An engineering approach for risk, resilience and vulnerability assessment of urban areas

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Abstract

A large part of the world's population, economic activity, and physical infrastructures is concentrated in fast growing urban environments. Among these, the security and citizen safety in densely populated areas has become a major issue. In view of the growing sensitivity to terrorism, large scale accident scenarios, natural disasters and crime, urban planning practice must incorporate appropriate security measures for vulnerability identification and resilience enhancements.

In this paper, a systematic approach is presented to evaluate possible threats and their expected consequences. The software assisted procedure is based on suitably defined risk analysis and management schemes and uses validated engineering tools for quantification. The paper provides a general description of the approach and the underlying methods. As an example application the evaluation of hazards from explosive threats is presented. The holistic approach is applied to assess decision variables like human injury, structural or monetary damage. Based on empirical data the susceptibility of a city is calculated to derive hot spots at risk. Afterwards a quantitative vulnerability approach including physical and engineering models is applied to identify weak spots in an urban surrounding. The results deliver decision support to see where countermeasures help most. For further detailed evaluation, a fast running CFD tool for explosions has been seamlessly incorporated into the software and offers more precise information concerning complex blast wave propagation. The results build the basis to derive security measures for the generation of robust and sustainable cities.

Keywords: Urban planning, explosive threats, vulnerability, resilience enhancement

1 Introduction

Security and safety relevant issues become an increasingly important factor in modern urban planning. Different facts prove this statement: For the first time in history in 2008 the physical degree of urbanization reached a value of 50 per cent and has a rising trend [1]. This concentration of population increases associated security issues. A growing population density in cities and their agglomerations has a pronounced effect on the vulnerability to hazardous events [2]. A further argument for considering safety and security measures is based on the formation of new threats. Urban areas comprise the most critical infrastructure of the society and specify significantly their respective resiliencies [3]. According to Branscomb [3] cities are increasingly vulnerable to natural disasters (e.g. hurricanes, flood, earthquake, tsunamis), technogenic disasters (resulting from human error and failing infrastructure, e.g. power failure) and terrorism.

The present work has the focus on contributing to counter terroristic threats. Terrorism is an asymmetric threat of growing importance that can pick targets anywhere [4]. Savitch emphasizes that urban spaces have become prime targets and cities are more likely to be attacked [5]. In general, such safety critical events are categorized as threats with low probability and potentially high consequences [6]. For the generation of sustainable and resilient cities there is a need for the quantification of expected losses and the identification of weak spots concerning these hazardous events. A software based solution is proposed in the following to assess quickly where and why security or enhancement measures are relevant.

The evaluation of expected losses brings in the terms risk, vulnerability and susceptibility. An interdisciplinary survey gives an overview concerning the meaning and understanding of these terms, like the approach of Ball [7] or Kröger [8], for example. Oriented to established assessment schemes [9] the procedure in Figure 1 is defined for quantification of expected losses and weak spot identification in urban environments. After the specification of the context and the scenario, the subsequent step is the assessment of risk including the two components of susceptibility and vulnerability analysis. The susceptibility analysis is applied to evaluate possible threats, their frequency and their magnitude. Furthermore, the exposition of single urban items to the threat will be derived. In the range of vulnerability analysis, the physics of possible threats are calculated and the expected consequences given a certain type of threat occurrence. Finally, a quantitative risk value is estimated and builds the basis for decision makers, if security measures have to be applied to minimize possible threats.

In this paper, single steps of the presented approach in Figure 1 will be assessed using new commercial software solutions including validated engineering models. An application example will evaluate possible explosive scenarios in the range of terroristic threats. In a first step, the VITRUV tool [10] is applied to assess susceptibility and vulnerability of a urban surrounding. After the identification of a weak spot, the software solution BlastSimulator [11] is applied to evaluate the detailed propagation of a shock wave in a developed area.

