteria reflecting the prevalence are defined:

- *Frequency* reflects the time interval in which a natural disaster occurs. For example: earthquake may occur with a log-normal frequency, while landslide may occur seasonally.

- *Duration* is the period of time that disaster continues. Hence it has a wide range from seconds to years. For example earthquakes are very short, while some of landslide types (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 changes between small to large.

- *Speed of Onset* is an important variable since it forms warning time. Most extreme ones 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. the earthquake zones are limited as they are governed by the tectonic plates.

- *Indoor Penetration*: Some natural hazards commit their fatal effects on built environment by intrusion of the hazard material into the built structure. This material can be soil, mud or rock in landslides or water in floods and tsunamis. Indoor penetration parameter is used to be able to find the answer question of: "Do we need indoor LoD at our visualization?" , together with the other criteria which are urban and disaster oriented as some hazard visualization cases may need different indoor LoD definitions at low LoD levels. For instance, floor level indoor representation would be beneficial in tsunami and flood cases which are pervasive hazard case, to find effected part of the building objects.

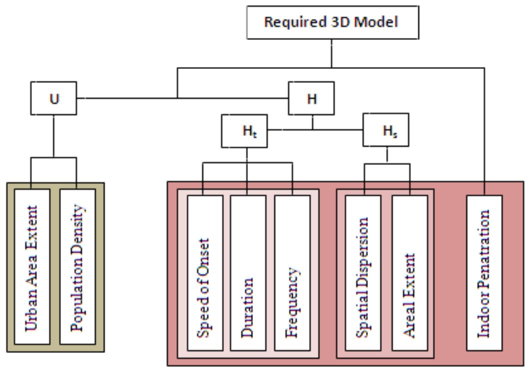
To be able to establish a link between the two groups (hazard and urban) a rule-based approach is used. Among the possible approaches, this study concentrates on the multi-attribute decision rule as described by (Malczewski 1999). The aim of Multi Attribute Decision Analysis (MADA) is to choose the best or the most preferred alternative by using decision criteria and attributes. The decision is made by applying four main MADA attribute combination rules (Malczewski 2006): *weighted summation, ideal/reference/point, outranking methods* and *analytic hierarchy process* (AHP).

The first rule assumes that all attributes have a linear relation with decision. The decision is made by summing the values of the attributes and the weights. The weights are often obtained simply by asking the decision maker to assign numerical values directly for a given maximum and minimum pre-defined quantization level (i.e. 0-1 or 0-100) for each criteria or sub-criteria. In the second rule, there is a theoretical ideal solution and the set of possible alternatives is ordered according to their closeness to this hypothetical ideal solution. The closest alternative to this point is chosen as the best alternative (Malczewski 1999). The outranking method deals with situations when some attributes have incomplete values. This method provides only an indication to rank the alternatives (Malczewski 2006). The AHP methods are the only ones that order the criteria sub-criteria and their attributes in a tree. These methods work based on three principles: *decomposition*, *comparative judgment* and *synthesis of priorities*. Decomposition means that the criteria have to be grouped accordingly, comparative judgment requires careful consideration of the place in the tree and the synthesis of priorities refers to the consideration of the branches in the tree. These principles are applied to construct the hierarchy (Malczewski 1999). The AHP method is found to be the most appropriate for our study since the weights of the attributes cannot be considered equal.

3. Decision Rule

We apply the AHP approach to build the relations between the different criteria, sub-criteria and their attributes in our rule-based tree. Criteria in this study are the valuation principles which apply to reach a decision. Some criteria could have some sub-criteria. All the criteria (sub-criteria) have attributes with measurable items, which can have well-defined values. The values are used to compare different alternatives at the end.

Figure 1. Rule-based decision tree



According to the decomposition principle, the criteria related to the decision are organised in a decision tree. The decision tree consist of thee levels, in which the criteria, sub-criteria and the attributes are placed. The weights of the attributes are derived from the location of the attribute in the tree. Branches at the same level have the same weight. For example, urban criteria U and hazard criteria H, both have weight of 50% (Figure 1).