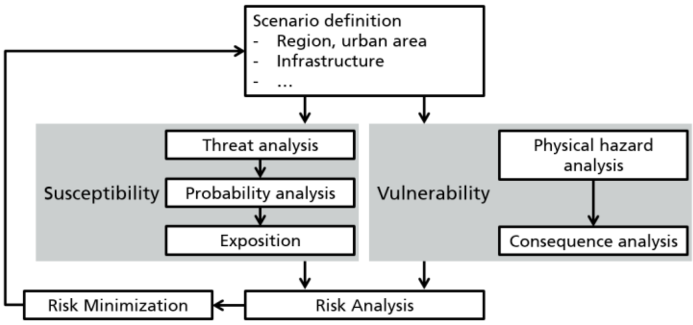


Figure 1: Comprehensive scheme for empirical and quantitative susceptibility, vulnerability and risk analysis for urban areas to improve resilience, oriented by [9].

2 Scenario definition

3D digital representations of an urban area are used for a detailed and quantitative assessment concerning explosive threats in a city. With a list of ten pre-defined building types, an arbitrary urban surrounding is approximated. As basis for susceptibility, vulnerability and risk assessment each urban object includes decisive attributes. For buildings, these parameter are:

- Name
- Position, rotation
- Dimension, number of floors, floor height
- Construction type, material
- Building quality, value [€/m²]
- Usage, building category
- Person density

Beside the name, position and dimension, traffic infrastructure elements have some further attributes:

- Route or rail type (e.g. highway or pedestrian area)
- Traffic density and portion of trucks
- Pedestrians density
- Rebuilding costs
- Information about rails
- Timetable cycle
- People per vehicle

The use of these attributes allows a precise definition of an urban area. This city model can be applied for further investigation of unexpected hazardous events concerning their probability of occurrence and the expected losses.

3 Susceptibility analysis

The frequency of occurrence for a certain type of threat in dependency of the usage $b_k(T_l)$ and the region G_h is derived by using empirical data from past events. In the present paper, the threat of terrorism, recorded in the “Terror Event Database – TED” at EMI [12] is used. Figure 2 shows a comparison of the derived events per year in dependency of the region and the building usage. The region of “open conflict” presents empirical data of countries in Near or Middle East. “Industrial society” uses empirical data of Western Europe and data of “emerging countries” are used for regions with a low development index. The usage is divided into the four main groups “public”, “civil”, “industry “ and “military”. For further analysis, these four main groups are divided into finer subgroups. There are significant differences in dependency of the region, e.g. the data of “Industrial society” have a higher frequency of occurrence in the range of corporation, SME, or finance and trading, for example.

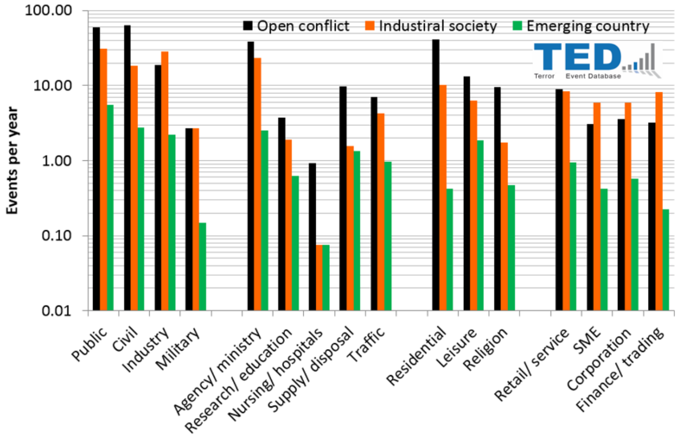
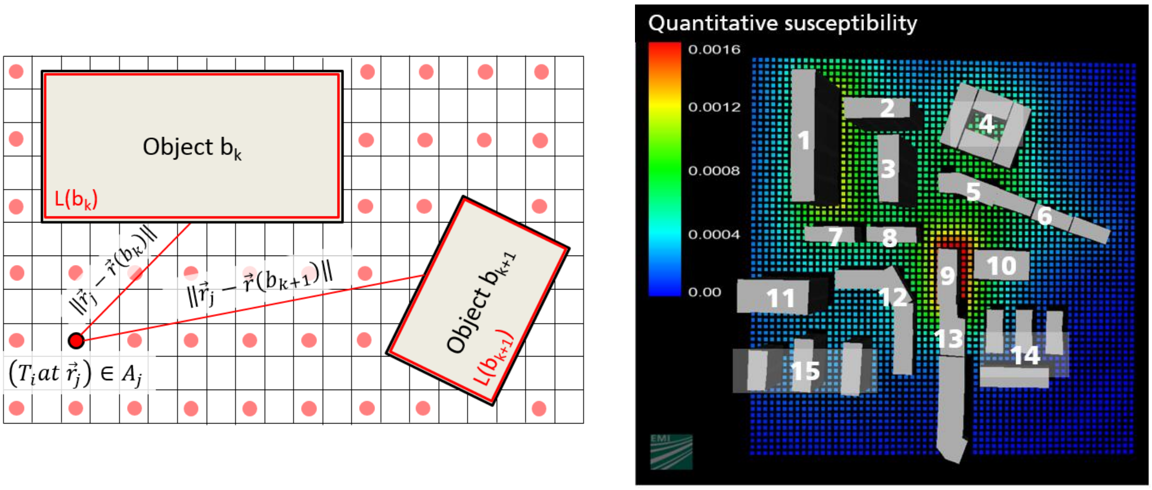


Figure 2: Empirical quantitative attack frequencies of terrorist events in dependency of the building usage and the region, derived by Fischer, et al. [12].

The presented empirical frequencies can be applied to derive hot spots at risk in a considered urban environment. The empirical approach allows a fast assessment of a physical defined urban area and critical elements are easily identified in dependency of the object type and the region. The visualized frequencies shows the criticality for single urban items but the interaction with neighboured objects and possible application of countermeasures are not considered. Therefore, the presented quantitative susceptibility approach will transfer the single empirical data of urban objects within a urban surrounding.

The left picture in Figure 3 presents the generalized approach for susceptibility analysis. A discretization is used to assess possible event locations. Possible event locations are placed into single area elements $\vec{r}_j \in A_j, j = 1, \dots, n_{locations}$. The probability of occurrence at a given position depends on the distance to a certain urban object $\|\vec{r}_j - \vec{r}(b_k)\|$ and the corresponding dimension (b_k) of the object. A single urban object b_k, k=1,…, $n_{\text{urban objects}}$ includes the empirical frequency $F(b_k, T_i)$ in dependency of the urban object b_k and the threat type T_i, i=1,…,n_{threats} e.g. a Vehicle Borne Improvised Explosive Device (VBIED). This value is obtained in dependency of the geographic region, see Figure 2.

The right picture of Figure 3 visualizes the calculated quantitative susceptibility of an urban environment. For each possible event location, the probability of occurrence is assessed with the use of empirical frequencies and the consideration of the developed surrounding.



(1) Corporation, (2,3) Finance/ trading, (4,5) Agency, (6,7,11,15) SME, (8) Supply/ disposal, (9) Embassy, (10), Retail/ service, (12) Nursing, hospital, (13) Religion, (14) Residential

Figure 3: Generalized approach for susceptibility analysis of urban areas (left) and the visualization of possible threat positions in an urban surrounding using an areal density function (right).