Our decision tree should help in making a decision on the required 3D model. As mentioned earlier, there are two main criteria which influence this decision, i.e. *urban* and *hazard* related. Therefore they are given at the first level below the root of the tree. In the second level of the decision tree the two sub-criterion of the hazard are placed: one sub-criterion related to the spatial characteristics H_s and another related to the temporal characteristics of the hazard H_t. The third level contains the attributes. While hazard spatial characteristics H_s are represented by *spatial dispersion* and *areal extent* attributes, hazard temporal characteristics H_t are given with *speed of onset*, *duration* and *frequency* attributes. *Urban area extent* and *population density* are the attributes of the urban related criteria U. The urban criterion does not have sub-criteria. Using this approach all the characteristics as specified in Section 2 are organized in a decision tree.

Following the AHP approach, we can derive the weights of for the attributes as follow. Urban related and hazard related criteria have the same effect on our decision, therefore they have equal weights. Similarly, each hazard temporal and spatial sub-criteria has 50% weight. The attributes of each of the sub-criteria have also equal weights. As the urban related criterion does not have sub-criteria, the attributes has practically higher weight compared to the attributes of the hazard criteria. Thus, the urban related two attributes have 25% weight, the hazard temporal attributes 8,3% and the hazard spatial attributes 12,5%. The syntheses of all these weights constitute the decision priorities.

The decision tree is further used to derive a mathematical expression to be able to compute the required 3D model and more specifically the LoD. We define a function *intensity value* I_v,, which together with the *indoor penetration* i parameter will define the LoD of the 3D model. Please, note that the i parameter does not follow the AHP approach. It is added to the result obtained for the intensity value (equation 9).

The intensity value function I_v is defined as multiplication of hazard and urban criteria. The intensity function represents the hazard risk. Generally, the risk in a given area is defined in the literature as multiplication of hazard and consequences (Duzgun and Lacasse 2005, Basta et al 2007) or multiplication of hazard, elements at risk and vulnerability (ISDR glossary). Elements at risk in our case are given by the urban criteria. Therefore:

$$I_v = (H \times U), \quad (1)$$

where I_v is *intensity value*, H is *hazard related criteria* and U is *urban related criteria*. The hazard criteria H can be subdivided into *temporal* and *spatial* sub-criteria:

$$H = H_t + H_s \quad (2)$$

where, H_t is hazard *temporal sub-criteria* and H_s hazard *spatial sub-criteria*. The temporal sub-criteria has three attributes: *speed of onset*, *duration* and *frequency*:

$$H_t = ((s_o + d + f) / 3) \quad (3)$$

where s_o - *speed of onset*, d - *duration* and f – *frequency*. The spatial sub-criteria has two attributes named: *spatial dispersion* and *area extend*:

$$H_s = ((s_d + a_e) / 2) \quad (4)$$

where s_d - *spatial dispersion* and a_e - *areal extent*. The Urban criterion does not contain sub-criteria, but have two attributes as specified earlier: urban area extend and population density and can be represented as:

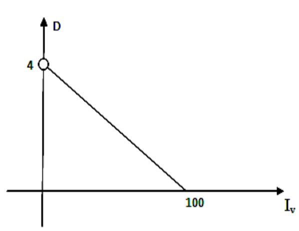
$$U = (a_{ue} + p) / 2) \quad (5)$$

where, a_{ue} - *urban area extent*, p - *population density*. Substituting (2),(3),(4) and (5) in (1) will result in the extended representation of I_v with all the attributes:

$$I_v = [(((s_o + d + f) / 3) + (((s_d + a_e) / 2)) / 2) \times ((a_{ue} + p) / 2)] \quad (6)$$

In the utilized decision rule I_v value could be in between 0 to 100. Figure 2 represent the relation between I_v and D. Attribute values are rated in the prevalence direction, which means that high I_v indicate pervasive situation so it needs low spatial detail and low I_v indicate intensive situation requiring high spatial detail.