The right picture of Figure 3 presents the susceptibility $\hat{S}(T_i, \vec{r}_j)$, which is normalized over all possible event locations and threat types, see equation (1). For a single threat at a single position, the frequencies of all urban objects are considered with a density function $\mu(\vec{r}(b_k), L(b_k); \vec{r}_j)$ in dependency of the distance and the dimension of a certain object.

$$\hat{S}(T_i, \vec{r}_j) = \frac{S(T_i, \vec{r}_j)}{S}$$

$$S = \sum_{j=1}^{n_{location}} \sum_{i=1}^{n_{threat}} S(T_i, \vec{r}_j) \qquad (1)$$

$$S(T_i, \vec{r}_j) = \sum_{k=1}^{n_{object}} F(b_k, T_i) \cdot \mu(\vec{r}(b_k), L(b_k);\ \vec{r}_j)$$

In summary, the susceptibility is realized with a discrete areal density function. The presented approach give insights to the probability of occurrence in dependency of the location, the threat type, the urban environment.

4 Vulnerability analysis

The quantitative susceptibility analysis of section 3 give insights to the probability of occurrence of a hazardous event in dependency of the threat type and the urban environment. Oriented to Figure 1 the next step includes the evaluation of consequences, if a hazardous event occurs.

4.1 Physical hazard analysis

Within the presented approach the threat is quantified with the hazard model $H(T_i, \vec{r}_j; P)$, in dependency of the threat type or intensity T_i and the position $\vec{r}_j$. The characteristics of the model are described with the physics P. In case of an explosive event the peak overpressure p_{so} and the blast impulse I_o are physical parameter of the hazard model H. In Figure 4, the hazard of a VBIED scenario in front of a building is evaluated. The considered building is separated into different segments for each floor. For a single segment the explosive quantity and the distance to the threat are used to calculate the physics of the hazard with the semi-empirical approach of Kingery and Bulmash [13]. The angle between the line of sight and the normal vector of the segment area is further used to consider the pressure increase due to reflection. With application of the semi-empirical approach, Figure 4 visualizes the impact of the considered hazard scenario and areas with maximum intensity become apparent.

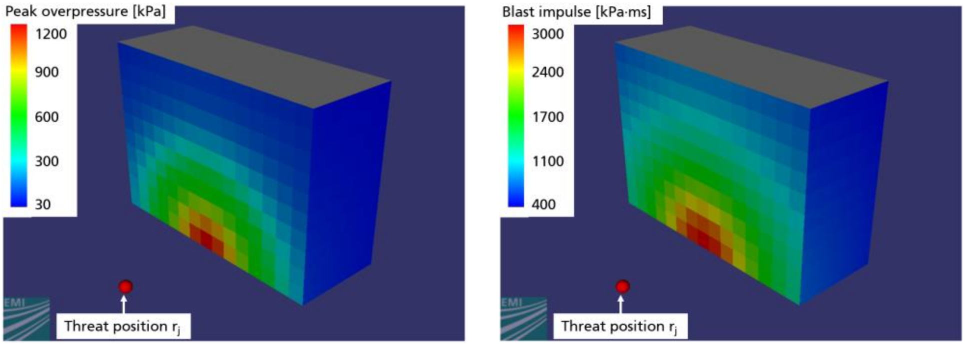


Figure 4: Evaluation of a single event scenario (VBIED) in front of a building. The physics P of the hazard model are the peak overpressure (left) and the impulse (right) in dependency of the position on the building façade.

4.2 Consequence analysis

To overcome poor statistical data the consequences due to exposition of a hazardous event are assessed with the use of physical and deterministic models. The consequences C (damage effects) of type D_n at position $\vec{r}_o, o = 1, \dots, n_{consequence\ postion}$ in the result grid are caused by the threat T_i at location $\vec{r}_j$ in the grid of the urban environment for a specific hazard model H. This size C is used to define the local vulnerability V.

$$V(H(T_i, \vec{r}_j; P), \vec{r}_o, D_n) := C(H(T_i, \vec{r}_j; P), \vec{r}_o, D_n) \tag{2}$$

The results in equation (2) are local individual damage effects per person or object with respect to the given consequence type in case of occurrence of the threatening event. A single hazardous event may have multiple consequences. Following equation (2) the quantitative assessment of consequences of type D_n are derived at position $\vec{r}_0$ in the investigated urban area with the use of a hazard model H. Similar to the decision variables of a performance based approach [14] three main categories of consequence types can be evaluated:

- personal damage (injuries or fatalities) inside or outside of a building,
- structural damage of building or infrastructure elements and
- direct or indirect monetary damage of building or infrastructure elements.

The derived blast loading parameter of the hazard model allows an estimation of injuries in open space and in buildings using quantitative models. Lethality estimation in dependency of the derived blast loading parameter for persons outside of a building can be made with the empirical model of Bowen et al. [15] or the physical model of Axelsson and Yelverton [16]. Injury assessment of people inside a building is derived with the probit curve model of Gilbert, et al. [17].

To predict the structural response due to blast loading single degree of freedom (SDOF) models are common practice and pressure-impulse diagrams are an extension of these models and provide a design chart for failure behavior of an arbitrary blast loading scenario [18] [19]. The application of the SDOF method delivers the initial damage of load bearing elements for a considered building. This information is further used for evaluation of the progressive collapse behavior. A complete building response estimation has been carried out for 10 building types in accordance with the construction information [20] and is implemented into the VITRUV software [10].

5 Risk analysis and management

The quantitative physical hazard and consequences for vulnerability assessment are valid for a single event with a given threat intensity and a single urban object. Similar approaches can be found in literature, e.g. the RAMCAP approach [21] or the reference manual FEMA-426 [6]. As indicated with the susceptibility analysis in section 3, the presented vulnerability approach (section 4) is extended to consider multiple threat intensities at multiple event locations. Furthermore, this extension includes the consideration of a complete city quarter.

In equation (3) a location and threat dependent value $R_{\vec{r}_j,T_i}(\vec{r}_o, T_n)$ is introduced to evaluate the risk at a given position $\vec{r}_o$ of a certain type of consequence T_n. In this equation the vulnerability (equation (2)) is weighted with the susceptibility of equation (1). A weighting factor θ_i^{threat} is applied to consider the probability of different threat intensities. With insights from empirical data of terroristic explosive events [12] it is assumed that events with a smaller charge weight have a higher probability of occurrence [22] and verify the size of the weighting factors.

$$R_{\vec{r}_j,T_i}(\vec{r}_o, T_n) = \frac{1}{n_{threat} \cdot n_{location}} \cdot \sum_{i=1}^{n_{threat}} \sum_{j=1}^{n_{location}} S(T_i, \vec{r}_j) \cdot \theta_i^{threat} \cdot V\big(H(T_i, \vec{r}_j; P), \vec{r}_o, T_n\big) \tag{3}$$

Oriented to the application example of Figure 3 equation (3) is applied for different types of consequence, as shown in Figure 5. The combination of empirical frequencies and validated physical vulnerability models allows a precisely identification of weak spots in an arbitrary urban surrounding. There are objects with an resulting low empirical frequency, but a relative high weighted vulnerability. Hence the approach presents in detail the consideration of neighboring effects. As a final result this assessment builds the basis for decision makers to see when and why security measures are relevant to generate more robust and sustainable cities.

The application of roadblocks, bollards, conversion of the building usage or structural retrofit are enhancement measures, which can be easily realized with the use of the presented approach. A recalculation of the modified scenario builds the basis to measure the effectiveness of single security measures and give a introduction into cost-benefit analysis.