Figure 2. I_v value and detail level relation



$$f(D) = \begin{cases} \text{If} \quad I_v > 0 & f(D) \\ \text{If} \quad I_v = 0 & \text{no need for modeling} \end{cases} \quad (7)$$

For the point of $I_v = 0$ f(D) function gave the highest detail result. However this case should be interpreted as modeling is not required; hence partial function of (7) is devised to eliminate this case. We define the *normalized intensity value* I_{vnorm} as:

$$I_{vnorm} = ((I_v - I_{vmax}) / (I_{vmin} - I_{vmax})) \times 4)_{round} \quad (8)$$

where, I_{vmax} is the maximum intensity value, I_{vmin} is the minimum intensity value. We apply linear transformation with quantization level four, because we have five different alternatives with respect to the LoD0 to LoD4. The obtained result is rounded because the LoD can be integers (0 to 4). Finally, we can compute the required LoD, denoted with *D*, of the 3D model as follows:

$$D = I_{vnorm} + i/2 \tag{9}$$

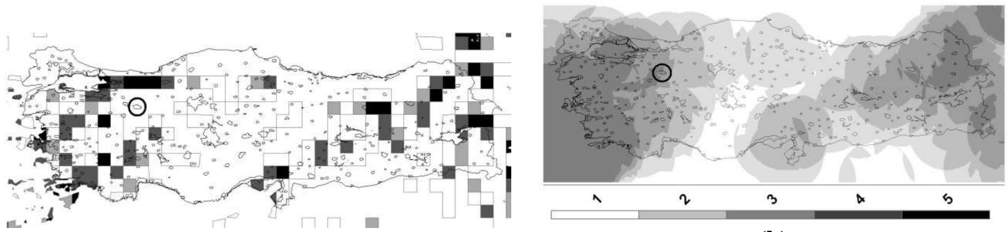
The indoor penetration attribute *i* can obtain Boolean value and gives an indication whether there is indoor (1) or not (0) indoor penetration. The value of the attribute *i* define whether indoor details are needed or not. Thus if *D* has an integer value, this means that there is no need for the indoor modeling, otherwise yes. For example, if we have D=2.5, the required 3D model will have outdoor LoD 2 (as defined in CityGML) and an indoor LoD which is compatible with the outdoor LoD. In case of building, this can be only floor compartments.

4. Application

To test the proposed rule-based approach, the earthquake case of Eskisehir, Turkey is used. In this case, 3D urban model environment is used to visualize 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 the central Turkey with a population about 500.000. The greatest part of the settlement in the city is located on alluvium. The largest earthquake (Ms: 6.4) was occurred in 1956. 3D urban modelling pilot area is a part of city centre and has various kind of different city development texture like low rise, historic buildings and high rise apartments. There are nearly four hundred buildings in the case study area.

To figure out the Eskisehir earthquake frequency and come up a comparison result to compute the *f* value, Columbia University CHRR 2005, Global Earthquake Hazard Frequency and Distribution result is utilized. Used earthquake database (Global Seismic Hazard Program) is cover 1976-2002 and greater than 4.5 on the Richter scale earthquakes. Utilized grid data show the global frequency distribution of earthquakes. Grid values were categorized (1-10) (figure 3a). Density function of ESRI ArcGIS software, with the weight of frequency is applied to the grid data to disperse the frequency information to whole country, to compare Eskisehir's earthquake frequency information with other settlements of the Turkey. (Density function devised a conic kernel which smoothly curved surface, center of the kernel takes high value than edges and this kernel is passed over each point of the study area) Generated raster density data than categorized to 1-5 (figure 3b), 5 indicating most frequent earthquake occurring areas of Turkey. According to the generated results Eskisehir's *f* value is 5.

Figure 3. (a) Columbia University Global Earthquake Hazard Frequency and Distribution output, dark grids have more frequent earthquakes. (b)Turkey earthquake frequency distribution



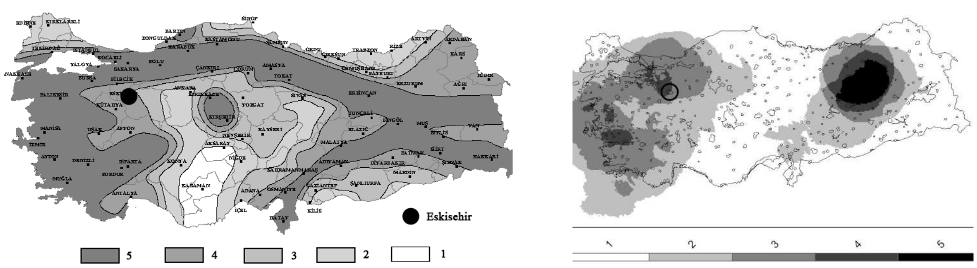
(a) **(b)**

The next temporal hazard attributes *d* and *so* is derived from empirical comparisons. If we compare earthquake with the other natural hazards, earthquake could be classified as short duration and fast speed of onset hazard (Burton et al. 1993). Therefore *d* and s_o attribute are given both value 1 in the scale of 1-5.