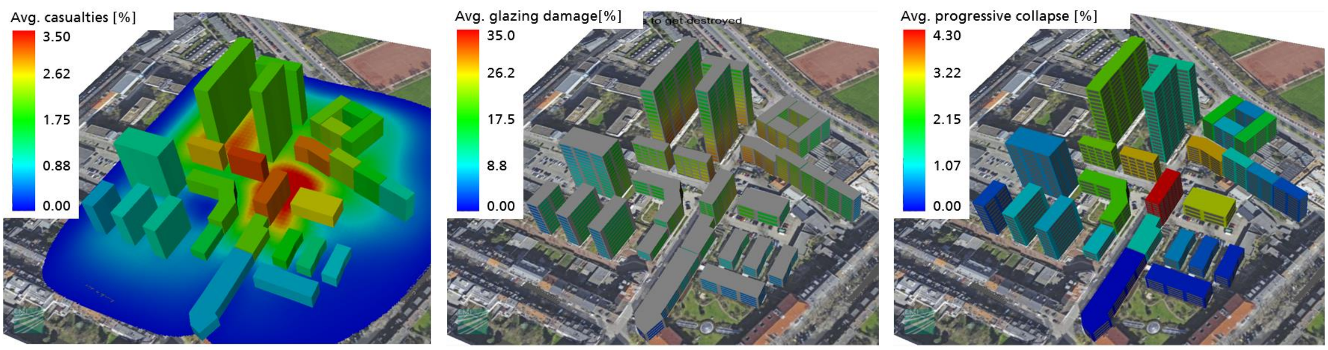


Figure 5: Averaged vulnerability of a urban environment with consideration of different threat intensities and multiple event locations. Predicted lethality (left), glazing and façade damage (middle) and progressive collapse behavior (right).

As shown in Figure 5 the presented approach is able to identify weak spots in an urban environment. As basis for vulnerability prediction, the hazard due to an explosion is quantified with the semi-empirical approach of Kingery and Bulmash [13]. This assessment is valid for a free propagating shock wave. Due to the propagation in an developed area, there are focusing and shading effects, which are not considered. Therefore the following section presents a fast assessment tool to overcome the weak points of the simplified approach and offers a detailed investigation of critical areas in the investigated surrounding.

6 Assessment of detailed blast propagation

6.1 Basic Models and Methods

The APOLLO Blastsimulator is a specialized CFD code dedicated to the simulation of detonations, blast waves and gas dynamics [11]. It is based on the conservation equations for transient flows of compressible, inviscid and non-heat conducting, chemically reacting gas mixtures.
The detonation process of an explosive charge is modelled on the basis of the Chapman-Jouguet theory, which is appropriate for the length and time scales typically considered in most engineering analysis. In addition, an empirical model for the effect of afterburning of TNT or other oxygen deficient explosives within ambient air is included. This model correlates the combustion rate to the fireball volume and is applicable to internal, external and partially confined explosions without scenario or charge specific calibration.
For the numerical approximation and solution of the non-linear partial differential equations a finite volume scheme with explicit time integration is used. The time integration is performed with a two-step scheme, which consists for each time step of a Lagrange step (acceleration and deformation of a material volume) and a subsequent step in which the updated material volume is remapped back onto the mesh cells. As for any finite volume scheme the core component is the method used for the calculation of the state quantities and fluxes at cell interfaces. For the Lagrange step we use a characteristics-based, linearized calculation of pressure and velocity at cell interfaces and for the remapping step we use the donor-cell method. These methods combine computational efficiency and flexibility, as they are not limited to specific type of equations of state.
Local thermal equilibrium is assumed for gas mixtures, i.e. all gases within one finite volume (a mesh cell) are supposed to have the same temperature. It is consistently assumed that the gas components within a grid cell are mixed and not spatially separated. A numerical diffusion of the gas components is thus accepted, which commonly however has a negligible effect on the pressure and temperature fields.
The finite volume method is extended to second order accuracy via a linear reconstruction of the conservative variables within the grid cells. The linear reconstruction is controlled through a slope-limiter to avoid artificial oscillations near shock waves or material discontinuities. The basic flow solver has been extended through several modifications which ensure full second order accuracy while maintaining a very high robustness. Important modifications are:
Extension of the linear, characteristics–based flux calculation through a conditionally performed iteration of non-linear terms added for strong shocks or strong expansion waves.
Three dimensionally coupled linear reconstruction for increased spatial isotropy of the second order extension.