The next group of attributes is related to the spatial hazard extend. The attribute a_e is related to the spatial density of the hazard. Earthquake database of General Directorate of Disaster Affairs Earthquake Research Department (DAD 2009) is utilized to find the occurred earthquakes which are between dates 1991 to 2009 and have magnitudes greater than 4 on the Richter scale. Earthquake spatial density map (figure 4b) is generated by using this dataset. The Kernel density function (ESRI ArcGIS software is used as in the *f* calculation) which is also applied for the calculation of *f* is used. The magnitude values of the earthquakes constitute the weights in this case. Eskisehir is in the second most earthquakes occurred zone so the attribute value of the a_e is 4.

The attribute s_d refers to the pattern of distribution of a hazard over the geographic area in which the hazard can occur. A probabilistic approach is applied by (Özmen et al. 1997) to find the earthquake hazard zones for 50 years period with confidence level 90% (figure 4a). According to this study Eskisehir is in the fourth hazard zone in the scale of 1-5, five indicate most dangerous areas. This information is used for s_d attribute value of the case. The last hazard related attribute is *i*. There is no indoor penetration of any hazardous material to the built environment in the earthquake, so the attribute value of *i* is 0.

Figure 4. (a) Turkey earthquake hazard zones (Özmen et al. 1997), (b) Earthquake spatial density classification



(a) **(b)**

The *p* and a_{ue} attribute evaluation done among 339 settlements of Turkey. Urban definition of the utilized database which has SEDAC gridded population of the world and the global rural – urban mapping project is the place which has population over 5000 and the area adjacent settlement points if within a 3 km buffer of the urban area (Balk and Yetman 2004). Data processing steps to compute area sizes and the population density are; map projection conversion global spherical system (WGS84) to local Cartesian system (UTM), spatial join operation between urban extent polygon objects and urban point objects which have settlement population information. After calculation of the area size and population density *p* and a_{ue} attribute values of the Eskisehir is defined by considering statistical distribution of the all values. To define the *p* and a_{ue} classes geometrical interval classification is applied to convert measurements to the reclassified attribute values. Because the relation between areal extent and model detail needs is not linear, areal extent adds complexity to the urban system and more complex systems need more detailed modeling approaches. The same situation is also valid for population density. In this way instead of a linear value/utility function geometric one better suit to both of these attributes. In the geometric interval classification, intervals of the classes are calculated by subtracting the minimum from the maximum (Joseph 2007). The coefficient which converts the data-set to a geometric one is calculated by dividing the previous interval by the current interval.

Statistics related with the population density attribute: Minimum population density value is 0.65 per/ha, maximum density value is 108.05 per/ha other statistics related with population density attribute: mean 6.88, standard deviation 6.84. Eskisehir *p* attribute value is 2 with the value of 14.11 per/he (table 1). In this attribute evaluation, high density values take low *p* attribute value because they need intensive approaches.

Table 1. Distribution of population density values

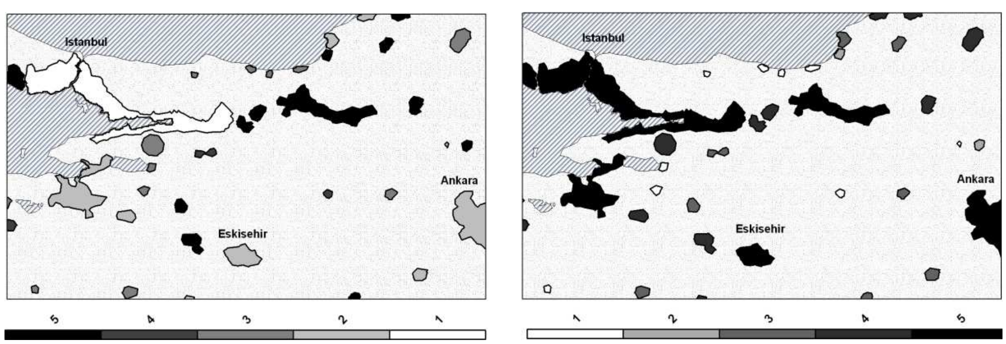
Classification	# of settelment	%	p
0.65 < pop_dens ≤ 4.47	108	0.31	5
4.47 < pop_dens ≤ 5.30	46	0.14	4
5.30 < pop_dens ≤ 9.12	119	0.35	3
9.12 < pop_dens ≤ 26.74	64	0.19	2
26.74 < pop_dens ≤108.05	2	0.01	1

Statistics related with the area extent attribute: Minimum urban area extent value is 726 ha, maximum urban area extent value is 199632 ha other statistics related with population density attribute: mean 12736, standard deviation 21944. Eskisehir a_{ue} value is 5 with 34208 hectares area size (Table 5).

Table 2. Distribution of area extent values:

Classification	# of settlement	%	a_{ue}
726 < area size ≤ 4516	90	0.27	1
4516 < area size ≤ 5089	22	0.06	2
5089 < area size ≤ 8880	108	0.32	3
8880 < area size ≤ 33940	98	0.29	4
33940 < area size ≤ 199632	21	0.06	5

Figure 5. (a) *p* attribute values for Eskisehir and near surrounding settlement (b) a_{ue} attribute values for Eskisehir and near surroundings



(a) (b)

Table 3 represents the attributes values of the case application. Decision rule is applied with these values to come up the urban model detail level decision.

Table 3. Eskisehir earthquake case attributes values

Criteria	H						U	
Sub-criteria	H_t			H_s				
Attribute	f	d	s_o	a_e	s_d	i	P	a_{ue}
Value	5	1	1	4	4	0	2	5

$$I_v = [(((1 + 1 + 5) / 3) + (((4 + 4) / 2)) / 2) \times ((5 + 2) / 2)] = 11.08 \qquad (10)$$

If these attribute values are entered into equation (6)

$$I_{vnorm} = ((11.08 - 25) / (0 - 25)) \times 4)_{round} = (2.23)_{round} = 2 \tag{11}$$

then the calculated I_v value is normalized with the utilization of equation (8).

$$D = 2 + (0/2) = 2 \tag{12}$$

The result of the decision rule is that the urban model detail level (D) for the specific disaster and this particular city has to be 2. According to the LoD2 definition of the CityGML, this requires that a building has differentiated roof structures and textures and vegetation objects may also be represented.
As it can be seen *i* take value of zero here, because there is no indoor penetration of the disaster. In case of floods or landslides, this attribute will have different value than zero. This attribute is closely related to the indoor LoD. It should be noticed that in some cases a course indoor detail may be more appropriate compared to a detailed LoD as given in LOD4 of CityGML. Moreover, combinations of indoor/outdoor CityGML LODs may be more appropriate to be established. For example, low outdoor (LOD1) resolution with low indoor resolution (floor level) can be used for a hazard application, which is a pervasive and have an indoor penetration (e.g. tsunami).

5. Conclusions

Eight attributes are used within proposed decision rule to establish a link between the hazard type and the spatial detail level of 3D urban model for the visualization of vulnerabilities in disaster management. These are two main groups: first, hazard related attributes: f (frequency), d (duration), s_d (spatial dispersion), s_o (speed of onset), a_e (areal extent) and i (indoor penetration), and second, urban related attributes a_{ue} (urban area extent) and p (population density). The variable D (level of indoor/outdoor detail) gives directly the needed LoD of the 3D model. The presented rule-based approach can be used as a tool by the technical group to decide on the necessary indoor and outdoor detail level of 3D models to be used in a particular disaster simulation and/or visualization applications.

Although the first application of this approach is very promising, further tests with different cities, countries and disasters are needed. Three of the attributes (s_o, d, i) are related to the empirical characteristic of the considered hazard, earthquake in this case. Five of them (f, s_d, a_e, a_{ue}, and p) are related to the local specification of the hazard and the settlement which is considered for the 3D urban modeling application. Attributes which have local specifications will change with the case. For example, the same hazard case may need different model detail level in a different settlement. The reverse is also true. The same settlement may require different 3D models if different hazard types are considered. Future research will investigate these possibilities in detail.

Another important observation from the first test is that LODs, as currently defined by CityGML, may not be sufficient for all the types of disasters. Hierarchical approach applied for the outdoor LoD could be beneficial for indoor LoD. Moreover further investigations could be needed for a multi hazard application. Future work will also explore these possibilities in detail.

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