6.2 Modules and Dynamic mesh adaption (DMA)

The above described finite volume method has been implemented in three different program modules, which enable the efficient simulation of both the detonation- and initial propagation- phase and the subsequent phase of interaction with the built environment. These modules are:

A. Detonation and free field blast wave propagation for spherical charges (1D solver)
B. Detonation and initial blast wave propagation for cylindrical charges (3D solver).
C. Blast wave propagation and interaction with arbitrary object geometries (3D solver)

In modules A and B a strategy of global mesh adaption is applied to achieve a high computational efficiency. A simulation starts on a small, highly resolved computational domain, which covers the charge and a small region around it. The domain is a 1D stretch in module A and a single block Cartesian grid in module B. When the wave front closely approaches a free boundary of the domain, the domain and the cell size are approximately doubled. The flow fields are remapped onto the new grid and the simulation is continued. This process is repeated until a termination criterion is reached. The simulation is then continued with module C, which covers the entire 3D scenario.
In module C a strategy of local mesh adaption is applied, which is based on the zonal concept depicted in Figure 6. The computational domain is here defined through an arrangement of equally sized cubic zones

in a multi-block structure. Each zone contains a uniform Cartesian mesh, the resolution of which can be changed at any cycle during the time integration. Thereby the mesh resolution can be dynamically adapted to the transient local flow fields. The available mesh resolutions are defined by mesh levels, c.f. Table 1. The zone length is determined automatically to suit the size of the entire scenario; the user just has to decide what the highest mesh level in the simulation shall be. This choice determines the accuracy and also the CPU time required for the computation.

Table 1: Overview of mesh levels and the resulting refinement.

Level	Cells/Edge	Cells/Zone		Level	Cells/Edge	Cells/Zone
1	1	1		4	8	512
2	2	8		5	16	4096
3	4	64		6	32	32768

Adjacent zones are either joined to form a continuous region or a wall boundary condition can be inserted between the zones for a zone-conforming model of rectangular shaped and oriented objects.
As an alternative or in combination with a zone-conforming model, geometric objects may be embedded into the zonal meshes, as illustrated in Figure 6. In order to maintain a high computational efficiency the embedding method distinguishes only between fluid cells and fully masked cells, partially masked cells are not treated. The embedding method thus permits to include arbitrary geometries but with step-wise approximated surfaces, with a minimum object thickness of one grid cell.
Objects are embedded in the highest mesh level. Zones which contain embedded objects are excluded from the local mesh adaption process and thus kept constantly on the highest level. As all objects are represented entirely on the same mesh level the object model is essentially a voxel representation.
The automatic control of the local mesh adaption, i.e. the selection of appropriate, time dependent mesh levels in the zones, is based on the time dependent gradients in the flow fields. Considered in this process are - equally weighted - the gradients of pressure, density, temperature, Mach number and mass fractions of gas components. The gradients are normalized with their time-dependent global maxima and then mapped onto a mesh level through a suitable function with an adjustable sensitivity parameter.
When changes of mesh levels are performed, the discrete flow fields on the current meshes are mapped to the new meshes. If zones are refined (the new mesh levels is higher than the current level) the discrete flow fields on the new mesh are obtained through interpolation from the old mesh using the same linear reconstruction of the conservative cell states as in the flux computation. For coarsening (the new mesh levels is lower than the current level) the discrete flow fields on the new mesh are obtained through conservative averaging of the cell states of the old mesh.

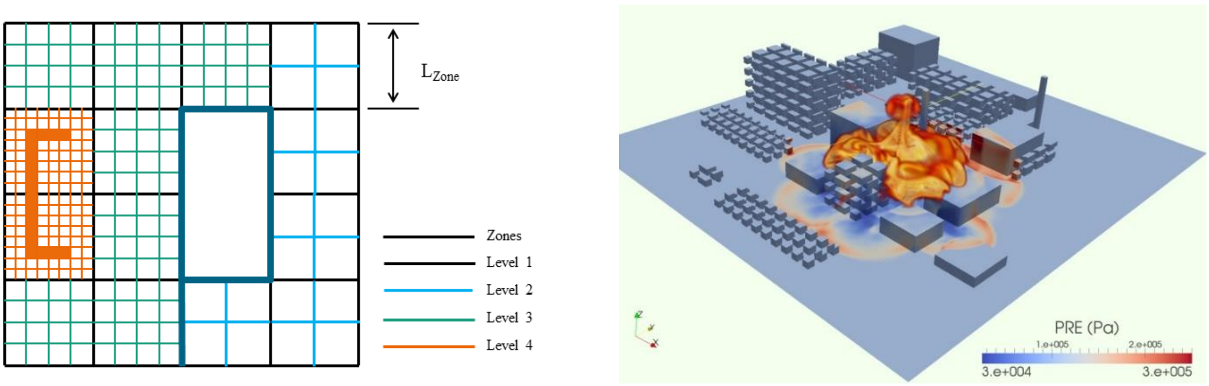


Figure 6: Left: schematic (simplified to 2D) of the zonal concept used for the dynamic mesh adaption: colors indicate mesh levels; a zone-conforming object is represented by dark blue thick lines and an embedded object by orang filled mesh cells. Right: example of a simulation model.

6.3 *Automatic processing and blast parameter sampling*

The entire processing chain is fully automated, i.e. no user-interaction is required for switching from the detonation phase simulation with module A or B to the subsequent simulation of the interaction phase with module C. Furthermore, suitable spatial resolutions are automatically determined, such that the user only

needs to specify the desired quality of the simulation in terms of a single attribute such as fast, typical or accurate.
The voxel model of the geometric objects used in module C can easily be derived from CAD data or other user-supplied scenario descriptions. It is therefore possible to embed the entire APOLLO Blastsimulator software into other software packets and run it in a fully automatic processing mode. Such an implementation has been realized in the software BREAS [23] or ESQRA [24].
To enable the evaluation of damage models based on PI curves the APOLLO Blastsimulator records the peak overpressure and the overpressure impulse in every grid cell. Furthermore local pressure transients are recorded on user defined gauge positions and surface averaged pressure transients (transient forces) are recorded for all objects within the scenario. These data permit a detailed assessment of hazards and consequences in the simulated scenario.

7 Conclusions

This paper presents a comprehensive and quantitative risk assessment scheme for the evaluation of urban areas. Beside the definition of a urban environment the susceptibility and the vulnerability analysis are the two main components to derive the risk for threat exposed urban objects.

In the presented approach physically designed urban object types are used to approximate an arbitrary environment. Historical data of hazardous events are applied to integrate the frequency in dependency of the region and the urban object type. The empirical frequency is considered into the quantitative susceptibility analysis scheme. Beside the empirical data, the susceptibility is derived with a multidimensional surface area density function including further information of possible threats and configuration of the considered urban environment. Therefore, the averaged probability of an event at a given position is estimated with the distance to and the dimension of urban objects.

The basis for the quantitative vulnerability estimation builds the implementation of established physical and engineering models to overcome poor statistical consequence data. The pre-defined building types are considered for the approximation of an given surrounding and allows an evaluation of personal structural, and monetary damage. In comparison to existing risk assessment schemes the presented approach considers multiple positions and multiple magnitudes of possible threats. Weak spots of an urban surround can be easily detected and build the basis for decision makers to apply possible security measures.

The identified weak elements of a urban surrounding can be evaluated in detail using the software BlastSimulator. In opposite to the fast running vulnerability approach this tool allows a detailed investigation of blast propagation in a developed surrounding for a single explosive event.

The new comprehensive approach of susceptibility, vulnerability and risk quantification is integrated in a suite of computerized tools and is readily available for security considerations in urban planning. Hence this approach give contributions to generate more robust and sustainable cities with an increasing resilience.

Acknowledgements

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